ECOLOGY, MORPHOTAXONOMY AND MOLECULAR CHARACTERIZATION OF CYCLOPOID COPEPODS FROM LAKSHADWEEP ISLANDS, SOUTH EASTERN ARABIAN SEA

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By

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Ecology, morphotaxonomy and molecular characterization of Cyclopoid copepods from Lakshadweep Islands, South Eastern Arabian Sea

Ph.D. Thesis under the Faculty of Marine Sciences

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Certificate

This is to certify that the thesis entitled "**Ecology, morphotaxonomy and molecular characterization of Cyclopoid copepods from Lakshadweep islands, South Eastern Arabian Sea**" is an authentic record of research work carried out by Mrs. Radhika.R (Reg. No. 4895) under my supervision and guidance in the Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology, in partial fulfilment of the requirements for the **Degree of Doctor of Philosophy in Marine Biology,** Cochin University of Science and Technology under the faculty of Marine sciences and that no part of this has been presented before for the award of any other degree, diploma or associateship in any university.

It is also certified that all the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the doctoral committee has been incorporated in the thesis.

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Declaration

I hereby declare that the thesis entitled "**Ecology, morphotaxonomy and molecular characterization of Cyclopoid copepods from Lakshadweep islands, South Eastern Arabian Sea**" is an authentic work carried out by me, under the supervision and guidance of Dr.S.Bijoy Nandan,Professor, Department of Marine Biology, Microbiology and Biochemistry, School of Marine Sciences, Cochin University of Science and Technology for the partial fulfilment of the requirements for degree of Doctor of Philosophy in Marine Biology of Cochin University of Science and Technology, and no part thereof has been presented for the award of any other degree, diploma or associateship in any university.

Kochi - 682 016 **Radhika.R**
February 2018

Dedicated to

My dear Achan…… who lives in heaven

&

My dear Amma

With indubitable support from the strong pillars of my life

My beloved Husband, Brother, daughter

&

Parents-in-laws

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CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

%	-	Percentage
≤	-	less than or equal to
≥	-	Greater than or equal to
°C	-	degree Celsius
Anon	-	Anonymous
cm	-	Centimeters
et al.	-	and others
Fig.	-	Figure
g	–	gram
i.e.	-	that is
Km	-	Kilometer
Km^2	-	Square kilometer
L	-	Litres
m	–	Meters
mg	–	Milligram
mm	-	millimeters
N	-	North
S	–	South
E	–	East
W	-	West
NW	-	North West
SW	–	South West
nm	-	Nanometer
No.	-	Number
ppt	-	Parts per thousand
v6	-	Version 6
µ mol	-	Micro mol
µm	–	Micrometer
C	-	carbon
y^{-1}	-	per year
day^{-1}	-	per day
DO	-	Dissolved Oxygen

Kvt	–	Kavaratti
Klp	–	Kalpeni
Mcy	–	Minicoy
Agt	–	Agatti
Bang	-	Bangaram
PreMon	–	Premonsoon
Mon	–	Monsoon
PoMon	–	Postmonsoon
No/100 m^3	-	number per hundred cubic meter
mtCOI	-	mitochondrial cytochrome oxidase subunit
spp. or sp.	-	Species
UNESCO	–	The United Nations Educational, Scientific and Cultural Organization.
BoB	–	Bay of Bengal
AS	–	Arabian Sea
GoM	–	Gulf of Mannar
PB	–	Palk Bay
PCR	–	Polymerase Chain Reaction.
EDTA	–	Ethylenediamine tetraacetic acid
NCBI	-	National Center for Biotechnology Information
ae	-	aesthetasc
A1	-	Antenna
A2	-	Antennule
CR	-	Caudal rami
PR	-	Prosome
GS/GDS	-	Genital somite/Genital double somite;
AS	-	Anal somite
P1- P6	-	first to sixth thoracopods
exp 1	-	3, exopods1-3
enp 1	-	3, endopods1-3
Mxp	-	Maxilliped.

Chapter 1

General Introduction

Contents

1.1 World Oceans –a glimpse

The oceans covering approximately 71% of the earth's surface, are well connected forming one "World Ocean". About 61% of the northern hemisphere and 81% of the southern hemisphere are covered by water. The average depth of the ocean has been estimated to be about 4000 m^2 that is substantially greater than the average height of land which is about 850 m^2 above the sea level. Living things inhabit all this vast stretch and these great depths. About 300 times of the habitable space provided by terrestrial and fresh water habitats are offered by the oceans. Almost 80% of the earth's primary production takes place in this environment. The warm waters of the dimly lit primeval oceans being the place where the first spark of life appeared million years ago, is now, a vast assemblage of varied forms of life. Remarkable stability and uniform grading with far less range of variation than that encountered on land or in fresh water, in respect of physical, chemical and biological characteristics, is the reason for this countless representation of organisms in the sea. The oceans are conventionally classified into four large basins. It has always been a matter of curiosity in science to know about the world's major ocean systems, the Pacific Ocean, Atlantic Ocean and Indian Ocean and their astonishing biophysical functions. The Pacific is the deepest and the largest ocean, almost as large as all the others combined. The Atlantic Ocean is a little larger than the Indian Ocean, but the two are similar in average depth. The Arctic is the smallest and shallowest ocean. Connected or marginal to the main ocean basins are various shallow seas, such as the Mediterranean Sea, the

Gulf of Mexico and the South China Sea. Though we usually treat the oceans as four separate entities, they are actually interconnected (Castro and Huber, 2003).

Indian Ocean has a low latitude land boundary to the north. Indian subcontinent partitions the northern basin, a feature that is different from the Pacific and Atlantic oceans. Indian Ocean having an unusually complex submarine topography with numerous major ridges influences the circulation, chemistry and biology, when compared with Atlantic and Pacific oceans, is highly asymmetrical both in north-south (with deep water, high latitude exchange confined only to the south) and east-west (with shallow water exchange along the eastern rim) directions.

Indian Ocean, the smallest of the three major oceans, is enormous, extending from the Tropic of Cancer to the shores of Antarctica, with its unique weather patterns and extraordinary wealth and variety of life. The Indian Ocean has been defined as the area between 25°N-40°S latitudes and 45°E-115°E longitudes but geographically it is an area from the latitude 40°S to the Gulf of Oman and the head of the Bay of Bengal on the north and from the east African and south African coasts on the west to the coastlines of Myanmar (Burma), Thailand, Malaysia (excluding the Strait of Malacca) and the western Australia on the east. The Indian Ocean can be classified into northern and southern regions of Equator. The northern region which includes the Arabian Sea, the Bay of Bengal and the Andaman and Lakshadweep seas, comes under the influence of monsoon. The land-locked nature and the biannual reversal of the direction of winds, known as monsoons are unique to the northern boundary. Therefore the hydrographical and hydro-chemical characteristics are very different in this area due to diverse geographical and meteorological conditions. However, the region south of the Equator is not affected by monsoon and hence the conditions of this region remain uniform except in the coastal regions of Africa, Australia or in the central Indian Ocean (QASIM1977)

Arabian Sea, being the North Western Indian Ocean is a region of negative water balance where evaporation far exceeds precipitation and runoff where off the Arabian coast is the region of the highest evaporation and decreases steadily

towards the south east. On the contrary, the Bay of Bengal, the southern counterpart, is a region of positive water balance with excess of precipitation over evaporation. These twin seas of Indian Ocean occupy only 3% of the world oceans, but receive 9% of the global run-off which is three times greater per unit area than the rest of the oceans (Budyko, 1972; Prasanna Kumar *et al*., 2004; Gauns *et al*., 2005; Sabu *et al*., 2015; Madhupratap *et al*., 2003; Jyothibabu *et al*., 2004).

Unlike the Atlantic and the Pacific oceans, morphologically, the Indian Ocean, does not extend into the cold climatic regions of the northern hemisphere. It communicates to the Antarctic ocean in the south. Hence, the Atlantic and Pacific oceans are supposed to be open oceans and Indian Ocean as a partially closed ocean. Occurrence of huge layers of extremely low oxygen water in the Arabian Sea and Bay of Bengal is the consequence of such an asymmetrical geographical structure and circulation. Climatological influence of Asian landmass over the northern part of Indian Ocean, by triggering the seasonal changing monsoon, reverses the seasonally changing circulation. Formation of high salinity water in the Arabian Sea and even more extreme in the Red Sea and the Persian Gulf is another unique feature of Indian Ocean. This layer of water mass affects the circulation severely at intermediate depths by preventing the water coming from the southern part of the Indian Ocean penetrating efficiently into the northern Indian Ocean. Comparing to the other two major oceans where the most pronounced oxygen minimum layers are found on the eastern sides, in the Indian Ocean, it is found in the two northern bays-the Arabian Sea and the Bay of Bengal (Qasim, 1998; Shankar *et al*.,2002).

1.2 Physico-chemical and Biological characteristics of the Indian Ocean

The Arabian Sea (AS) and **the Bay of Bengal (BoB)** are both tropical basins located in similar latitudes but separated by the landmass of Indian peninsula. Both the basins are under the influence of seasonally reversing monsoon, south westerly during June to September and North easterly during November till February. The Arabian Sea on its northern, eastern and western sides is bordered by Asian and African landmass and is connected with the Persian Gulf through the Gulf of Oman by a deep sill called the Hormuz Strait. The total area

of the Arabian Sea between latitudes 0°-25°N and longitudes 50°-80°E is about 6.225×10^6 Km^2.The AS receives lower volumes of river runoff (0.3-1012m^3 yr^{-1}) (Gauns *et al*., 2005). Annually, the Arabian Sea loses freshwater through intense evaporation (~1m yr^{-1}) and hence evaporation exceeds precipitation. Rivers Tapti and Narmada are two of the very few major rivers draining into the AS (Prasanna Kumar *et al*., 2004; Gauns *et al*., 2005).**The Bay of Bengal** with the total area of approximately 4.087×10^6 km^2, between latitudes 0°-23°N and longitudes 80°-100°E, where all the major rivers of India, Bangladesh and Myanmar drain, is surrounded on three sides by landmass (Qasim, 1998). In BoB, the precipitation exceeds evaporation as it receives large quantities of fresh water both from rainfall and river runoff (Sabu *et al*., 2015; Prasad, 1997; Rao and Sivakumar, 2003). The major rivers such as Ganges, Brahmaputra, Godavari and Irawaddy discharge about 1.5×1012 m^3 yr^{-1} of fresh water into the BoB (UNESCO 1988).Due to suggested possible reasons like cloud cover, large sediment load, narrow shelf, stable stratification and weak winter cooling ,generally, the BoB is considered to endure low biological production (Qasim 1977; Madhu *et al*.,2002; Senguptha *et al.*,1977; Radhakrishna *et al.*,1978; Gomes *et al.*,2000; Madhupratap *et al*.,2003; Jyothibabu *et al*.,2004)

Since the Indian Ocean is under the influence of annually occurring monsoons [the seasonally reversing wind systems that is driven by a pair of low (high) and high (low) pressure zones over the sea and land, respectively during winter or summer],the seasons are mainly classified as south west monsoon (summer monsoon-June to September),North east monsoon (winter monsoon-December to March) and spring intermonsoon period (transition period from winter to summer-March to May) and Fall inter monsoon period (transition period from summer to winter-September to October) (Madhupratap *et al*., 2001).

This annual cycle of monsoon governs the enrichment of the Indian Ocean. The river discharge and land run-off which are maximum during the monsoon period deliver enrichment to surface layers particularly along the coastal areas. While deeper layers get enriched by the process of upwelling when water rich in nutrients and low in oxygen content is fetched from the deep to the surface. Due to photosynthesis in the euphotic zone, the upper layers of water get impoverished

from nutrients while bottom cold waters are the main reservoir on nutrients. But in certain seasons, due to convergence of surface water which extends deeper than the euphotic, there occurs, an influx of the cold, nutrient rich deeper water to replace the upper layers. This phenomenon is called upwelling. The major upwelling areas are off the Somali coast, the south west coast of India (southwest monsoon), east coast of India and coast of Burma (north east monsoon).

Euphotic zone or the compensation depth (the depth where the illumination is 1% of the surface) increases in depth from coastal waters to the offshore regions. Transparency is low in all productive areas. The euphotic zone in the northern Arabian Sea, west coast of India and the African coast ranges between 40 to 60m while in the northern Bay of Bengal and along the east coast of India, the euphotic range in 60m due to large scale influx of turbid river water in the Bay. The euphotic zone ranges between 80m to 140m and transparency is higher in southern Indian Ocean.

Marine net primary production (NPP:mg Cm^{-2}) is a key metric of ecosystem health and carbon cycling and is commonly estimated as the product of plant biomass, incident solar flux and a scaling parameter that accounts for variations in plant physiology (Behrenfeld *et al.,*2005). Productivity fuels life in the ocean, drives its chemical cycles and lowers atmospheric carbon dioxide. Western Indian Ocean which encounters the strongest monsoonal wind forcing points to a strong coastal and open ocean upwelling resulting from coastal divergence of Ekman transport and from Ekman pumping, supplying nutrients to the surface and supporting elevated rates of primary productivity. Ekman pumping have been identified as the important forcing mechanism for the formation of northern cyclonic eddy (NCE) during summer monsoon. While its existence is maintained by the westward propagating semi-annual Rossby waves during fall intermonsoon and early winter monsoon. Continuous existence of NCE provides sufficient time for zooplankton to exhibit reproductive response which in turn increases secondary standing stock (Lévy *et al.*, 2007; McCreary *et al.*, 2009; Prasanna Kumar *et al.*, 2001; Resplandy *et al.*, 2011; Wiggert *et al.*, 2005; Roxy et al., 2015c).

The Arabian Sea is one of the most highly productive regions of the world ocean (Ryther *et al.,* 1966*;* Qasim,1988) while Bay of Bengal, the eastern counterpart, is a basin of low productivity because of low phytoplankton biomass, low availability of nutrients , heavier cloud coverage and turbidity arising from sediment fluxes that limit effective penetration of solar radiation in the upper euphotic column (Radhakrishna *et al.,* 1978 a&b; Qasim, 1977; Gomes *et al.,* 2000; Prasanna Kumar *et al.,* 2001*;* Madhupratap *et al.,* 2003; Sabu *et al*.,2015). Seasonally changing physical processes in accordance with the semiannual switching of atmospheric forcing contributes to the high biological productivity of Arabian Sea. It also follows seasonal cycles, reversing directions twice a year, in summer and winter. Rather than spreading across the expanse of the sea, the southwest (summer) monsoon is often concentrated into a jet over the central Arabian Sea. Evidence suggests that, variations in wind stress force substantiate upwelling in the ocean to the west of the jet, and weaker upwelling or even downwelling to the east. This upwelling provides nutrients to the euphotic zone and enhances biological productivity (Kenneth *et al*., 1998).

Annual total global ocean productivity averaged 67 Pg C yr^{-1} (Behrenfeld *et al.,* 2005) whereas the primary productivity of Arabian Sea was 163-337mg C $m^{-2}d^{-1}$, that of Bay of Bengal (512-32 mg C $m^{-2}d^{-1}$) (Gauns *et al*.,2005), Atlantic Ocean was 0.4-0.5 Pg C $month^{-1}$, that of Pacific Ocean was 0.8-1.6 Pg C $month^{-1}$,that of Arctic Ocean was 0.4 Pg C yr^{-1} and Antarctic Ocean was 8.3 Pg C yr^{-1}) (Behrenfeld and Fallowski 1997; Behrenfeld *et al*.,2001).

1.3 Current status of Indian Ocean

Since the beginning of the 20^{th} century, the global average Sea Surface Temperature (SST) has been increasing. During 1950-2009, the average SST of the Indian Ocean has increased by 0.65°C which is the highest warming rate of the major ocean basins. Consequently a significant sea level change has been detected in the Indian Ocean due to ocean warming and freshwater addition from glaciers (IPCC, 2013b).SST rise can augment near-surface stratification inhibiting vertical mixing and consequently inhibiting primary production which cascades through the entire food web in the region. Studies by Behrenfeld *et al* (2006) indicated a

reduction in primary productivity consequent to surface level stratification over most of the tropics. However, recent studies suggests an increase in net primary productivity with respect to elevating SST over the western Indian Ocean from 1998-2004 (Beaulieu *et al.*, 2013; Henson *et al.*, 2010; Patara *et al.*, 2012a).Thus, Western Indian ocean where rates of primary productivity is witnessing higher trends, is interestingly, a region with the long term(~100years) impact in sea surface temperatures (SST) in the tropics (Roxy *et al.*, 2014; Roxy *et al.*, 2015a; Roxy *et al.*, 2015c), even though such large trends in SST to productivity changes remains ambiguous (Behrenfeld *et al.*, 2006; Goes *et al.*, 2005; Gregg and Rousseaux, 2014; Gregg *et al.*, 2005; Prasanna Kumar *et al.*, 2010).

Another significant factor affecting the Indian Ocean system is recurring occurrence of cyclones in the Northern Indian Ocean which in turn show an increase in wind speed at its maximum. Prolongation of all these trends enhances the environmental stress on beaches and coral reefs with far reaching consequences on fishing and coastal protection. Acidification of the surface ocean due to uptake of anthropogenic carbondioxide is another significant factor which in turn decreases surface pH. Rashid *et al* (2013) has documented a decrease in pH of 0.2 in the period from 1994-2012 from the eastern Bay of Bengal. Coral reefs of the Indian Ocean are vulnerable to mass coral bleaching and mortality due to constant warming and acidification.

Hutchins *et al* (2007) opined that surface ocean carbon dioxide enhancement could lead to increased primary productivity for some species. This could have an impact on coral reefs and other calcifying organisms by altering their biogeochemistry. Another impact due to reduced pH in the oceans is the shifting of chemical equilibrium of nutrients especially from ammonia (NH_3) to ammonium (NH_4^+) which in turn modify phytoplankton nitrogen assimilation (which affect zooplankton in its next step) and microbial nitrification (Gattuso and Hansson, 2011). Recent studies by Hoegh Guldberg *et al* (2014) have documented the vulnerability of commercially fished species to ocean acidification. Studies by Bednarsek *et al* (2012) have established the fact that ocean acidification has disrupted the upper levels of pelagic food webs in the southern sector of the Indian Ocean which corroborates the previous studies.

Due to intensified industrial and agricultural activities, population density of the Indian Ocean rim countries has increased tremendously. This has led to eutrophication and increased atmospheric pollution. The main source of eutrophication in the coastal oceans is riverine inputs of dissolved nutrients. A high degree of eutrophication during premonsoon and minimum in post monsoon period has already been reported in the estuaries of South West Indian coast (Jayachandran and Bijoy Nandan, 2012). Harmful algal blooms are one of the main outputs of local eutrophication that has been observed during the past three decades in the coastal waters of Arabian Sea and Bay of Bengal (Padmakumar *et al*., 2012).

Intensity of premonsoon tropical cyclones in the Arabian Sea, that increases damage in coastal zone areas, has immensely increased in the period from 1979 to 2010 (Evan *et al*., 2011) which in turn, has an repercussion of enhanced anthropogenic black carbon and sulfate aerosol emissions. Deoxygenation affects the overall productivity of the Indian Ocean system as well as the other major world oceans, by expansion of intermediate layers and loss of nutrients which consecutively has caused increase in respiratory stress and has threatened the existence of fish populations. Sea-level rise and intensification of cyclones in future will cause substantial damage of coastal infrastructure and alter coastal ecosystem such as mangroves, beaches and coral reefs. Indian Ocean being a dynamically complex and highly variable system under monsoonal influence, the scenario gets compounded.

However recent studies (Kwon *et al*.,2014) indicates that by reason of comparably small area and its special geographic conditions, the overall uptake of anthropogenic carbon dioxide in the Indian Ocean is comparatively low than that of other major ocean basins. Consequently the physico-chemical parameters of the Indian Ocean will obviously be lower when compared to that of other oceans even though the causes for these differences are not well understood (Takahashi, 2014).In and around the Indian Ocean, several uncertainties persist in terms of geological, oceanic, climatic and marine biogeochemical cycles. Budding concerns about food security in the context of global warming and of anthropogenic impacts on coastal environments and fisheries sustainability also exist. So, there is an imperative need of time series measurements on the spatio-temporal evolution of

major ocean surfaces and its related islands for the proper and systematic knowledge of all these aspects.

1.4 Island ecosystems (coral reef ecosystem)

Island ecosystems (coral reef ecosystem) which forms an important constituent of ocean ecosystem provides home for about one-tenth of the world's population ie, about 600 million people. Islands account for nearly 1/6th of earth's total land area, yet the ecology of island ecosystems is vastly different from that of mainland communities (Pauly, 1995).Their isolation and high availability of empty niches leads to increased speciation. Accordingly, island ecosystems comprises 30% of the world's biodiversity hotspots, 50% of marine tropical diversity and some of the most unusual and rare species (Zeitzschel, 1973). Many species still remain unknown in this incredible ecosystem. In addition to the aesthetic, spiritual, educational and recreational values, islands harbour numerous discrete ecosystems, from mountain and forests to wetlands. By defending against natural disasters, supporting nutrient cycle, soil and sand formation, regulating climate and diseases; islands maintain the ecosystem functions. The characteristics that simultaneously make many of these islands ecologically and culturally unique are their fragility, vulnerability, size, shape and degree of isolation. Island ecosystem which primarily includes coastal ecosystems also fulfill many ecological roles, ranging from shoreline protection to buffer zones, from land-based activities and pollution to feeding, breeding and nursery grounds to many marine species.

Among the oceanic islands, **coral reefs** which form a specialized ecosystem command the greatest importance by virtue of their very high productivity, maximum diversity of fauna representing all animal phyla, complexity of trophic organization and finally the resources that are of direct economic importance to mankind (Qasim, 1998).Coral reefs forms unique and spectacular ecosystems of the tropical seas with most striking features of biological activity occurring in the sea leading to a large assemblage of reef-forming animals. Coral reefs, one of the supreme examples of the natural architecture in ocean's blue warm waters of the world with startling complexity, are essential to the health of the world's oceans and to many human communities as well. They provide support for marine

fisheries, which provide the principal protein source for many island populations. Coastal communities exploit coral reefs for commercial purpose along with their livelihood. Such an over dependence on reefs as means of human sustenance have made corals reefs and island ecosystem more susceptible to destruction. According to current records, highest proportions of species extinctions are also taking place in islands inspite of its high biodiversity. A large number of coral ecosystems located all over the world are on the brink of extinction. Coral reefs of the Indian Ocean consist of atolls, fringing reefs, patch reefs, elevated banks and submerged banks. Under the category of major oceanic coral reefs, three areas are described: Lakshadweep Islands, Andaman and Nicobar Islands and Maldive Islands. Besides these, coral reefs of the fringing and patch-types in the Indian Ocean are found in Sri-Lanka, Chagos Archipelagos, Mauritius, Seychelles, Malagasy, African coasts, Burma, Thailand, Malaysia and Indonesia.

An atoll is a ring of reef and often islands, surrounding a central lagoon. The vast majority of atolls occur in the topical Indian and western Pacific Ocean, Caribbean and the rest of the tropical Atlantic Ocean. Atolls, being different from fringing and barrier reefs, can be found far from land, rising up from depths of thousands of meters or more. In atolls, there is no river-borne silt and have very little freshwater runoff. Atolls, immersed in pure blue ocean water, display spectacular coral growth and breathtaking water clarity. Atolls range in size from small rings less than a mile to 30km (20miles) in diameter. Atolls include a dozen or more islands and are home to thousands of people. The two largest atolls are Suvadiva, in the Maldive islands in the Indian Ocean and Kwajalein, one of the Marshall Islands in the central Pacific.

A coastal lagoon which is a "shallow coastal water body separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets" are highly productive natural service provider of fisheries productivity, storm protection, tourism and others. By supporting a variety of habitats including salt marshes, seagrasses and mangroves, they contribute to the overall productivity and also provides habitat for many fish and shellfish species. Coastal lagoons favour primary producers by means of their comparatively low

flushing rate. Lagoon nutrients often exchanges or mixes up with that of ocean which uphold primary productivity which sequentially fosters secondary productivity.

The major islands of Indian Ocean are Lakshadweep islands, The Andaman and Nicobar Islands, The Maldives and The Great Barrier Reef. **Lakshadweep islands**, are a group of 11 inhabited and 25 uninhabited tiny islands and geographically separated from the Malabar Coast along the west coast of India by a distance of about 200-400km.Comprising twelve atolls, three reefs and five submerged banks, the archipelago covers an area of 32sq.km. **The Andaman and Nicobar islands** are situated about 1150km east of the Indian subcontinent near Burma and Sumatra that constitutes 325 islands of which 38 are inhabited. The total land area of both groups of islands amounts to 8120sq.km of which most of them are natural forests. These are of volcanic origin with elevated sedimentary mountain ranges. Eastern side is bordered by fringing reefs at depths ranging 5-7m and western side by barrier reefs with lagoons upto 40m deep. Due to anthropogenic activities, the inshore waters of some islands have become turbid leading to large scale mortality of corals while some others have luxuriant coral growth. Corals have a great aesthetic appeal and are a great source of tourist attraction for scuba diving and underwater photography. The reef serves as a nursery and breeding ground for many organisms such as fishes, crustaceans and molluscs. Most of the islands have luxuriant mangrove forests. **The Maldives** include 1190 islands forming a double chain with a total land area of about 300sq.km.Three islands have an area of about 4sq.km and nine islands with 2 sq.km. Out of the total islands, about 200 are inhabited, with Male as its capital. There are many fish canning factories of different islands. More than 86000 living (aquarium) fishes and a major amount of red corals, cowries and sea cucumbers are being exported from the Maldives family. **The Great Barrier Reef** of northern Australia is still considered as a natural wonder. It is the largest and a complicated system of more than 2500 small reefs, sand cays , lagoons, channels and islands which runs more than 2000km along the north eastern coast of Australia, varying in width between about 15 and 350km and covering an area of over 225,000km^2.

However, in islands outlined by coral lagoons, the population has comparatively increased when compared to previous years and is mounting day by

day which in turn will have an impact on physicochemical and biological aspects. Currently marine food web is undergoing serious changes due to climate change, top down and bottom up processes which in turn has a strong bearing on various components of the trophic tier occupied at primary, secondary and tertiary levels. Since 1998, the least productive oceanic habitats or the oligotrophic gyres in three of the world's major oceans have been expanding at average rates between 0.8%/year and 4.3%/year. Recent studies on changes in ocean productivity during the recent post-1999 warming period have provided insight on how future climate change can alter marine food webs (Polovina *et al.,*2008). It is however imperative to have a firm understanding on the trends in productivity of Indian Ocean since it has been experiencing one of the largest warming trends over the tropical oceans. Such a trend can have great repercussions for ecosystem processes which in turn have feedback on ocean-atmosphere dynamics (Murtugudde *et al.*, 2002; Patara *et al.*, 2012b). Variation in plankton production can have massive impact on marine species as well as humans (Colwell, 1996; Harvell *et al.*, 1999). Since the Indian Ocean including its islands and associated lagoon systems remains under-sampled in both space and time, especially when compared to the Atlantic and Pacific oceans, understanding of its ecological, physico-chemical and biological processes is still rudimentary (Second International Indian Ocean expedition(IIOE-2)-Science Plan, 2015).

1.5 Scope of the study

Lakshadweep (coral) islands in the South Eastern part of Indian Ocean forms the world's most spectacular tropical island ecosystem with extreme diverse geomorphologic and climatic variations with the foremost component being coral reefs, lagoons, seagrasses, seaweeds, algae and mangroves. These flimsy ecosystems are in turn colonized by wide variety of fishes, tunas, live-bait, octopus, crabs, molluscs, sponges, echinoderms, other invertebrates, reptiles, dolphins and whales. Apart from the marine face, a terrestrial face is also significant with coconut plantations, rodents and the birds playing their roles that has attracted the attention of several researchers and naturalists.

The hydrography of a marine ecosystem is strongly influenced by various factors including currents and tides which turn have an influence on the pelagic components of the system of which the important one is plankton. Among the planktonic components, **zooplankton** functions in regulating the food web and the biological pump. Zooplankton includes a categorization, spanning a range of organisms with size including small sized protozoans and large metazoans. There has been an upsurge of interest during recent years in understanding the distribution and composition of zooplankton for evaluating the production potential of water bodies as they occupy a crucial position in the pelagic food web by transferring organic energy produced by primary producers through photosynthesis to higher trophic levels in aquatic biosphere. Their role in ocean carbon flow dynamics, through their interactions with higher and lower trophic levels within the water column have been very well depicted (Isari *et al*., 2007; Bhattacharya *et al*., 2014). Zooplankton as potent indicators of climate change and pollution in marine systems have also been well understood (Chiba and Saino, 2003; Molinero *et al.,* 2005).Therefore, understanding the composition, distribution and abundance of zooplankton is a prerequisite to assess the ecological status including the productivity of any aquatic ecosystem**.**

Of all the marine zooplankton groups, copepods are probably the most familiar, since they are the dominant constituent of the plankton in all marine ecosystems, comprising about 70% of the plankton fauna and ranked as the world's most abundant metazoans (Raymont, 1983). The pelagic copepods which occupies the highest biomass in the marine ecosystem, exhibits great diversity in morphology and habitats (Radhika *et al*., 2014; Sanu *et al*., 2014). Copepods, meaning "oar foot", aquatic crustaceans are the largest and most dominant and diversified group of crustaceans in zooplankton communities. They inhabit all types of aquatic (fresh, brackish and sea water) and semi-terrestrial habitats or living in symbiotic relationships with other organisms (including fish). They constitute the main secondary producers in the marine environments and a fundamental step in aquatic food chain as many other nekton and benthos rely on them as food. Copepods are sexually dimorphic with females larger, are of prime importance in marine ecosystems. The majority of copepods feed on

phytoplankton, forming a direct link between primary production and commercially important fish, such as sardine and herring. Copepods are also the main food source for a great variety of invertebrates. Studies on copepod abundance and species composition are particularly relevant, because most larvae of commercial fish feed on copepods. Hence, changes in the abundance of these plankton from year to year, may determine inter annual population fluctuations of the commercially exploited fish stocks in a particular region.

Diatoms and dinoflagellates, the largest primary producers form the basis of classic grazing food chain in oceans. These phytoplankton cells are consumed by the herbivorous grazers especially the copepods, a crucial component of zooplankton crustaceans. Copepods measuring 1-2mm in length, using their tiny mouth appendages, filter the phytoplankton. These zooplankton are then consumed by small to large fishes and then by larger predatory organisms. The huge mass of faecal pellets (poop) are produced by zooplankton, the dead and decaying phytoplankton as well as zooplankton constituting the particulate organic matter (POM) forms the detritus food chain. Some POM is also consumed by zooplankton which gets recycled to grazing food chain. A schematic representation of marine epipelagic food web is given in Figure 1.1.

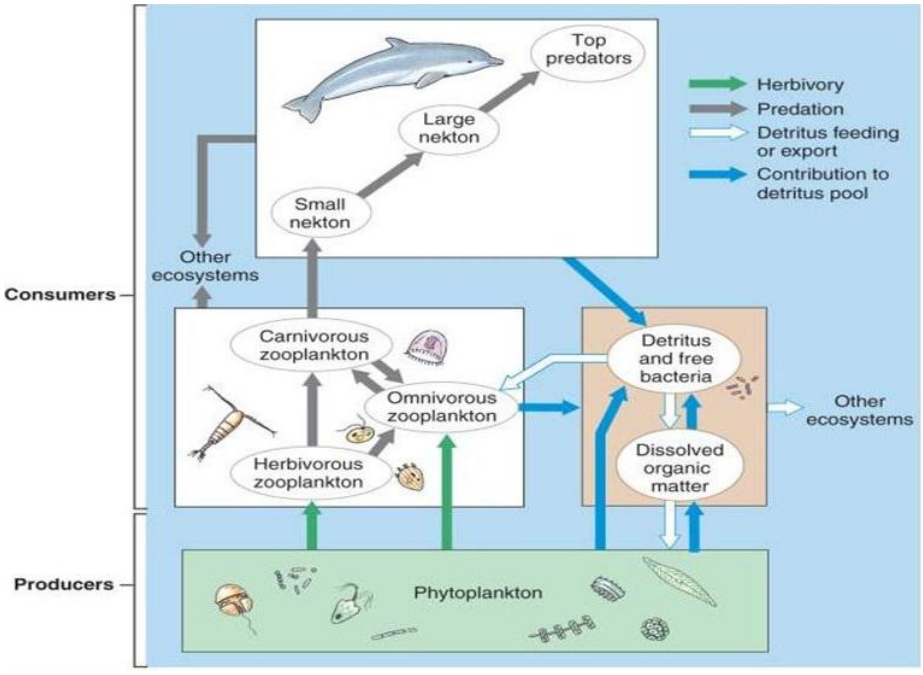

Fig.1.1 A simplified epipelagic food web-source - (Castro and Huber, 2003)

Since last decade and even before, there have been numerous revisions on the systematics of copepods. Copepoda comes under the Phylum Arthropoda and Class Crustacea. Neocopepoda and Progymnoplea are the two Infra Classes under the Subclass Copepoda. The infraclass Progymnoplea includes a single order, the Platycopioida. The infraclass Neocopepoda contains two superorders: Gymnoplea and Podoplea. Gymnoplea includes the Calanoida and Podoplea includes remaining seven orders (Misophrioida, Monstrilloida, Mormonilloida, Siphonostomatoida, Harpacticoida, Gelyelloida, Cyclopoida).The Monstrilloida and Siphonostomatoida mostly contains exclusive symbiotic or parasitic species, the others as a rule include free-living forms (Huys and Boxshall, 1991).The old order Poecilostomatoida has been recently moved to Cyclopoida (Boxshall and Halsey, 2004; Dussart and Defaye, 2006), but Suarez -Morals and Fuentes-Reina (2015) still consider the genus Kelleria in the order Poecilostomatoida (Family Kelleriidae Humes and Boxshall, 1996) with valid species (Walter and Boxshall, 2014).The marine environment mainly encounters with mainly three orders, Calanoida, Cyclopoida (syn-Poicilostomatoida) and Harpacticoida. Generally the zooplankton community is dominated by Calanoids .Cyclopoids (syn-poicilostomatoids) are found in swarms. Hapacticoids are mainly benthic. A diagrammatic representation morphology of cyclopoid copepod is given in Fig.1.2.

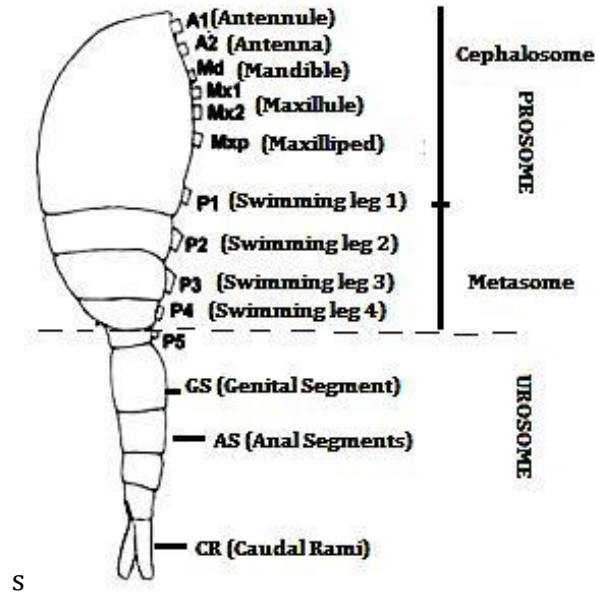

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Fig.1.2 A diagrammatic representation morphology of cyclopoid copepod

Among the copepods, **cyclopoids** are raptorial carnivores which often feeds on larger prey including fish larvae, while calanoids are both omnivorous particle grazers and opportunistic predators on micro zooplankton whereas harpacticoids are grazers or browsers of benthic microflora and fauna (William and Dennis,2012).

The importance of copepods is not only embodied in the role they play in the transfer of energy from primary production to higher tropic levels (Mauchline, 1998), but also, some species may be used as water mass indicators (Longhurst, 1967; Dawson and Knatz, 1980; Cross and Small, 1967), or as bio-indicators for chemical contamination and eutrophication (Dawson and Knatz, 1980).Thus, understanding the grazing as well as detritus food chain in oceans requires knowledge on the zooplankton and the dominant role of copepods in partitioning the trophic elements as well as the physico-chemical attributes influencing their community structure patterns. Therefore this Ph.D. thesis chronicles the work on mesozooplankton ecology, community diversity of copepods (cyclopoids) and their morphotaxonomy and systematics from the Lakshadweep Sea and lagoons of the South Eastern Arabian Sea.

Overall, it was felt necessary for a continuous assessment so as to understand the trophic status and diversity of these ecosystems. Furthermore biodiversity assessment is not valid, without having a proper knowledge on the species characteristics; its morphology, the pattern of distribution and abundance, succession and related information. Moreover, an in depth knowledge on a particular species character of an organism in terms of its taxonomy and systematics in an ecosystem is very vital for evolving its biodiversity, in relation to the tropic status. The study of these organisms (cyclopoid copepods) including species identification, is important in discovering new processes within the ocean.

The rapidly dwindling copepod taxonomic expertise in the ecosystem over the years has restricted local scientists in their ability to study changes in copepod community structure in detail. Such knowledge is essential to understand and to predict the impact of environmental changes on fish stock fluctuations. Copepod taxonomic analyses will provide with practical applications to a range of issues such as climate change, biodiversity, the introduction of alien species, pollution

and eutrophication in addition to fisheries. Therefore, in view of paucity of information on the species character in terms of its taxonomy, systematics and phylogeny in an ecosystem, it was critical to have a contribution on classical and molecular taxonomy of marine cyclopoids from the coastal ecosystems.

Many of the existing taxonomic descriptions of many ecologically important copepods (cyclopoid) species seems to be insufficient and incomplete since most of the studies are concentrated on calanoid copepods. Moreover, previous studies are focused on aspects related to ecology and biodiversity of these organisms, thus having serious lacunae on the taxonomic and morphological aspects. The taxonomy part is too tedious that most of the scientists restrict their study to general diversity aspects rather than their morphological characterization. In view of the dearth of information, many of the cyclopoid copepod species are now being redescribed for the future taxonomists, for an accurate and easy identification (Radhika *et al*., 2014).Unless and until a species is morphologically characterized, never can it be molecularly assessed too, which has now become a supporting factor to species conclusion. Thus it was felt necessary that, deciphering the morphology of marine cyclopoids from Lakshadweep Sea (South Eastern Arabian Sea) is too imperative as it becomes a primary attempt supported by molecular characterization (DNA barcoding).

Morphological identification of species was consistent with the formation of genetic groups obtained with COI gene and its corresponding barcode without overlap between the sequences. This morpho-genetic match would lead to a startup of barcode library of copepods from selected marine habitats of south west coast of India that would certainly help to ascertain the taxonomic significance of intraspecific genetic separation discovering cryptic species especially sibling species that have been discriminated only with few or subtle morphological characters. The ability to understand the dynamics of plankton community depends on the ability to accurately measure the diversity of species and to accurately identify individual species which are morphologically similar.

Consequently, under these circumstances, Department of Biotechnology(DBT), Govt. of India, initiated a major research project on ***"Taxonomy and genetic***

***characterization of pelagic copepods from marine habitats along south west coast of India*"** from 22-Aug-2012 to 22-Feb-2016 under the project investigatorship of Dr. S. Bijoy Nandan in the Dept. of Marine Biology, Microbiology and Biochemistry. The project was implemented from 2012-16 period that explored and documented the ecology and community structure of mesozooplankton with thrust on the morphotaxonomy and systematics by classical and molecular methods of pelagic copepods. The study also fulfills the goals enshrined in UN convention in Biodiversity (CBD) where India is a signatory under the Aichi Biodiversity Targets (2011-2020) that stresses the need for reducing biodiversity loss, strengthen capacity building (taxonomists) and to make available scientific data and knowledge on biodiversity and its application.

1.6 Objectives of the study

The physico-chemical factors influencing the distribution of the organisms along with the detailed morphotaxonomy and molecular status of copepods (cyclopoids) are discussed based on the following objectives.

- Assess the distribution and diversity of mesozooplankton from Lakshadweep sea
- Study the abundance pattern and community structure of cyclopoid copepods
- Explain the biophysical functions influencing mesozooplankton and cyclopoid copepods
- Elucidate the morphotaxonomy and molecular characteristics of cyclopoid copepods

Chapter 2

Review of Literature

Contents

2.1 Hydrographic characters

It has been almost more than 50 years ago (1960-1965) that efforts were made to understand the physico-chemical factors and biological productivity of the Indian Ocean as a part of International Indian Ocean Expedition. Till then, Indian Ocean remained almost *mare incognitum* (*latin: unknown sea*). The Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) carried out IIOE, one of the greatest oceanographic expeditions of all time that marked a turning point in the hunt of knowledge of the Indian Ocean. On behalf of IIOE, several researchers from several institutions published many works on the physico-chemical and biological aspects of Indian Ocean.

Anyhow, maritime expedition sent by Queen Hatshepsut of Egypt (1478 BC) to explore the southern Red sea and the Somali coast turned out to be the first organized one (Aleem,1972). Earliest reference about semiannual reversal of winds in the northern Indian Ocean pertain to Arabs who were the leading traders and mariners in the Indian Ocean during the medieval period (AD 800-1400) (Warren, 1966). Oceanography, as a science, was later established by British (AD 1757-1947). However, commencement of modern scientific marine expedition in Indian Ocean was initiated by Challenger Expedition (1872-76) by *HMS Challenger* visiting the region twice. Substantial information on oceanographic features of Indian Ocean was brought about later by *John Murray Expedition* (September 1933-May 1934).

Contributions of Indian Ocean Experiment (INDEX);investigations by the Netherlands (Netherlands Indian Ocean Program,1992-1993);the United Kingdom

(1994);Germany (German Joint Global Ocean Flux Studies-JGOFS, ARABESQUE (1995-1997);Pakistan (North Arabian Sea Environmental and Ecological Research-NASEER (1992-1995), India (JGOFS-India, Arabian sea Process Study Data and Information 1994-1997) and the United States (JGOFS-US, 1994-1996), towards the understanding of Indian Ocean are commendable. Indeed, the five year research plans organized by the Government of India (MLR-P) was helpful in gathering information on seas around Indian subcontinent. Bay of Bengal Process studies (BoBPs) (2000-2006) also proved to be good in gathering irrefutable information on biogeochemistry of north western Indian Ocean.

Perusal of the available literature reveals that the water quality of world oceans has been studied by several authors in order to understand the short and long term variations of different hydrographic events. Banse (1959) documented on upwelling along the south west India coast. Ramasastry (1959) surveyed on the distribution pattern of temperature, salinity and density in the Arabian Sea along the south Malabar Coast (South India) during the post-monsoon season. Ramamirtham and Jayaraman (1960) presented the hydrographical features of the continental waters off Cochin. Ramesh Babu *et al* (1980) documented on water masses and hydrography along south west India Coast whereas Varadachari *et al* (1974) conducted along west coast of India.

The physical characteristics of the east coast of India (10°N 40°E-10°N 80°E) were studied by Suryanarayana *et al* (1991); Murthy *et al* (1992a, 1992b); Shetye *et al* (1991b, 1993, 1996); Sarma *et al* (1999); Gopalakrishna *et al* (2002); Gones *et al* (2002); Maheswaran *et al*.,2000. Muraleedharan *et al* (1995) made a comparative study of currents and hydrography during monsoon and non monsoon periods along the southwest India coast. Madhuprathap (1996) and Prasannakumar *et al* (2001) also reported on the hydrography along Northern Arabian Sea. A comparison between coastal and open ocean upwelling of Arabian Sea was reported by Muraleedharan and Prasanna Kumar (1996). Shankar *et al* (2002) surveyed exclusively on the monsoon currents in the north Indian Ocean. A comparison on the productivity of BoB and Arabian Sea was given by Prasanna kumar *et al* (2002). Behrenfeld *et al* (2006) reported on the climate driven trends in contemporary ocean productivity trends. Prasanna kumar *et al*(2004) studied

the hydrography of BoB during winter monsoon. Sanalkumar (2009) reported on the physicochemical characteristics of the south west coast of Indian Ocean. Lathika *et al* (2013) documented the hydrography of south eastern Arabian Sea during summer monsoon.

Variation in productivity patterns of Indian Ocean and associated trends in climate change have been extensively studied by various investigators. Gauns *et al* (2005) made a comparative account on the biological productivity characteristics and estimation of carbon fluxes in the Arabian Sea and Bay of Bengal. Roxy *et al* (2014) portrayed the curious case of Indian Ocean warming. A bigger picture on the same scenario was given by same authors in the coming year (Roxy *et al*., 2015a). Drying of the Indian Ocean by rapid Indian Ocean warming was studied by Roxy *et al* (2015b). A reduction in the marine primary productivity driven by warming over the tropical Indian Ocean was conveyed by Roxy *et al* (2015).

Jagadeeshan *et al* (2013) reviewed on the ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, south east coast of India. Jyothibabu *et al* (2012) and Jagadeeshan *et al* (2013) presented the physicochemical aspects of Gulf of Mannar and Palk Bay thus covering both the north-eastern and north-western part of the Indian Ocean. Chaturvedi *et al* (2013) documented on the impact of climate change on biological productivity in the Indian Ocean. Jyothibabu *et al* (2014) gave implications on the vertical biogenic flux along the southern BoB. Fernandes and Ramaiah (2013) documented on mesozooplankton community structure from western Bay of Bengal during fall intermonsoon. Sabu *et al* (2015) documented on the characteristics of a cyclonic eddy in the northern Bay of Bengal during early winter monsoon. Recently Karnan *et al* (2017) reported on the biophysical impacts of coastal upwelling and mud banks along south west India coast.

Several surveys and studies regarding hydrography of different lagoons and associated islands of the world oceans have been reported. Kennish and Pearl (2010) surveyed on coastal lagoons, the critical habitats of environmental change. More recently, Rakesh *et al* (2015) studied the trophic salinity gradients and mesozooplankton dynamics in a large tropical coastal lagoon (Chilka lagoon) along

the east coast of India. Badsi *et al* (2010) studied the ecological factors affecting the zooplankton community distribution in the Massa lagoon (Southern Morocco). Long term vegetation changes in a tropical coastal lagoon system after interventions in the hydrological conditions was carried out by Roderstein *et al* (2014). Specchiulli *et al* (2008) surveyed on the environmental heterogeneity patterns and assessment of trophic levels in two Mediterranean lagoons. Effects of changing environmental conditions on lagoon ecology was reported by Gamito *et al* (2005). Studies on restoring ecological balance and livelihoods through desalinization of Chilka lagoon was done by Ghosh *et al* (2006).

Dharani *et al* (2004) reported the impact of water quality and bioactivity of extracts from Minnie Bay, Port Blair. Satapoomin *et al* (2004) documented the spatio-temporal variations in biomass, production and role in the pelagic food web in Andaman Sea. Some physical aspects of the surface waters around the little Andaman Island was reviewed by Murty *et al* (1981). Rangarajan and Marichamy (1972) studied the seasonal changes in temperature, salinity and plankton volume. Disease and stress induced mortality of corals in Indian reef and observation on bleaching of corals in the Andamans was documented by Ravindran *et al* (1999).

The hydrography of various islands of Lakshadweep have been surveyed by different studies (James, 1989; Koya, 2000; Vargis, 2005). The hydrobiology of Minicoy lagoon along with a comparative study of all the lagoons of Lakshadweep was studied by Girijavallabhan *et al* (1989) during January-March. Gangadhararao and Jayaraman (1982) also mentioned on the hydrography of Minicoy open ocean area. On the dynamics of the Lakshadweep high and low in the southeastern Arabian Sea was commented by Shanker and Shetye (1997). Lierheimer and Banse (2002) commented on the geography, hydrography and of Lakshadweep Sea. Prabhakaran (2008) made an exclusive study about the sea grass of Minicoy along with its physicochemical aspects. He also investigated on the species composition, distribution, abundance and community structure of macro invertebrate fauna and icthyofauna of the seagrass meadow and highlighted the importance of seagrass ecosystem for the existence of oceanic coral island by delineating the ecological relationships between flora and fauna with the hydrographic parameters.

The existence of four distinct water masses in Arabian Sea near Lakshadweep islands was identified by Jayaraman *et al* (1960) and stated that the "Lakshadweep chaos ridge has great influence on the circulation of water in this area. Paul and Ramamirtham (1963) made a detailed study on the summer hydrography of Laccadive offshore waters. A comparison of summer-winter conditions of Lakshadweep offshore waters was done by Patil and Ramammirtham (1963) and discussed on the vertical distribution of various parameters. High surface salinities during winter, lateral movements at surface and at very high depths were also noted. Rao and Jayaraman (1966) reported upwelling in the Minicoy atoll region of Arabian Sea.

The physico-chemical characters like temperature, pH, dissolved oxygen, salinity and their diurnal variation of Kavaratti waters was studied by Sankaranarayanan (1973). Physical properties of Lakshadweep Sea were provided by Varkey *et al* (1979). Jones (1986) recorded the general features of Lakshadweep. An account on the environmental features of the seas around Lakshadweep was given by Nair *et al* (1986). Hydrobiology of Lakshadweep atolls was observed by Girijavallaban *et al* (1989). While Sing *et al* (1990) studied the vertical distribution of nutrients in Lakshadweep waters, Wafar *et al* (1990) studied the nitrification in reef corals and its importance in reef nitrogen economy. A brief review of the oceanological features of the Indian waters (Minicoy island of Lakshadweep, Mangalore, Calicut, Cochin and Vizhinjam) was documented by Silas and Pillai (1987).

Vadivelu *et al* (1993) studied various aspects of geology, geography and environmental features of five atolls of Lakshadweep. Vinoth *et al* (2012) studied the coral reef bleaching at Agatti island of Lakshadweep. Later Balachandran *et al* (1997) studied the chlorophyll profile of the euphotic zone in the Lakshadweep Sea during southwest monsoon season. At the same time, Suresh and Mathew (1997) studied the variations in physico-chemical parameters, zooplankton abundance, their distribution, seasonal and diurnal variations in Kavaratti atoll, Lakshadweep. The ranges in physico-chemical parameters depicted no significant variation between stations. Lowest values of salinity and temperature was observed during

monsoon season and substratum appeared to control the day time density of drifting zooplankton.

Chlorophyll a concentration have been measured during various expeditions and cruises in different areas of Indian seas.The distribution of chl-a in the Indian Ocean has been described by Qasim (1978).The average values of chl-a in the Indian Ocean during south west and north east monsoon sesons have been articled by Krey and Babenard (1976).Based on the data collected during IIOE (International Indian Ocean Expedition),they have also published a map on chl-a distribution. Annual and seasonal distribution of chl-a for a small sector of Arabian Sea and Bay of Bengal have been published by various authors (Radhkrishna, 1978; Dehadrai and Bhargava, 1972; Bhattathiri,1984;Dalal *et al*.,1998;Desai *et al*.,1990;Gomes *et al*.,1992). Seasonal variation of surface phytoplankton and chlorophyll from the coastal waters of Calicut coastal waters was reported by Subrahmanyan (1959). Information on chlorophyll *a* during the southwest monsoon period in the shelf waters of the Arabian Sea have been given by Banse (1968).General picture of chlorophyll a distribution along South Eastern Arabian Sea was manifested by various authors (Krey,1976; Sumitra Vijayaraghavan and Krishnakumari.,1989;Balachandran *et al* (1989) have studied the surface chlorophyll *a* and pheophytin in the inshore waters off Cochin. Distribution of surface chlorophyll *a* from south to north in the Lakshadweep Sea during south west monsoon season was reported by Balachandran *et al* (1997).

Physicochemical parameters of Kavaratti waters, their diel variation in the lagoon, water circulation in the lagoon, productivity of the atoll and individual production of algae, seagrasses and corals were studied by Qasim *et al* (1972). Plankton production in Kavaratti and Agatti atolls of Lakshadweep has been studied by Wafar (1977). Wafar *et al* (1986) studied about the nitrogenous nutrients and primary production in Lakshadweep waters. Other major investigations on primary production in Lakshadweep waters were those of Bhattathiri and Devassy (1979); Kaladharan (1998); Kaladharan *et aI* (1998); Kaladharan and David Raj (1989); Mohammed *et aI* (2000); Koya *et aI* (1999) and Dhargalkar *et al* (2000). A detailed study on the physicochemical parameters of Kavaratti waters of Lakshadweep was given by Robin *et al* (2012); Radhika *et al*

(2014) and Sanu *et al* (2014). Hydrography of Amini and Kadamat islands of Lakshadweep was surveyed by Varghese *et al* (2015).

2.2 Zooplankton

Since time immemorial, the scientific world has looked at the marine world with enthrallment. A series of expeditions began in the latter half of the 18th century itself for the exploration of the oceans to understand on the distribution, abundance and composition of microscopic organisms (Battish, 1992). J.V. Thompson and Johannes Muller in the mid-1800s, started a new era of discovery by the use of nets for plankton collection. However, the HMS Challenger expedition (1873-76) led by the British men, Sir Charles Wyville Thompson and Dr. John Murray made astonishing discoveries of plankton fauna in the deep sea. The first use of the term 'plankton' is attributed to the German marine biologist, Hensen in 1887. It was in 19th century that the pioneers in marine ecology approached the ocean from the coast. Recognition of variety of species including crustaceans, echinoderms, molluscs and fishes (342BC-322) was done by Aristotle by committing a noteworthy part of his biological life (Raffaelli and Hawkins, 1996).

The mesozooplankton investigation in the Indian Ocean pioneered in 1857, by Novara (vessel) extending from Madras (northwards) up to Sumatra (eastward).Later International Indian Ocean Expedition (IIOE), in the latter half of 20th century, made an exhaustive exploration on the distribution and zoogeography of various groups (UNESCO, 1965-72, lOBC, 1968-73, 1969-73, Zeitschel, 1973; Rao, 1979; Panikkar and Rao, 1973)

Definitive life history information for the first time was conducted by raising many Mid-Atlantic crustacean larvae in the laboratory by John. D. Costlow, Jr. C. G. Bookhout and Austin. B. Williams. Works on planktonic food webs that led to studies on productivity, energy flow and trophic efficiency was initiated in the 1940s and 1950s by Deevey (Johnson and Allen, 2012). Extensive oceanographic expeditions in the last quarter of the 19th century brought an unbelievable harvest of aquatic crustaceans. Probably the most thoroughly explored region of the North Pacific is the waters around Japan. The earliest work in these waters were that of the *Challenger expedition* (Brady, 1883), but these works has subsequently been

greatly extended by Japanese, American and Soviet workers. Farran, G.P through Great Barrier Reef expedition (1928-29) presented various zooplankton, their relative abundance, it's seasonal and vertical distribution. Parameswaran Pillai *et al* (1973) articled on the zooplankton in Cochin estuary, a part of Arabian Sea. Calanoid copepods as the major component of zooplankton along with hydrographic features was documented through the study.

Panicker (1968) reported on the zooplankton from Somalia coast and Arabian coast. Madhuprathap *et al* (1990) also documented on zooplankton from central west coast of India. Madhuprathap *et al* (1981) earlier documented on the zooplankton abundance from Andaman Sea. Smith and Madhuprathap (2005) documented on the mesozooplankton of the Arabian Sea. Jyothibabu *et al* (2012) investigated the role of ocean currents in molding the mesozooplakton community structure and threw light on the physicochemical parameters, zooplankton biomass and diversity indices of both zooplankton and copepods along south east coast of Indian Ocean. Jagadeesan *et al* (2015) reported on the ocean currents structuring the mesozooplankton in the Gulf of Mannar and Palk Bay along south east India coast. Fernandes and Ramaiah (2013) documented on the hydrography of western Bay of Bengal during fall intermonsoon. Sabu *et al* (2015) documented on the mesozooplankton community in the northern Bay of Bengal during early winter monsoon.

Recognition of the scientific importance of island ecosystems dates well back over a century to the observations of Charles Darwin in the Galapagos Islands in 1835.On reviewing through the available literature exposed the zooplankton studies carried out by several authors in different lagoons and islands. Resilience of zooplankton community subjected to marine intrusion at Imbossica lagoon at Brazil was surveyed by Kozlowsky and Bozelli (2004). Kouasso *et al* (2006) studied the diel vertical migrations and feeding behavior of zooplankton in a tropical coastal lagoon at Gulf of Guinea. Badosa *et al* (2007) studied on the zooplankton taxonomic and size diversity in Mediterranean coastal lagoons. Ecological factors affecting the zooplankton community distribution in the Massa lagoon (Southern Morocco) was carried out by Badsi *et al* (2010). Studies on the spatio-temporal variations of the zooplankton abundance and composition in a

West African tropical coastal lagoon was carried out by Etile *et al* (2009). The coupling of copepod assemblages and hydrography in a eutrophic lagoon in Taiwan was done by Hsu *et al* (2008). Setubal *et al* (2013) made studies on the effects of sandbar openings on the zooplankton community of coastal lagoons with different conservation status.

Icthyoplankton from Andaman and Nicobar seas was documented by Devi *et al* (1996). Marichamy (1983) reported on the zooplankton production in coastal waters of Andaman and Nicobar islands. Studies on the marine fauna of the Mahatma Gandhi marine National park was discussed by Doarairaj *et al* (1997). Ekblad (2008) presented the effect of predatory chaetognaths on zooplankton assemblages at the start of the spring bloom in Glacier Bay, Alaska. Nair *et al* (2008) reported two new species of chaetognaths from the Andaman Sea whereas Nair and Gireesh (2010) discussed on the biodiversity of chaetognaths of the Andaman Sea. A comparative study on mesozooplankton abundance and diversity between a protected and an unprotected coastal area of Andaman Islands was given by Honey *et al* (2014). The composition and abundance of zooplankton have been studied by Gerber (1981) from Eniwetak Atoll, Marshal Islands.

As a part of oceanographic cruises and various surveys, different group of scientists and researchers have recorded the biophysical aspects of Lakshadweep islands (James, 1989; Koya, 2000; Vargis, 2005). A glance of the available literature reveals that the Marine Biological and Fisheries research in Lakshadweep Sea dates back to the latter half of the nineteenth century when some British naturalists attempted to study the flora and fauna of Lakshadweep and Maldives Archipelagoes. Documenting the account of the work carried on and collections made by an expedition during the years 1899 and 1900, Prof.J.Stanley Gardiner published two volumes of Fauna and geography of the Maldives and Lakshadweep Archipelago. Gardiner (1903) gave a description of Minicoy Atoll. Ellis (1924) and Mannadiar (1977) gave comprehensive information about Lakshadweep, its geographical features, land flora and fauna. Central Marine Fisheries Research Institute (CMFRI) established a research centre at Minicoy Island in 1958. As a part of this, a monumental treatise on fishes of Laccadive archipelago was published by Jones and Kumaran (1980) and a special issue on Lakshadweep incorporating

series of articles with reviews of marine fisheries research up to 1986, were also published (Anon, 1986).While James (1987) described about the pole and line tuna fishery of Lakshadweep; James (1989) reviewed the marine research in Lakshadweep.

Tranter and George (1972) have studied the zooplankton abundance at Kavaratti and Kalpeni atolls of Lakshadweep. Goswami (1973) observed the total zooplankton biomass with diurnal species variations in the lagoon and of the surrounding sea of Kavaratti atoll. Wolfenden (1906) studied the copepod contents of zooplankton of Lakshadweep. Comparative studies on the zooplankton abundance of Kavaratti, Agatti and Suhelipar lagoons were carried out by Madhuprathap *et al* (1977). The results showed higher biomass and density of zooplankton in the sea than lagoons. Goswami and Usha goswami (1990) studied the diel variation in zooplankton in Minicoy lagoon and Kavaratti atoll.

The densities and emergence rates of demersal zooplankton from Agatti atoll was reported by Madhuprathap *et al* (1991).He also studied the zooplankton from the lagoons of Minicoy, Agatti, Kadmat and Bitra. Recently Jose *et al* (2010) presented a hierarchical analysis of zooplankton assemblages over semidiel pattern in Kavaratti atoll. Similar abundance of molluscs has been reported for Kavaratti lagoon. The zooplankton population of copepods showed higher degree of abundance in species composition in the sea than in the lagoon of Kavaratti atoll (Madhupratap *et al*., 1977). Robin *et al* (2012) provided a baseline information on the productivity, pigment concentration and plankton community structure and their trophic state with respect to marine food web. Primary objectives were to relate the phytoplankton community composition to the physical variables of the ocean and explore potential links between the phytoplankton and zooplankton communities in the Kavaratti waters. However, both the phyto- and zooplankton communities appeared responsive to the physical environment; little correlation between the two trophic levels was evident.

The zooplankton studies in the adjacent open sea of Minicoy lagoon were made by Mathew and Gopakumar (1986). Achuthankutty *et al* (1989) worked on zooplankton of Kalpeni and Agatti atoll. Stephen (2008) conducted a study on the

biodiversity and density of zooplankton in Kavaratti Atoll. Later, while Sanu *et al* (2014) reported mesozooplankton distribution with reference to calanoid copepods from Kavaratti Atoll; Radhika *et al* (2014) mentioned the same along with the community structure and species assemblage of cyclopoid copepods. A more recent work on zooplankton abundance in Amini and Kadamat islands of Lakshadweep was surveyed by Varghese *et al* (2015).

2.3 Studies on copepods

Copepod research having started in 1770 with the description of a calanoid copepod, *Monoculus finmarchicus* by Gunnerus, made excellent contributions to the systematics of this group of small (up to 10 mm long), planktonic crustaceans. Sars (1837-1927) meticulously accounted for anatomical details and described all features observed on the organisms. Giesbrecht (1854-1913) have done an unprecedented taxonomic work with beautiful and indispensable monographs. William Vervoort's extremely precise verbal descriptions and highly accurate drawings, in the years between 1946-1965, remained unparalleled on the taxonomy of copepods. In retrospect, they even appear to constitute the sole match for Giesbrecht's unprecedented taxonomic work (Giesbrecht, 1892).Vervoort's impressing standards meticulously accounted for anatomical details undoubtedly set the scene for new generations of copepodologists. One of the true impacts of his work certainly comprises a revival of the classical way of fully dismembering and next painstakingly describing all features observed on the organisms in an invaluable enhancement of the current practice in those days, taking into consideration the irreplaceable character of reliable descriptions in establishing the true identity of species and of specimens, as well as the nature of their phylogenetic relationships.

An account of pelagic copepods including calanoids and harpacticoids was presented by Farran (1928-29) through Great Barrier Reef expedition (1928-29) from Australian waters. The decade before and after 1900 was the Golden Age of Copepodology, with the beautiful and indispensable monographs of Wilhelm Giesbrecht (1854-1913, Germany and Italy), and George Ossian Sars (1837-1927, Norway). In 2004, a new plankton database effort began, incorporating over ten

years of plankton data management experience and user feedback into designing and building a new online data system designed specifically for plankton data and plankton scientists. The **C**oastal & **O**ceanic **P**lankton **E**cology, **P**roduction & **O**bservation **D**atabase (**COPEPOD**) now contains the entire reprocessed plankton content of Brien *et al* (2002), the significant amounts of new plankton data presented in COPEPOD-2005 (Brien,2005) and new data added since 2005. COPEPOD also represents a new approach to providing data access and investigator acknowledgement in a global scale database.

Pillai *et al* (1973) articled on the copepod component of zooplankton in Cochin estuary, a part of Arabian Sea. Calanoid copepods as the major component of zooplankton along with hydrographic features was documented through the study. Remarks on the distribution of a calanoids copepod (*Temora turbinate*) along with its post- naupliar development stages from Indian Ocean was illustrated by Pillai (1975). Studies on copepods (calanoids-*Pontella*) species from International Indian Ocean expedition collections (1960-65) from Arabian Sea, Bay of Bengal, Central, South East and South West part of Indian Ocean was carried out by Pillai (1975).

Study on copepods from the Indian Ocean was initiated with the work of Thompson (1900) from the east coast of Africa to Ceylon and Bay of Bengal. Cleve (1901) studied copepods from Aden to Java in the Malay Archipelago. Subsequently Scott (1902) and Thomson and Scott (1903) studied copepod fauna from Suez to Colombo and around Pearl Banks of Ceylon. Wolfenden (1906) and Scott (1909) gave detailed information on copepods from Maldives and Malay Archipelago. The copepod population of Indian Ocean has been scripted from various oceanographic expeditions. Sewell (1929 and 1947) furnished the taxonomy and distribution of oceanic copepods. Later, South African copepods was dealt by Dedecker and Mombeck (1965).While Grice and Hulsemann (1967) documented on the copepods from western Indian Ocean, Haq *et al* (1973) reported on copepods from Pakistan coast. Northern Indian Ocean pelagic copepods was studied from different localities (Stephen, 1984; Madhuprathap and Haridas (1986, 1990) and Madhuprathap *et al*., 1989). Similarly lots of works have been put forward emphasizing the abundance and taxonomy of calanoid copepods

from the Indian Ocean by several authors (Pillai *et al*., 1973; Pillai, 1975. Pillai, (1973) have mentioned on the copepod component of zooplankton from a tropical estuary. Stephen (1991) has reported on the abundance and copepod composition along south west and south east coast of India. Stephen *et al* (2014) reported on the copepod diversity of Mumbai coast, west coast of India.

Brady (1910) and Wolfenden (1911) gave detailed account on copepods from Southern part of Indian Ocean. Sewell (1912, 1914) studied the copepods of the coastal regions of Bay of Bengal, Arabian Sea, Chilka Lake, coastal region of South Burma, Andaman and Nicobar islands. Sewell (1929 -1932) described the copepods of west coast of India and Malay Archipelago. Copepod of John Murray Expedition was dealt by Sewell (1947 and 1948). In 1977 while Goswami and Selvakumar (1977) studied copepods along inshore water of Goa; Thompson and Easterson in the same year studied the dynamics of cyclopoid copepod population of the Cochin backwaters. Stephen and Saraladevi, Silas and Pillai, Saraswathy, Saraswathy and Iyer (1973-1986) provided authentic information on the distributional range for different species of copepods from the entire Indian Ocean. Madupratap *et al* (1979) dealt with the distribution, community structure and species succession of copepods from Cochin backwaters. Nair *et al* (1981) discussed the diversity of copepods around Bay of Bengal. Copepods of Hooghly-Maltah estuarine system was taken up by Sarkar *et al* (1986). Various ecological aspects of copepods from the estuaries and coastal waters of Goa were reported by Goswami and Selvakumar (1977). Stephen (1992) studied copepods along the southwest and southeast coast of India. Padmavathi *et al* (1998) gave an account on the vertical distribution of copepods for the Central and eastern Arabian Sea. Achuthankutty *et al* (1998) elucidated the copepod assemblage in the estuarine and coastal waters of Goa. An account on the free living copepods of the Arabian Sea was given by Madupratap (1999).

Qasim et al (1972) reported the primary production of Kavaratti atoll. Goswami and Usha goswami studied the diel variation in zooplankton in Minicoy lagoon and Kavaratti atoll and recorded 31 copepod species. Goswami *et al* (1992); Achuthankutty *et al* (1998) and Madupratap *et al* (1996) presented the tropic relations of copepods within the mezozooplankton community from Lakshadweep

waters. From Kavaratti atoll thirty calanoids, ten cyclopoids and five harpacticoids were recorded by Sanu *et al* (2014). The total number of species reported in the present study was comparatively higher than other reports from the same area. Among the calanoids, the families Candacidae, Calanidae, Pontellidae, Temoridae, Psuedodiaptomidae, Centropagidae dominated whereas Radhika *et al* (2014) reported thirty cyclopoid species from the same island. A more recent work by Varghese *et al* (2015) from Amini and Kadamat islands of Lakshadweep reported calanoids and cyclopoids along with other zooplankton such as ostracods, chaetognaths, Lucifer sp., medusae, doliolids, mysids, tintinnids, polychaete larvae, siphonophores, cladocera, amphipods, isopods, prawn larvae, crab larvae, squilla larvae, molluscan larvae, fish eggs and fish larvae.

The composition and abundance of zooplankton have been studied by Gerber (1981) who recorded ninety six copepod species from Eniwetak Atoll, Marshal Islands. Madupratap *et al* (1981) discussed the diversity of copepods around Andaman and Nicobar Islands. Satapoomin *et al* (2004) documented the Andaman sea copepods, spatio-temporal variations in biomass, production and role in the pelagic food web.

2.4 Morpho-molecular taxonomy of copepods-a brief review

Despite the dramatic examples of morphological diversity found between certain divergent copepod groups as detailed at a closer level of relationships; morphological stasis is also a commonly found pattern (Lee and Frost 2002; Thum and Harrison 2009) making genetic techniques crucial for the identification of divergent lineages and cryptic species. Interestingly, for a number of groups that had been previously relatively well-studied from an ecological perspective, genetic analyses of populations have revealed extremely divergent copepod lineages (Burton 1998) or clear cases of sympatric cryptic species (Lee 2000; Goetze 2003; Caudill and Bucklin 2004; Chen and Hare 2008). The further development of genomic resources will aid the study of the physiological differences that are likely to be important drivers of divergence between such cryptic species. Although some species of copepods show these surprising patterns of dramatic genetic divergence over short geographic distances, other species have world-wide distributions with

apparent genetic exchange between ocean basins (Goetze 2003; Eberl *et al*.,2007) highlighting the diversity patterns of population diversity found within the copepods as a group.

Study on cyclopoid copepods from the Indian Ocean was intimated with the work of Brady and Wolfenden (1910-1911) who gave detailed account on copepods from Southern part of Indian Ocean. Sewell (1912-14) also studied the copepods of the coastal regions Bay of Bengal, Arabian Sea, Chilka Lake, coastal region of South Burma, Andaman and Nicobar islands which was mainly concentrated on taxonomy of calanoid copepods. However, while Ummerkutty (1961) just listed out the presence of *Corycaeus spesiosus* from south east coast of India; Kasturirangan (1963) from Indian coastal waters provided a detailed key of three species under the family Corycaeidae ie.*C.spesiosus*, *C.danae, Onychocorycaeus catus and Farranula gibbula* which rather helped out the near future taxonomists to identify the same.In Indonesian waters, hitherto, seventeen species of this family have been reported by Carl (1907); Scott, (1909) and Früchtl (1924). Thompson (1986) studied the seasonal distribution of cyclopoid copepods of the mudbanks off Kerala coast and listed thirty two species of cyclopoid copepods belonging to five genera and four families. Taxonomic study was made on the species of the family Corycaeidae by Mulyadi (2003) from Indonesian waters that recorded twelve species, including two of genus *Corycaeus*, four of genus *Ditrichocorycaeus*, one of subgenus *Monocorycaeus*, two of genus *Onychocorycaeus*, one of genus *Urocorycaeus* and two species of genus *Farranula*.

Monograph by Dahl. M (1912) on Corycaeid group of marine cyclopoids has contributed much to the knowledge of their classification and geographical distribution. Tanaka (1957) gave detailed descriptions of twenty three species of cylopoids under the family Corycaeidae from Pacific coast and Sea of Japan where the Kuroshiwo Current and its tributaries prevail. Motoda (1963) gave taxonomic descriptions of sixteen species of the family Corycaeidae from Hawaiian waters. Karanovic (2003) from Australian waters provided detailed taxonomic descriptions of some of the species under family Corycaeidae that included *C.crassiusculus* as well as *O.catus.* Al-Yamani *et al* (2011) gave taxonomic descriptions of five species under this family including genus *Ditrichocorycaeus*

and *Onychocorycaeus* from North western Arabian Gulf. Fernandes and Ramaiah (2013) recorded seven species under the family Corycaeidae from western Bay of Bengal during fall intermonsoon. Wi and Soh (2013) taxonomically described one new species under the genus *Farranula ie. F. orbisa sp.nov.* and redescribed *F.carinata* from off Jeju island, Korea. Recently, Radhika *et al* (2015) redescribed two species (female) under the Family Corycaedae ie. *Corycaeus crassiusculus* and *Onychocorycaeus* catus from Kavaratti, Lakshadweep.

Fourteen species under genus *Ditrichocorycaeus* have so far been described from the world oceans and more similar morphological features and deficient identification keys led to frequent taxonomic confusion (Tanaka, 1957; Vidjak and Bojaniæ, 2008). Tanaka (1957) compared the proportional lengths of abdominal segments, caudal rami and the absence or presence of the ventral hook of genital double-somite/somite to discover morphological differences between nine species of *Ditrichocorycaeus.*

Wi and Soh (2013) described three species of cyclopoids under genus *Agetus* and redescribed three species of genus *Ditrichocorycaeus* from Korean waters. Taxonomic composition and abundance of copepoda in the coastal waters of Bintulu-Sarawak, Malaysia was carried out by Johan *et al* (2013). Vidjak (2008) redescribed a cyclopoid species, *Ditrichocorycaeus minimus* from Adriatic Sea which was recorded primarily in the same area during the planktonic investigations of the offshore middle Adriatic Sea in 1999. Hure and Krsinic (1988) have recorded two species of this genus from Adraitic Sea. The presence of *Ditrichocorycaeus anglicus* in the Adriatic Sea was reported by Zavodnik (1956, 1961).*Ditrichocorycaeus brehmi* was first reported from the Gulf of Trieste (Brehm, 1906) and subsequently described as *Corycaeus brehmi* by Steuer (1910).*Corycaeus aucklandicus* that was described rather inadequately from the Hauraki Gulf by Kramer (1895) was later on redescribed by Bradford (1978) from New Zealand waters.

Several researchers have dealt with the taxonomy of the marine species of Family Oithonidae (genera *Oithona* and *Dioithona*),Oncaedae (genus *Oncaea*) and Sapphirinidae (genus *Sapphirina* and *Copilia*).Kiefer (1935) have dealt with the

separation of a new genus *Dioithona* from *Oithona* Baird. Ferrari (1975) recorded taxonomic notes on genus *Oncaea* from the Gulf of Mexico and Northern Carribean Sea. Ferrari (1980) reported several *Oithona* species from Caribean Sea, a part of Atlantic Ocean. Ummerkutty (1961) just listed out the presence of *Oithona plumifera* from south east coast of India. *Oithona simplex* had already been reported from Indian Ocean by Rosendorn (1917) and Nishida(1985). Wellershaus (1970) also provided detailed identification key, taxonomic description and morphometry of eight *Oithona* species (*O.brevicornis, O.simplex, O.nana, O.similis, O.plumifera, O.setigera, O.ovalis and O.atenuata*) and two *Dioithona* species (*D.rigida and D.oculata*) from Cochin Backwaters, an estuary of Arabian Sea and a part of Indian Ocean. Tanaka (1960) from Japanese waters also made contributions on *Oithona* taxonomy. Giesbrecht (1892);Shmelva (1965); Nishida (1977,1985); Chen and Roserdorn (1917);Zang (1974); Shuvlov (1980)are the other contributors. McKinnon (2000) described two new species of *Oithona* from Mangrove waters of North Queensland, Australia. Cornils and Wend-Heckmann (2013) gave first report of *Oithona davisae* in the North Sea.

Temnykh and Nishida (2012) documented a new record of the planktonic copepod *Oithona davisae* Ferrari and Orsi in the Black Sea. Conway *et al* (2003) reported fourteen *Oithona* species, five *Oncaea* species, four *Copilia* species, fourteen *Sapphirina* species and eighteen species of Family Corycaeidae from the South western Indian Ocean. Al Yamani (2011) reported five *Oithona* sp, one species each under *Oncaea*, *Copilia* and *Sapphirina*, three species under *Ditrichocorycaeus* and two species under *Onychocorycaeus* from North western Arabian Gulf. A taxonomic study of *Oithona bervicornis* have been carried out by Temnykh and Nishida (2012) from Black Sea. Gubanova *et.al* (2013) has also reported *O.brevicornis* from Mediterranean Sea. Veronica and Ramaiah (2013) recorded five *Oithona* species (*O.brevicornis, O.plumifera, O.setigera, O.similis, O.spinirostris and Oithona sp.*) and three *Oncaea* sp. along the western Bay of Bengal. Jose et al (2014) described the morphology of marine egg bearing cyclopoid copepod *Oithona similis* from south west coast of India

Employing molecular techniques in addition to traditional morphological ones was one of the priorities of this study to aid in species delineation and

reconstruction of their phylogenetic relationships. Recently, DNA-based species identification methods, referred to as "DNA barcoding", have been widely employed to estimate levels of species diversity, with the 5'end of the mitochondrial cytochrome C oxidase subunit 1 gene (mtCOI) proposed as the "barcode" for all animal species (Hebert *et al*.,2003). The advantage of the mtCOI gene is that it often shows low levels of genetic variation within species, but high levels of divergence between species; for the most common divergence values in a variety of crustacean taxa (Lefébure *et al.,* 2006).

In recent years several studies on copepods showed that combining molecular and morphological methods can help answer questions related to cryptic speciation (Bláha *et al*., 2010; Sakaguchi and Ueda, 2010; Karanovic and Krajicek, 2012a, Hamrova *et al*.,2012), invasions of new habitats and colonization pathways (Lee *et al.,* 2003, 2007; Winkler *et al*., 2008; Karanovic and Cooper, 2011a, 2012), anthropogenic translocation (Karanovic and Krajicek, 2012a), short range endemism and allopatry (Karanovic and Cooper, 2011a), and definition of supraspecific taxa in conservative genera or families (Huys *et al*., 2006, 2007, 2009, 2012; Wyngaard *et al*., 2010; Karanovic and Cooper 2011b; Karanovic and Krajicek, 2012b; Karanovic and Kim, 2014).Phylogenetic relationships of copepods using mt COI gene have been delineated by several taxonomists, including the pioneering works of Bucklin *et al*., (1995; 1996a; 1996b; 1998; 1999; 2003; 2010).

Wang.M; Sun,S; Cheng,F and Wang,R (2016) identified and obtained three sequences of *Corycaeus afffinis* based on mtCOI gene from the samples collected from Jiaozhou Bay along the western coast of Yellow sea. These are the only sequences available of *Corycaeus* sp. based on mtCOI gene. Rest of the few species are completely sequenced based on 18s rRNA, ITS2 and 28s rRNA out of which most of the data are unpublished. Kim and Kim (2000) elucidated the molecular phylogeny of nine cyclopoid copepods based on 18s rDNA squences from Korean waters. Cepeda *et al* (2012) performed the molecular systematics of three species of *Oithona* from the Atlantic Ocean based on 28S rDNA sequences. The complete mitochondrial genome of the cyclopoid copepod *Paracyclopina nana* was published by Ki *et al* (2009). Sequencing of mtCyt b gene region of *Oncaea venusta* and *Oncaea media* was done by (Elvers *et al*., 2006) from Indian and Pacific Ocean.

Hirai *et al* (2013) made use of 28s rRNA based gene sequences to resolve the phylogenetic relationships among the subtropical western North Pacific calanoid copepods along with *Corycaeus sp*. Molecular characterization of *Corycaeus danae* was done by Jagadeesan *et al* (2010) from Paragipettai coastal waters along north west coast of India based on 18s rRNA gene sequence.

Molecular data based on mtCOI gene is limited to only very few species of genus *Oithona.* Ueda *et al* (2011), through molecular study, pointed out that *O.dissmiliis* can be a species complex containing more than two cryptic species. Razouls *et al* (2017) opined that *Oithona brevicornis* Giesbrecht (1891) and *O. davisae* Ferrari and Orsi (1984) are coexisting close relatives in contrast to the findings of Nishida *et al* (1977) that they were different forms of the same species. A comparative analysis using 28srDNA on the molecular systematics of *O.similis*, *O.atlandica* and *O.nana* has been reported by Georgina *et al* (2012). Copepod diversity of Kaneohe Bay, a subtropical bay in Hawaii Island was established by Jungbluth (2013) using mt COI gene. More recently, Radhika *et al* (2016) established the generic status of *Dioithona rigida* through a morphological and molecular study based on mtCOI sequences from Lakshadweep Sea, a part of Indian Ocean.

Chapter 3

Materials and Methods

Contents

3.1 Study Area

Lakshadweep is an archipelago in the Lakshadweep Sea (South Eastern Arabian Sea, part of Indian Ocean) located between 8°12'13"N and 71°45'-74°45'E, comprising twelve atolls, three reefs and five submerged banks. The synonymous name of Lakshadweep is Laccadive (Anandaraj, 2002). The Lakshadweep Islands meaning the hundred thousand islands, consist of a group of coral atolls lying between 115 and 215 miles off the South West coast of India; several detached shoals and banks lie off the islands. The islands are divided into two groups, N and S, separated approximately by the parallel of 11˚N. The N group, known as the Amindivi Islands, consists of Chetlat, Bitra, Kiltan, Cardamum, and Amini. The S group, known as the Cannanore Islands, consists of Agatti, Androth, Pitti Islet, Kavaratti, Suheli Par, Kalpeni (on the N side of Nine Degree Channel) and Minicoy (on the S side of Nine Degree Channel). Minicoy lies about 110 miles S of other islands of the S group and is of special importance due to its location in the principal navigational route of the Indian Ocean.

Of the thirty six islands only ten (Androth, Amini, Agatti, Bitra, Chetlat, Kadmat, Kalpeni, Kiltan, Kavaratti and Minicoy) are inhabited (Ramamurthy, 1995).Among the uninhabited islands, Bangaram is well known for the numerous adventure activities like SCUBA (Self-Contained Underwater Breathing Apparatus) diving, snorkeling whereas Suheli Par are well known for its coconut growing and fishing centre. Each of these islands lies on extensive coral shoals and no parts of these formations are more than about 4m high. The outer edges, which generally enclose a regularly formed lagoon, are higher than the body of these shoals; the lagoons remain calm in the worst weather. The receding tide leaves the outer edges of the reef nearly dry and the tide runs out of the lagoon through breaks in the edges, which are large enough to admit

light craft into the natural harbor. A tropical humid climate prevails in Lakshadweep that is more or less comparable to the coastal areas of Kerala. The only natural source of water is ground water and rainfall as there are no streams in any of these islands.

3.2 Sampling Design and study stations

Since the Indian Ocean is under the influence of annually occurring monsoons, the seasons are mainly classified as south west monsoon (summer monsoon-June to September), North east monsoon (winter monsoon-December to March) and spring intermonsoon period (transition period from winter to summer-March to May) and Fall inter monsoon period (transition period from summer to winter-September to October) (Madhupratap *et al*., 2001).

3.2.1 Lagoon stations along five islands of Lakshadweep

Field sampling were conducted invariably during the early morning hours by hired boats in different Lakshadweep islands (lagoon stations of Kavaratti, Kalpeni, Minicoy, Agatti and Bangaram) from 2013 to 2016 during premonsoon (spring intermonsoon), monsoon (fall inter monsoon) and postmonsoon (winter monsoon) seasons for the collection of mesozooplankton and water samples for hydrographic analysis .The lagoon area of Kavaratti, Agatti and Bangaram was divided into three transects, code named T1 (coral area), T2 (inner lagoon), T3 (boat channel) and that of Kalpeni and Minicoy ,into two transects, T1 (coral area) and T2 (inner lagoon) (Fig.3.1 and 3.2).Samples have been taken for qualitative and quantitative analysis for zooplankton from each station. Physico-chemical variables were also measured.

3.2.2 Open ocean Stations along Minicoy Island

Inorder, to have a comparison of the zooplankton, copepod fauna and its biophysical characteristics, sampling from open ocean zones in Minicoy island was also undertaken during premonsoon (spring intermonsoon) on board the Fisheries and Oceanographic Research Vessel (FORV) Sagar Sampada (Cruise #338) in April 2015. The data collected from eighteen hydrographic stations occupied during the cruise (located between 8°12'-8°24'N and 72°54'-73°12'E) have been presented and discussed. The station details of cruise # 338 are shown in Table3.2 and Fig.3.3.

Table.3.1 Details on the sampling schedule in Lakshadweep islands

Lagoon stations	Depth	Latitude	Longitude	Sampling date and time		
				Premonsoon	Monsoon	Post monsoon
Kavaratti	3.5m	10°33'43.80" N	72°37'43.97"E	27.04.2013 Morning (6am-8am)	10.09.2013 Morning (6am-8am)	27.01.2014 Morning (6am-8am)
				05.03.2015 Morning (6am-8am)	.....	.....
Kalpeni	3m	10°06'29.14" N	73°38'31.66"E	.....	08.09.2013 Morning (6am-8am)	28.01.2014 Morning (6am-8am)
Minicoy	4m	8°17'59.98" N	73°02'31.16"E	.....	09.09.2013 Morning (6am-8am)	29.01.2014 Morning (6am-8am)
Agatti	1m	10°50'42.75" N	72°09'47.93"E	05.03.2015 Morning (6am-8am)	.....	.....
Bangaram	4.5m	10°56'27.38" N	72°17'29.02''E	05.03.2015 Morning (6am-8am)	.....	.....

Table 3.2. Open Ocean Station locations (Cruise # 338)

Sl.No	Latitude	Longitude	Stn.depth (m)
1	8 °25'8N	73 ° 01'E	300
2	8 °2' N	72 ° 95'3 E	300
3	8 ° 05'2 N	72 ° 77' E	300
4	8 ° 03'8 N	73 ° 3' E	300
5	8 ° 21'7N	73 °11'7 E	300
6	8 ° 26'2 N	73 ° 06'5 E	300
7	8 ° 3' N	73 ° 07'8 E	300
8	8 ° 3' N	73 °16' E	300
9	8 ° 3' N	73°34' E	300
10	8 ° 55'8 N	73 ° 32' E	300
11	8 °38'3 N	73°13'3 E	300
12	8 °33'7 N	73 °09' E	300
13	8°33'8 N	73 °03'2E	300
14	8°38'3 N	72°98'7E	300
15	8 °55' N	72°8' E	300
16	8 °3' N	72 °68'E	300
17	8 ° 3' N	72°94' E	300
18	8°3' N	73 °01'E	300

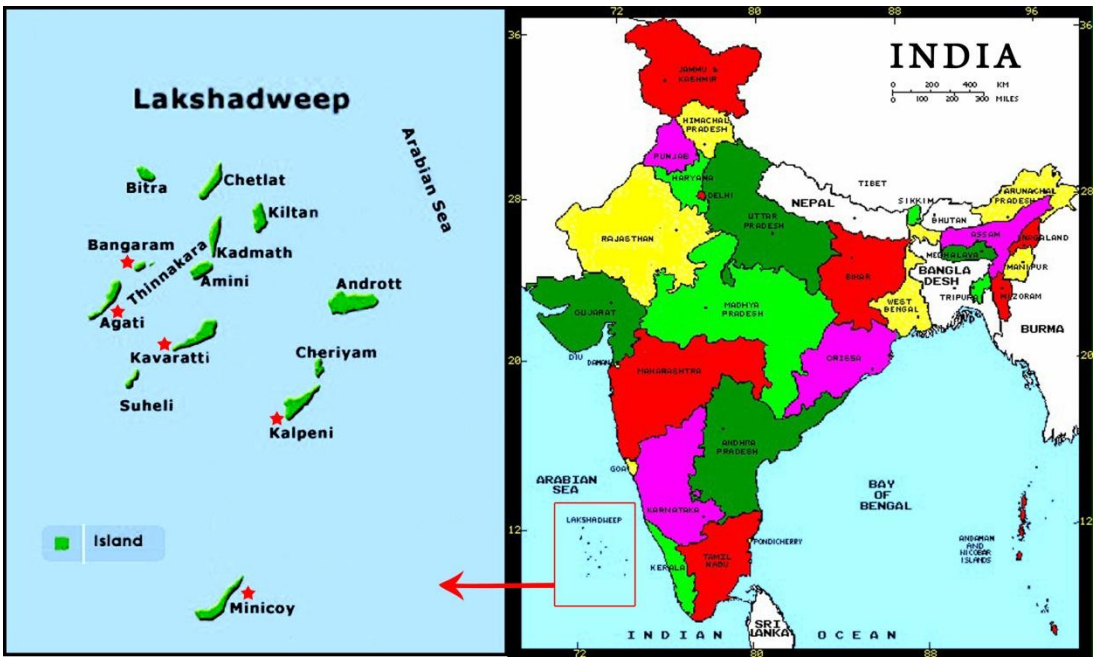


Fig.3.1 Geographical location of the hydrographic stations in the Lakshadweep island (source: https://www.mapsofindia.com/maps/india/india-political-map.htm)

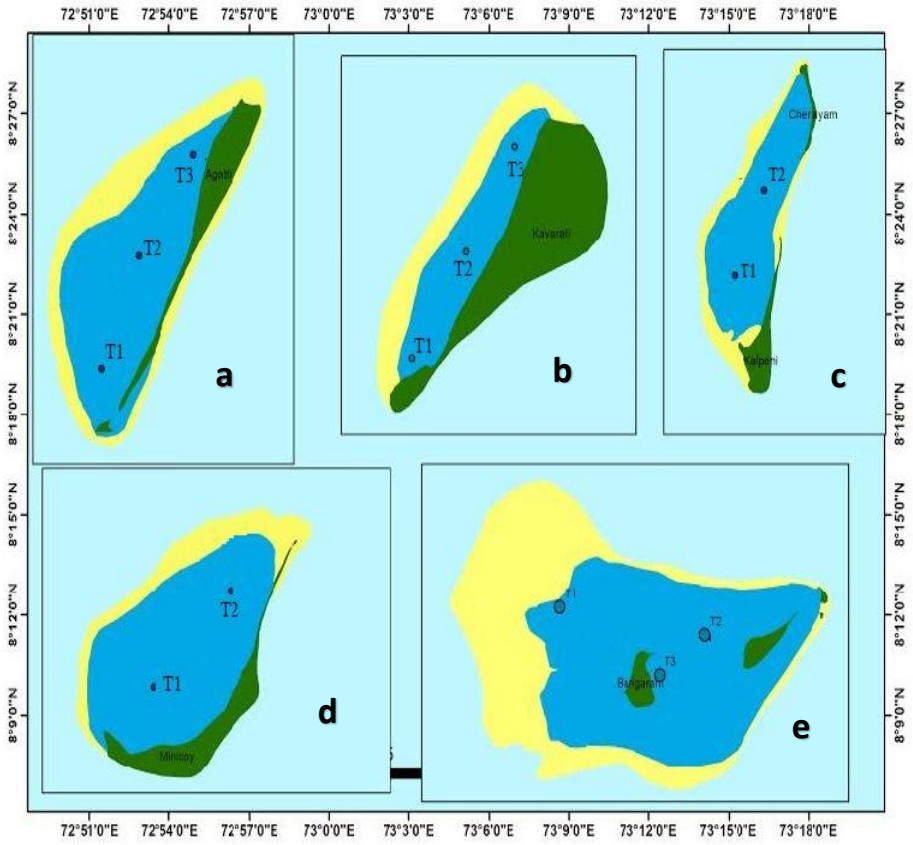


Fig.3.2 Lagoon stations of (a)Agatti, (b)Kavaratti, (c)Kalpeni, (d)Minicoy and (e)Bangaram islands of Lakshadweep

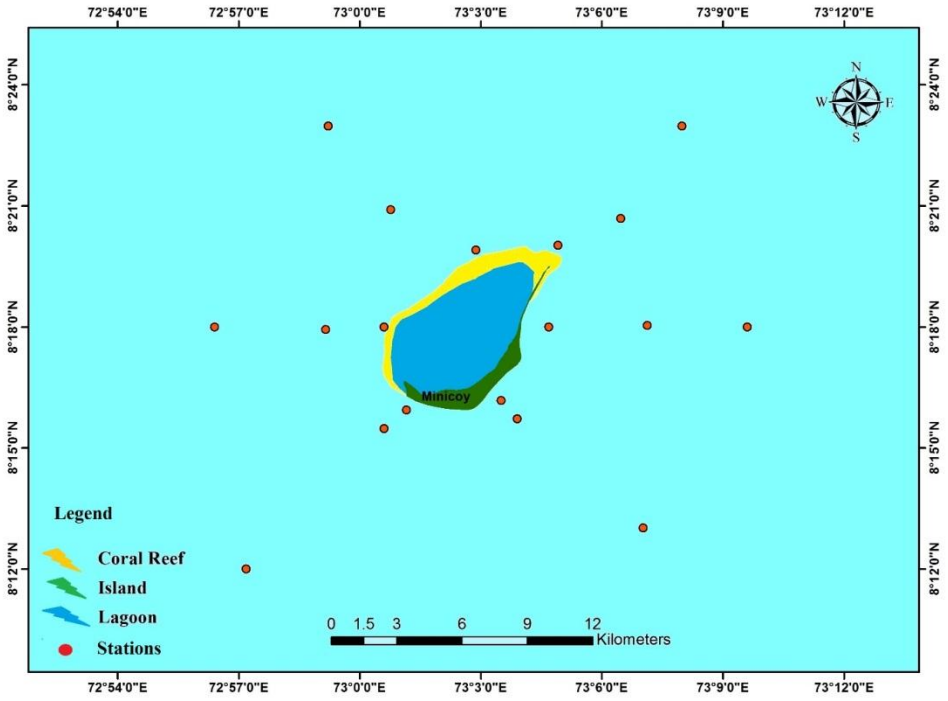


Fig.3.3 Study Area- Cruise track of FORV Sagar Sampada Cruise #338 (Minicoy Island)

3.2.1.1 Islands selected for the study

1. Kavaratti (10°33'N-72°36'E)

Kavaratti is the capital of Union territory of Lakshadweep in India. It has a land area of 4.22 km^2 with lagoon area is 4.96 km^2, island perimeter-11.46 km, reef perimeter-12.88 km, reef area - 9.02 km^2 and located at a distance of 404 km off Cochin (Raheem, 2012). The reef, which is situated on the western side of the island, encloses a lagoon in between the reef and Island. The lagoon oriented in north to south direction which is approximately 6000m long and 1200m wide with a maximum depth of 3.5m The Northern part of the island is more heavily populated; the Administrator for the Lakshadweep Islands resides on the island. Kavaratti island light is situated on the South Eastern point of the island. (Fig.3.4).

Fig.3.4 A view of the Kavaratti Island with boats plying

Three transects namely T1 (coral area), T2 (inner lagoon) and T3 (boat channel) (Fig. 3.2b) were selected from the Kavaratti island for the study. T1 having an average depth of 1.5 m, with bottom characterized by white lagoon sand, coral rubbles and live corals. T2 having an average depth of 3m, with bottom characterized by live and dead corals. T3 was located very near to the open sea, having a depth more than 20m.

2. Kalpeni (10°076'N-73°64'E)

Kalpeni, the South East atoll of the Laccadive island is an inhabited island with many satellite islets in the same lagoon. Kalpeni has a land area 2.79 km^2 with lagoon area of 25.60 km^2, island perimeter 11.86 km, reef perimeter-25.60 km and reef area -15.36 km^2 (Raheem, 2012). It is 218 km west from the port of Kochi. Kalpeni forms a single coral atoll along with the uninhabited Islands of Cheriyam, Tilakkam and Pitti islet. The lagoon situated to the west of the island is enclosed by reefs which have an elliptical shape with good coral growth (Fig.3.5).

Fig.3.5 A view of Kalpeni lagoon with a ship anchored and glass boats plying in the lagoon

Two transects namely T1 (coral area) and T2 (inner lagoon) (Fig.3.2c) were selected from Kalpeni. Both transects in Kalpeni were having an average depth of 3.0m with luxuriant growth of seagrasses, occasionally intermixed with algae. Some area of the lagoon was characterized by white loose sandy bottom, without any apparent vegetation.

3. Minicoy (8°15'N-73°52'E)

Minicoy, the second largest and the southernmost among the islands of the Lakshadweep archipelago, is located 398 km away off Cochin. It has a land area of 4.8 km^2 with lagoon area of 30.60 km^2, island perimeter-23.08 km, reef perimeter-29.55 km and reef area -17.73 km^2 (Raheem,2012).The lagoon in Minicoy island is large and deep enough for small ships to enter. Lagoon and outside the reef have a

rich growth of corals. The lagoon has two entrances, one in the west and the other in the northern end. This large lagoon protects the Island from the fury of the southwest monsoon currents. The 12 km long Island does not exhibit significant geomorphologic differences except for micro level relief differences on the north. The elevation of the island from mean sea level is about 3-4 m in the east (Anandaraj, 2002) (Fig.3.6).

Fig.3.6. A view of Minicoy island

The lagoon area of Minicoy is also divided into two transects namely T1 (coral area) and T2 (inner lagoon) (Fig.3.2d).T1 having an average depth of 4m and T2 having an average depth of 3.5m. Bottom zone of both the stations were characterized by live and dead corals and algal growth.

4. Agatti ($10^0$50'N-$72^0$09'E)

Agatti is 7.6km long island located about 459 km off Kochi in the mainland and 7 km to the south west of Bangaram, the nearest island. Agatti is the western most island in the union territory of Lakshadweep with a total land area of 3.226km^2,width-0.85km and lagoon area of 24.84 km^2 (Fig.3.7).To the northern part of the island is a shallow submerged bank (16m depth) which extends north and connected to the bank of Bangaram (Sinha,1994).The southern portion consists of a long narrow stretch almost 2 km long and an average breadth of 100 m. An airstrip has been built in this stretch in 1987. Kalpitti (Pitti) island lies further south and it is separated from the airstrip by a shallow strait of about 200 meters. It is possible to walk to Kalpitti on very low tide dates.

Fig.3.7. A view of Agatti Island with a distance view of light house

Three transects namely T1 (coral area), T2 (inner lagoon) and T3 (boat channel) (Fig. 3.2a) were selected from Agatti. T1 having an average depth of 1m and floor is generally smooth.T2 having an average depth of 4m, with bottom characterized by coral knolls and reefs. T3 was more near to the open sea.

5. Bangaram (10°56′N 72°17′E)

Bangaram atoll being the largest island has a roughly rectangular shape and is 8.1 km in length with a maximum width of 4.2km and with a lagoon area of 36km^2 (14sq mi). It is located over 400km (250mi) off Kochi and 525km (326mi) from Kollam port in the Indian Ocean. Bangaram atoll is about 7km north east of Agatti Island. The western and south western part of lagoon is marked by a shallow sand flat extending west and southwestward from the Bangaram island (Fig.3.8).

Fig.3.8 A view of Bangaram island and boats anchored

Three transects namely T1 (coral area), T2 (inner lagoon) and T3 (boat channel) (Fig. 3.2e) were selected from Bangaram. T1 having an average depth of 3-5m with bottom characterized by dead corals. T2 has an average depth of 12-218m with bottom characterized by coral knolls and reefs. T3 with a depth of about 30-40m with bottom characterized by coral knolls and reefs.

3.3 Sampling and Analytical methods

The hydrographic parameters, temperature, pH and dissolved oxygen (DO) were measured on board the hired boat. For nutrient analysis, a known volume of water was filtered and the filtrate was collected in Tarsons air tight bottles and kept in icebox until analysis. Physical parameters such as temperature, salinity and chemical parameters such as pH, dissolved oxygen (DO), ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, phosphate-phosphorus and silicate-silicon were analyzed.

Rain fall data was collected from the Indian Meteorological Department website (imd.gov.in) and expressed in millimeter.

3.3.1 Physico-chemical parameters

Water temperature was measured on board the hired boat itself using a standard degree centigrade thermometer ranging 0°C to 50°C and 0.1°C accuracy. Salinity was estimated by collecting water samples in Tarsons air sample containers and stored in an insulated box till they were analyzed. Salinity was estimated by Mohr-Knudsen method (Grassoff *et al*., 1983) and refractometer. The halides present in 10ml of the sample was titrated against silver nitrate ($AgNO_3$) solution, which was standardized using sea water, and potassium chromate as indicator. The values were recorded as parts per thousand (ppt).

Water pH was measured using a portable pH meter (Systronics model 371 (accuracy± 0.01) (APHA 2005). Dissolved oxygen was analyzed by modified Winkler method (Strickland and Parsons 1972; Grasshoff *et al*., 1983).This method depends on the oxidation of manganese dioxide by the oxygen dissolved in the samples resulting in the formation of a tetravalent compound, which on acidification liberates iodine equivalent to the dissolved oxygen present in the sample. The result is expressed in ml/L of dissolved oxygen.

During the open ocean zone sampling on board Sagar Sampada(Cruise #338),vertical profiling of parameters such as temperature, salinity, density and dissolved oxygen was acquired using Conductivity-Temperature-Depth profiler (CTD, Sea Bird Electronics Model 911 series, Sea-Bird Inc).

Ammonia-nitrogen was analyzed using the phenate method (Grasshoff *et al*., 1983; Parsons *et al.,* 1984). In a moderately alkaline medium, ammonia reacts with hypochlorite to form monochloramine, which forms indophenol blue in the presence of phenol, a catalytic amount of nitroprusside ions and excess hypochlorite. The blue colour were measured at 640 nm with a light path of 1 cm and expressed in µmol/L.

Nitrite-nitrogen (NO_2-N) was analyzed using the diazotized method (Strickland and Parsons,1972; Grasshoff *et al*.,1983; Parsons *et al.,*1984). In this method, the nitrite in the water samples was allowed to react with sulphanilamide. This process is called diazotization. Thereafter, the same sample reacts with N-(1-Naphthyl) ethylenediamine dihydrochloride. The absorbance of the resultant azo dye was measured at 543nm in a spectrophotometer and expressed in µmol/L.

Nitrate-nitrogen (NO_3-N) was estimated using the resorcinol method (Zhang and Fischer, 2006). This method is based on the conversion of nitrate to nitric acid in the presence of resorcinol in acidified seawater. Chloride ion reduces the nitrate to nitrite to form a nitrosyl chloride as an intermediate, which in turn reacts with resorcinol to form a pink coloured nitrosophenol. This pink colour measured at 505 nm with a 1 cm path length cuvette and expressed in µmol/L.

Dissolved inorganic phosphate-phosphorus (PO_4-P) was measured using the ascorbic acid method (Strickland and Parsons, 1972; Grasshoff *et al*.,1983). In an acid solution containing molybdic acid, ascorbic acid and trivalent antimony, inorganic phosphate forms a reduced phosphomolybdenum complex, which is blue in colour. This technique was used to quantify the amount of phosphate-P in the sample. The absorbance was measured at 882nm and expressed in µmol/L.

Silicate-silica(SiO_3-Si)- in the water was estimated by molybdosilicate method (Grasshoff et al., 1983).Ammonium heptamolybdate reacts with silica to form a yellow silicomolybdic acid at pH approximately 1.2. This is further reduced by ascorbic acid in

the presence of oxalic acid to form a blue coloured complex (molybdenum blue). This blue colour is measured at 810 nm and expressed in µmol/L

3.3.2 Chlorophyll a

The chlorophyll a was estimated by the Vacuum filtration – acetone extraction method using the membrane filter assembly (Parsons et al., 1984; APHA, 2005). A known volume of water samples were filtered through 47 mm GF/C filters (pore size 0.7 µm). Before filtration, 1 ml of 1% $MgCO_3$ solution was added to the water samples, which $MgCO_3$ prevent the development of any acidity and subsequent degradation of pigments in the extract. The filtrate was extracted with 90% acetone for 20-24 hours in dark in refrigerator. After the incubation the extraction was stirred and centrifuged for about twenty minutes at 5000 rpm. The supernatant was decanted and made up to 10 ml. The extinction was measured at 665 nm and 480 nm in a spectrophotometer before and after acidification, using a 1 cm cuvette with 90% acetone in the reference path. The chlorophyll a is expressed in mg/m^3 (APHA,2005; Parsons *et al*., 1984).

3.3.3 Mesozooplankton samples

Sub-surface water samples were collected using a modified WP (working Party) plankton net (mesh size 200 µm) having a mouth area of 0.28 m^2 for collection of mesozooplankton and copepod samples (Jagadeesan *et al.*, 2013).Sub-surface horizontal tows at a fixed speed of 1 Knot for 10 min were carried out with the net attached to a calibrated flow meter (General Oceanics model number -2030 R, 2012). The propeller of the flow meter rotates with the flow of water and records number of revolutions. The revolution corresponds to the length of water column which has passed through the net. The volume of the water filtered can be calculated and expressed in cubic meters. Major portion of sample was in the cod end bucket, the sample left on the walls of the net was washed with water and transferred into two different bottles in equal volumes for preservation. Sub-surface water samples were collected from open ocean zones of Minicoy island using Bongo net (mesh size 200 µm) having a mouth area of $0.25m^2$.

Immediately after sampling, those for DNA analysis were fixed in 95% ethyl alcohol and those for morphological examination were preserved in 4% buffered

formaldehyde. Magnesium chloride (7-10%) was used as narcotizing agent (Steedman, 1976; Anon, 1968, Omori and Ikeda, 1984, Harris *et al*., 2000) in high quality air tight bottles labeled with date, time, location of the station and season.Depending on the size of the sample, sub samples were taken using Folsom plankton splitter (Plate.1).Biomass was volumetrically estimated after removing large detrital particles, using displacement volume method and was expressed in ml/m^3 (Harris et al., 2000; Varghese et al., 2015).

Sorting and analysis of major zooplankton taxa and copepods were done under Stereo Microscope in the Ecology lab of the department using standard references (Omori and Ikeda, 1984; Tait 1998; Todd and Laverack,1991) and enumerated for composition, abundance, distribution and expressed as No/100m^3(Goswami 2004; Johnson and Allen 2005;Harris *et al*., 2000).The cyclopoid copepods were sorted and further identified upto species level using standard keys (Boxshall and Halsey 2004; Dahl, 1912; Farran, 1911, 1929; Kasturirangan, 1963; Mori, 1964; Sewell, 1947a; 1948b Karanovic, 2000; Mori, 1964; Tanaka, 1957;http://copepodes.obs-banyuls.fr/en/).

3.3.4 Molecular Analysis of copepods

DNA isolation

Genomic DNA was extracted from single adult copepod specimens that had been alcohol preserved and were rehydrated in 500µl milliQ for 10-12hrs at room temperature (Bucklin *et al*.1995, 1996a, b).Individual copepods, cut into pieces with a needle, were transferred to a 2ml tube. Total DNA extraction was performed with the DNeasy Blood and Tissue Kit (Qiagen) using spin column protocol and the isolates were stored at -20°C for further analysis. Mitochondrial DNA sequences of five specimens were determined for portions of the mitochondrial cytochrome *c* oxidase subunit I gene (mt COI). PCR amplification was performed with 25µl samples using a gradient thermal cycler (BIO-RAD Model Number 621BR07085). The PCR (Polymerase chain reaction) mixture (25µl) contained: 12.5 µl PCR Master mix (Takara Clontech Emerald Amp® GT PCR Master Mix (Takara Bio, Otsu,Shiga Prefecture, Japan), 1µl LCO 1490,1 µl HCO 2198,4 µl template DNA and 6.5 µl milliQ.

Amplification and sequencing of mitochondrial cytochrome c- oxidase sub unit I (COI) gene

PCR primers were LCO-1490 (5- GGTCAACAAATCATAAAGATATTGG-3′) and HCO-2198 (5′-AAACTTCAGGGTGACCAAAAAATCA-3′). The PCR protocol started with preheating for polymerase activation at 94ºC for 5 min followed by 40 cycles of 1min each at 94°C for denaturation, 37°C for 2min for annealing, extension of 72°C for 3min,a final extension for 10mn at 72°C.

Agarose gel Electrophoresis

For analysis of the PCR products,1% agarose gel was prepared by pouring 0.3g agarose powder into microwave flask along with 30ml of 1xTAE buffer. It was then microwaved for 1min until the agarose is completely dissolved. After cooling,1µl EDTA was added to this solution and was poured on to the gel tray and was allowed to solidify. The gel tray was submerged in 1xTBE buffer filled in a buffer tank. Approximately 4µl of each PCR product was mixed with 1µl loading dye and loaded into the well. Electrophoresis was carried out and the gel was visualized on a UV transilluminator using the Gel Doc system.

Sequencing

The PCR products were sent to ScieGenom labs (ScieGenom labs Pvt, Ltd, Kerala, India) for purification and sequencing. All the sequences developed in this study and obtained sequences from NCBI were manually checked and aligned using the default parameters by Clustal X (Karanovic *et al*., 2014; Thompson *et al*., 1997).Phylogenetic and molecular evolutionary analyses were conducted using a Maximum Likelihood tree and intraspecific pair wise distance matrix was calculated using Kimura 2 parameter model in MEGA5 (Tamura *et al*., 2011; Karanovic *et al*., 2014).

3.4 Statistical Analysis/Data Analysis

For a better explanation of sample data, statistical analysis including univariate and multivariate analysis was carried out. The software programs SPSS Vs 18 (Statistical Programme for Social Sciences version 18.0) and PRIMER Vs. 6.1.9 (Plymouth Routines in Multivariate Ecological Research, version 6.1.8) were

employed. ArcGIS v. 10.2.2 and Origin pro 8.5 were used to plot spatial variation of various physico- chemical parameters. SPSS Vs18 was employed for statistical analysis of two way ANOVA and correlation analysis for testing the presence of significant differences among the water quality parameters between stations and between seasons. Correlation results were used to correlate the environmental parameters with the biological parameters.

Univariate analysis like species diversity, species richness, species evenness, Simpson dominance index and multivariate analysis like Principal Component Analysis (PCA), Similarity percentage (SIMPER) analysis, MDS plots (Non metric multi-dimensional scaling), cluster analysis, ABC curve-Abundance Biomass Comparison Curve (evaluate the disturbance to the biota),BEST analysis (BIO-ENV to find out the relationship of environmental variable with faunal composition),Funnel plots and Species accumulation plots were performed using PRIMERv6 (Plymouth Routines In Multivariate Ecological Research- Clarke and Gorley, 2006)software.

3.4.1 Univariate Analysis

3.4.1.1 Diversity indices

i) Shannon index (Shannon-Wiener [H'])

For measuring species diversity Shannon index was used (Shannon, 1949) by the formula

$$H' = -\Sigma i\ pi \log (pi)$$

Where, pi = proportion of the total count

log = log2

ii) Margalef richness index (d)

It is used to analyze the species richness of the community based on Margalef 1958) formula. Species richness index standardizes the number of species encountered against the total number of individuals encountered.

$$d = (S-1) / \log N$$

Where S = number of individuals of one species

N = total number of all individuals in the sample

iii) Pielou's evenness index (J')

Species evenness refers to how close in numbers each species in an environment (Pielou, 1975). Pielou's evenness index is expressed as

$$J' = \frac{H'}{(\log_2 S)} \text{ or}$$

Where, J' : Pielou eveness index

H' : Shannon index

S : number of classes

iv) Simpson dominance index (Lambda or λ)

The dominance of species was measured by Simpson's index (Simpson, 1949).

$$\lambda = \Sigma Pi2$$

D is a measure of dominance, so the D increases, diversity decreases

$$D(1- \lambda) = 1- (\Sigma Pi2); 1- \lambda' = 1- \{ \Sigma i \, Ni \, (Ni-1)\}/\{N \, (N-1)\}$$

Where Pi2 = the proportion (ni/N) of individuals of one particular species found (ni) divided by the total number of individuals found (N)

3.4.2 Multivariate analyses

3.4.2.1 Cluster analysis

Cluster analysis is indicative of the degree of similarity in species, composition either between stations or at the same station over time. Sites that are grouped into the same cluster are more similar in species composition. The most commonly used clustering technique is the hierarchical agglomerative method. It produces a hierarchy of clusters, ranging from small clusters of very similar items to larger clusters of increasingly dissimilar items. Hierarchical methods produce a graph known as a dendrogram or tree that shows the hierarchical clustering structure in which x-axis represents the full set of samples and the y-axis defines the similarity level at which the samples or groups are fused. The dendrogram was produced using the Bray-Curtis coefficient (Bray and Curtis ,1957).

3.4.2.2 MDS Plots (Non-metric multi dimensional scaling)

The primary outcome of MDS is a spatial configuration in which the objects are represented as points. The points in this spatial representation are arranged in such a way that their distances correspond to the similarities of the objects. Similar objects are represented by points that are close to each other and dissimilar objects by points that are far apart. In metric multi dimension scaling developed by Shepard (1962) and Kruskal (1964) the ordinal information in the proximities is used for constructing the spatial configuration. (Clarke and Gorely, 2006).

3.4.2.3 Principal Component Analysis (PCA)

PCA is one of the best statistical tools for extracting linear relationships among a set of variables (Iyer et al., 2003) providing information regarding the driving environmental variables that effect on ecological response variables (Hobbie, 2000).An important aspect of PCA is the production of eigen values, which are the measure of the significance of the components; the components with the highest eigen values are chiefly significant. Also eigen values of 1.0 or larger are considered significant (Pejman et al., 2009; Garizi et al., 2011). Generally, the most significant variables in the components represented by high loadings (>0.6) are taken into consideration for evaluating the components (Mahloch, 1974).

3.4.2.4 BEST analysis

BIO-ENV procedure is used to link biological community analyses to environmental variables or to examine the extent to which environmental data, such as physico-chemical data, is related to the observed biological pattern (Clarke and Gorely, 2006). The BIO-ENV procedure calculates a measure of agreement between the two similarity matrices: the fixed biotic similarity matrix (using Bray- Curtis similarity on the biotic data) and each of the possible abiotic matrices (PCA on combinations of the abiotic data). This is done by using the Spearman rank correlation, which ranks the subsets of variables that best 'matches' the biological pattern

3.4.2.5 Abundance Biomass Comparison curve (ABC plot)

ABC plots are used to evaluate the disturbances at the particular site based on the trend of ABC curve, without any reference site (Warwick, 1986). Uniformity in the distribution of abundance and biomass values represents the level of stress in the community. In undisturbed communities the biomass curve lies above the

curve for abundance. Under moderate pollution (or disturbance), the biomass and abundance curves are closely coincident and may cross each other one or more times. In disturbed condition, abundance curve lies above the biomass curve throughout its length. The W-value (Warwick value) were used to statistically define the relationship between curves and quantify the level of stress that a community experiences. When the biomass curve is above the abundance curve the W-value will be positive. The negative W-value emanates when the abundance curve is above the biomass curve, with intermediate cases tending toward zero.

3.4.2.6 Taxonomic distinctness indices (Funnel plots)

Taxonomic diversity (Δ) and the taxonomic distinctness (λ+) are indices based on the taxonomic spread of species. It plots the distributions of Average Taxonomic Distinctness (Δ+) and Variation of Taxonomic Distinctness (λ+). A master data aggregation file is used to generate the distribution of samples and the results were presented as a funnel plot (Clarke and Gorley, 2006).

Average taxonomic distinctness index (Δ+) is the average taxonomic distance apart of all its pairs of species and **Variation in taxonomic distinctness index (Λ+)** is a measure of the evenness of the spread of species across higher taxa. Average taxonomic distinctness index (Δ +) and variation in taxonomic distinctness (Λ+) were used to construct funnel plots (**95% confidence limit funnel plot)** to test for any significant departure of species from the expectation (Warwick and Clarke, 2001).Taxonomic diversity and taxonomic distinctness of cyclopoid copepods was plotted in the present study in order to have a comparison between the two.

3.4.2.7 Species accumulation plot

Species richness of cyclopoid species was estimated using various species estimators such as Chao 1 (Chao's estimator based on number of rare species) Chao 2 (Chao's estimator using just presence-absence data), Jacknife 1 (based on species that only occur in one sample) Jacknife 2 (Second order jacknife estimator), Bootstrap (based on proportion of quadrats containing each specie s), UGE (Calculated species accumulation curve (Ugland et al., 2003), SOBS (Curve of observed species counts) and MM (Michaelis-Menton -Curve fitted to observed S curve) were done in PRIMER.

PLATE-1

Gadgets and equipments used for filed and laboratory studies

Global positioning system

Niskin's water sampler

Zooplankton collection (200µm)

Analogue Handheld Refractometer

Flow meter

Folsom plankton splitter

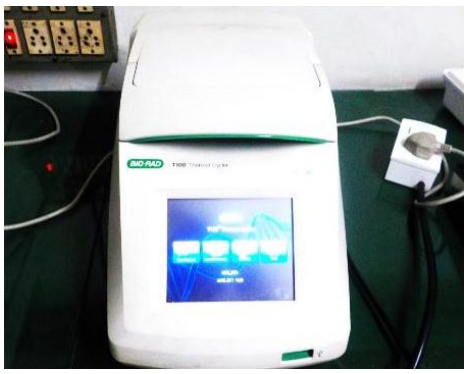
PLATE-2

Compound microscope

Stereo microscope

Blood and Tissue kit (Qiagen)

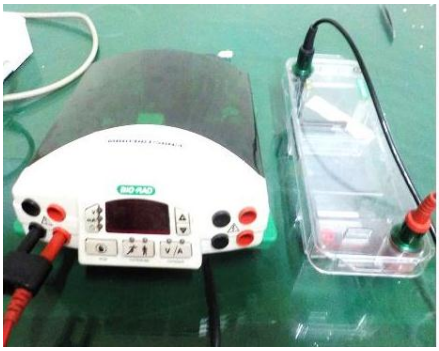
Deep Freezer



Thermal cycler (BIO-RAD)

Thermal Cycler (Agilent)

PLATE-3



Agarose Gel Electrophoresis unit

UV transilluminator

Micropipettes

Waterbath

Microcentrifuge

Hot air oven

PLATE-4

Field sampling in Kavaratti island, Lakshadweep during 2013-15

Cruise ship (M.V.Arabian Sea) to the lagoon

Our research team

On board sampling in sampling

Operating Niskin's water sampler

Marking GPS location of stations

Field sampling in progress

PLATE-5

Field sampling in Kalpeni island, Lakshadweep during 2013-15

A view of taking passengers in small boats from ship to the island

Ready for net hauling

Collection of plankton samples

In hired boat (a distant view of island at the back)

Analysis of nutrients

PLATE-6

Field sampling in Minicoy island, Lakshadweep during 2013-2015

All set for sampling

Sample fixation in progress

Labelling the samples

Sample fixing with formalin

Sample collection in progress

Zooplankton sample

PLATE-7

Field sampling in Agatti and Bangaram islands, Lakshadweep during 2013-2015

All set for sampling

Hauling plankton nets

A view of underwater corals

Fixing Dissolved Oxygen on board

With "kolan" (*Hemiramphus sp.*) fish caught unexpectedly while sampling

Our team

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Chapter 4

Hydrography

Contents

4.1 Introduction

"Everything affects everything, all living things exist as parts of system, in each system there are factors that limit the growth; each system has a definite capacity to carry the organisms of that system, in these systems all natural cycle are used, but the energy of the system flows in one direction-downward to uselessness; stability of system increases with specialization" is the principle that governs each and every ecosystem where man and social system forms an integral part (Srivatsava,1992).To understand the dynamics of any aquatic ecosystem, sufficient knowledge on its hydrographic conditions and parameters that regulate it's community structure and existence is unavoidable. Spatial and temporal variation of the independent and interrelated actions of abiotic elements definitely influences the biota which it supports. Hydrological parameters are essential for proper functioning of organisms and furthermore a favorable range of abiotic factors are vital for the growth and functioning of the organisms. Conferring to the optimum range, organisms prefer different habitat within the zone. An ecosystem's population size and distribution is clearly determined by the interaction of organisms with the environment. Therefore, it is vital to have a continuous monitoring on the water quality in any geographical area, for the survival and well-being of organisms inhabiting these aquatic biotopes.

Coastal ecosystem is impacted by the combined effect of both terrestrial and proximate aquatic ecosystems. The hydrography of coastal ecosystems such as mangroves, coral reefs and saltmarshes are to a great degree controlled by climate,

tides and fresh water influx and moreover the hydrography of a lagoon is chiefly determined by seasonal rainfall and tidal flow. The morphology of a coral reef ecosystem is defined to have the following distinctive features: a sloping fore-reef, a shallow reef flat and a relatively deep lagoon. Waves, tides, winds and buoyancy effects drive the circulation on reefs. Further, regional precipitation and radiation induced surface heating and cooling are also the factors which control hydrography in the reef and the lagoons (Andrews and Pickard, 1990).Abundant light energy available in clear waters of the lagoon and the complex current pattern around the islands as well as open ocean will,hence have a strong influence on its hydrography.

In a coastal lagoon, during summer, wind and tide forms the major controlling factors of salinity distribution and circulation whereas in winter; wind, tide and fresh water input control the circulation and mixing pattern (Mohanty and Panda, 2009).High biotic diversity is the characteristic feature of coral reef lagoons and surrounding open ocean zones. Since the surface-depth ratio of lagoon is larger than that of open sea, both are subjected to extreme variations in properties.

The physico-chemical factors that were taken into consideration in the present study were rainfall, Sea Surface Temperature (SST), Sea Surface salinity (SSS), pH, dissolved oxygen (DO), carbon dioxide (CO_2) and the nutrients, phosphate, silicate, nitrate, nitrite and ammonia. Nothing except temperature as a physical factor has so much intense direct or indirect impact on bio-physical, metabolic and physiological behavior of aquatic ecosystem (Welch, 1952) and moreover it is a key factor leading to species distribution, zonation and stratification too (Issac, 1938; Stephenson, 1944; Lewis, 1964).

Another viewed factor which influences the abundance and distribution of flora and fauna in coastal marine ecosystems is salinity. Salinity which affects the structural and functional responses of marine organisms, is a function of evaporation, precipitation and land runoff. Besides, salinity has indirect impacts by modifying the species composition of an ecosystem. Since all the lagoons considered here are associated with oceanic islands, absence of any freshwater sources as well as less influence of land run off; salinity here is determined by rainfall and surrounding oceanic region.

Since any aquatic organism is adapted to live in an optimum pH, any abrupt variation of this cannot be tolerated by the inhabitants and therefore is considered as one of the important ecological factor. A significant change in pH can alter the oxygen and carbon dioxide concentrations in aquatic environment which in turn affects the respiration and primary production of the organism. Solubility and biological availability of nutrients are also determined by pH.

Dissolved oxygen, generally determined in milligrams or milliliters is the amount of oxygen which is dissolved in one liter of water and the key regulator of any aquatic community metabolic processes (Zutshi and Vass, 1978).By the exchange with the atmosphere and through various biological processes (respiration and photosynthesis),it's distribution in a marine environment is well-ordered.

Nearly all the ecological processes are linked to the nutrients. The mechanism of nutrient transport and transformation is very complex in marine ecosystem. As the inorganic nutrients such as phosphate, nitrate, nitrite, ammonia and silicate are vital to the primary producers of marine ecosystem, a systematic assessment of the same is also crucial.

A critical analysis on the hydrography of the Lakshadweep lagoons (Kavaratti (Kvt), Kalpeni (Klp),Minicoy (Mcy), Agatti (Agt) and Bangaram (Bang) and open sea stations of Minicoy are detailed in this chapter. In addition, seasonal reversal of ocean currents influencing the hydrodynamics of the lagoons are also discussed.

4.1.1 Rainfall

The average seasonal rainfall during 2013-14 in Lakshadweep islands ranged from 53.6±6.2mm in premonsoon to 273.2±25.9mm in monsoon and 59.3±10.2mm for postmonsoon. Whereas during 2014-15,the average seasonal value ranged from 28.3±23.4mm in premonsoon, 209.9±53 mm for monsoon and 78.5±13.2mm for postmonsoon. When compared, the first year witnessed higher rainfall during premonsoon and monsoon but postmonsoon rainfall was higher during the second year. Mean seasonal rainfall in Lakshadweep islands is given in Fig.4.1

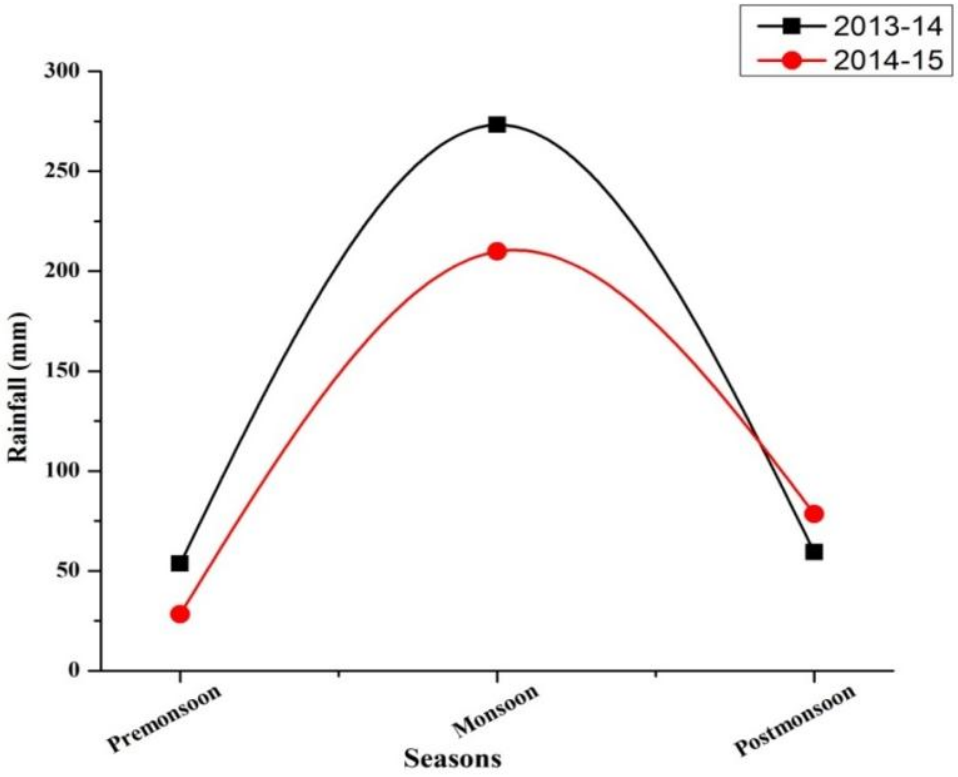


Fig.4.1 Mean seasonal variation of rainfall in Lakshadweep islands during 2013-2015

4.2 Physicochemical parameters of lagoon stations of five islands of Lakshadweep

4.2.1 SST (Sea Surface Temperature)

During 2013-14, the mean Sea Surface Temperature (SST) of Kavaratti showed minor fluctuations. During premonsoon, SST values ranged from 29.64 to 30.07°C (av.29.86°C±0.213), 27.97 to 28.30°C (av.28.13°C±0.163) during monsoon and 29.01 to 29.24°C (av.29.12°C±0.115) during post monsoon. During 2013-14, in Kalpeni lagoon, SST fluctuated from 28.13 to 28.18°C during monsoon (av.28.16°C±0.035) and 29.05 to 29.10°C (av.29.08°C±0.035) during post monsoon. Here also monsoon season showed a lower value than that of post monsoon season. In Minicoy lagoon also monsoon season exhibited a low value ranging between 28.31°C to 28.32°C (av.28.31°C±0.005), when compared to postmonsoon with values ranging from 28.95°C to 28.98 °C (av.28.97 °C±0.021) (Fig.4.2).

However during 2014-15, Kavaratti lagoon showed SST values ranging from 28.97°C to 29.99°C (av.29.64°C±0.577) and in Agatti lagoon SST values fluctuated between 29.42°C to 29.44°C (av.29.43°C±0.012).Bangaram showed values of 29.43°C to 30.04°C (av.29.77°C±0.310). A seasonal comparison revealed that the values were minimum during monsoon and maximum in premonsoon. ANOVA of SST showed a significant variation at 1% level ($p \leq 0.001$) ($F=63.247$) (Table.1)

4.2.2 Sea Surface Salinity (SSS)

Salinity values fluctuated seasonally in all the islands during the study period (Fig.4.3).In 2013-14, Kavaratti lagoon exhibited mean SSS values of 35.05-35‰ (av.35.19‰±0.140) during premonsoon, 35.75-35.91‰ (av.35.88‰±0.122) during monsoon and 35.59-36.45‰ (av.36.09‰±0.445) during post monsoon. Whereas in Kalpeni the values ranged from 35.56-35.89‰ (av.35.73‰ ±0.233) in monsoon and 36.02-36.07‰ (av.36.05‰ ±0.035) in post monsoon. Minicoy lagoon also showed values of 35.43-35.62‰ during monsoon (av.35.53‰±0.134) and 35.35‰-36.02‰ (av.35.69‰ ±0.473) during post monsoon 2013-14. Only slight variation existed in various islands in all seasons. In 2014-15 premonsoon in Kavaratti exhibited SSS values between 34.55-35.52‰ (av.34.93‰ ±0.523), 34.62-35.39‰ (av.34.88‰ ±0.438) in Agatti and 34.60-35.57‰ (av.34.98‰ ±0.520) in Bangaram (Fig.4.3). On the contrary towards the highest rainfall received during the monsoon season in both years coincided with medium range of salinity and lowest being during premonsoon season in both years.

ANOVA of SSS was significant at 1% level between seasons ($p \leq 0.001$) ($F=32.416$) and between area ($F=2.30$) (Table 2)

4.2.3 pH

pH in Kavaratti lagoon fluctuated between 8.64-8.65 (av.8.64±0.005) in premonsoon, 7.75-7.76 (av.7.75±0.006)in monsoon and 8.74-8.75 (av.8.75±0.004) in postmonsoon 2013-14. The highest pH value was observed during post monsoon and the lowest in monsoon.

Kalpeni during 2013-14 recorded pH values of 7.02-7.03(av.7.02±0.007)in monsoon and 8.512-8.514 (av.8.513±0.001) in post monsoon. Here too the highest

pH value was observed during post monsoon and the lowest in monsoon. Minicoy lagoon during 2013-14 recorded 7.52-7.53 (av.7.525±0.007)in monsoon and 8.568-8.61 (av.8.589±0.029) in post monsoon. An inter-island comparison during 2013-14 revealed that Kavaratti (postmonsoon) showed the highest values and Kalpeni (monsoon) was showing the lowest values. During premonsoon 2014-15,pH fluctuated between 8.61-8.616 (av.8.613±0.003) in Kavaratti, 8.58-8.6 (av.8.59±0.01) in Agatti and 8.423-8.45 (av.8.44±0.016) in Bangaram. Kavaratti showed the maximum pH value and Bangaram showed the lowest (Fig.4.4).

ANOVA of pH showed a significant variation at 1% level between seasons ($p \leq 0.001$)($F=1.09$) and area ($F=32.54$) and between season and area ($F=16.70$) (Table.3).

4.2.4 Dissolved oxygen (DO)

Dissolved oxygen (DO) values of Kavaratti fluctuated between 5.93-6.11mg/L (av.6.02±0.09) in premonsoon, 6.15-6.33mg/L(av.6.24±0.09) in monsoon and 6.82-6.96mg/L (av.6.89 ±0.07) in postmonsoon 2013-14. But in Kalpeni, DO values ranged from 3.54-3.94mg/L (av.3.74mg/L±0.282) in monsoon season and 6.3-6.66mg/L (av.6.48 mg/L±0.254) in postmonsoon period. In Minicoy DO values fluctuated between 4.05-5.02mg/L (av.5.53 ±0.685) in monsoon and 4.33-5.09mg/L (av.4.71±0.537) in postmonsoon. However, during pre-monsoon season 2014-15, Kavaratti showed DO values of 4.72-7.08 mg/L (av.5.09±1.18), Agatti showed 3.35-3.54 mg/L (av.3.44±0.095) and Bangaram showed 6.02-6.12 mg/L (av.6.07±0.05). Agatti lagoon showed the minimum value and a maximum at Bangaram lagoon.Inter annual comparison of dissolved oxygen showed the highest mean seasonal values during 2013-14 periods.

ANOVA of DO recorded a significant variation at1% level between different islands ($F=13.442$) and between seasons ($p \leq 0.001$) ($F=5.618$) (Fig.4.5) (Table 4).

4.3 Inorganic Nutrients

4.3.1 Nitrate-nitrogen

In 2013-14, Kavaratti lagoon recorded values of 2.05-2.65µM/L (av.2.35±0.30) during premonsoon, 2.8-3.4µM/L (av.3.13±0.31) during monsoon

and 2.63-3.13µM/L (av.2.93±0.264) during postmonsoon. Whereas in Kalpeni the recorded values were 3.2-3.3µM/L(av.3.25±0.07) during monsoon and 3.13-3.135 µM/L (av.3.14±0.014) during postmonsoon. In Minicoy, nitrate values ranged between 3.51-3.6µM/L (av.3.55±0.063) during monsoon and 3.56-3.62 µM/L (av.2.59±0.042) during postmonsoon. Spatially, Minicoy and Kalpeni recorded a comparatively higher concentration and Kavaratti being the lowest. Seasonally, monsoon season recorded highest values and the lowest value in the post-monsoon. However during pre-monsoon 2014-15, Kavaratti recorded nitrate ranging from 2.35-2.36 µM/L(av.2.35±0.005), 3.12-3.18 µM/L (av.3.15±0.030) in Agatti and 2.41-2.45 µM/L (av.2.43±0.02) in Bangaram (Fig.4.6).

4.3.2 Nitrite –Nitrogen

During the first year Kavaratti lagoon recorded values of 0.42-0.43µM/L (av.0.43±0.005) in premonsoon 0.51-0.52µM/L (av.0.51±0.005) in monsoon and 0.49-0.5µM/L (av.0.493±0.006) in postmonsoon period. Whereas in Kalpeni nitrite values ranged from 0.62-0.63µM/L (av.0.625±0.007) in monsoon and 0.46µM/L in postmonsoon. In Minicoy, the values were 0.55/L in monsoon and 0.47 in postmonsoon. A spatial assessment revealed that highest nitrite value was observed in Kalpeni and the lowest being Kavaratti whereas a seasonal comparison revealed the maximum values in monsoon followed by postmonsoon and premonsoon.While during 2014-15, nitrite values fluctuated from 0.41- 0.43 µM/L (av.0.42±0.01) in Kavaratti, 0.47- 0.49µM/L (av.0.48±0.01)in Agatti and 0.43-0.45µM/L (av.0.44±0.01)in Bangaram. Inter annual comparison of nitrite showed a slightly higher mean during 2013-14 periods (Fig.4.7).

4.3.3 Phosphate -phosphorus

During 2013-14, Kavaratti lagoon recorded phosphate values ranging from 0.34-0.35µM/L (av.0.34±0.005) in premonsoon 0.41-0.42µM/L (av.0.41±0.01)in monsoon and 0.38-0.39µM/L (av.0.38±0.003) in postmonsoon. Whereas in Kalpeni values ranged from 0.451-0.452 µM/L (av.0.45±0.01)in monsoon and 0.381-0.382 µM/L (av.0.38±0.01)in postmonsoon. In Minicoy, the values were 0.442-0.443 µM/L (av.0.442±0.01) in monsoon and 0.385µM/L in postmonsoon. Spatially, Minicoy and Kalpeni recorded a comparatively higher concentration and Kavaratti being the

lowest. Seasonally, monsoon season recorded highest values and pre-monsoon, the lowest.While during 2014-15, phosphate values fluctuated from 0.355-0.356µM/L (av.0.355±0.001) in Kavaratti, 0.432-0.451µM/L (av.0.441±0.01) in Agatti and 0.432-0.441µM/L (av.0.437±0.004) in Bangaram. Inter annual comparison of phosphate showed a slightly highest mean during 2014-15 periods (0.40µM/L) (Fig.4.8).

4.3.4 Silicate-silicon

In 2013-14, Kavaratti lagoon recorded silicate values ranging from 0.455-0.456µM/L (av.0.455±0.001) during premonsoon, 0.3-0.32µM/L(av.0.31±0.01) in monsoon and 0.31-0.33µM/L (av.0.32±0.01) in postmonsoon. In Kalpeni, values ranged from 0.32-0.33 µM/L (av.0.32±0.01)in monsoon and 0.33-0.34µM/L (av.0.335±0.01)in postmonsoon. In Minicoy, the values were 0.44-0.45µM/L (av.0.445±0.01) in monsoon and 0.37-0.38µM/L (av.0.375±0.01) in postmonsoon. Seasonally, premonsoon recorded highest values and the lowest value was recorded during the postmonsoon. While during 2014-15, values fluctuated from 0.51-0.52µM/L (av.0.516±0.01) in Kavaratti, 0.44- 0.49µM/L (av.0.47±0.03) in Agatti and 0.45-0.47µM/L (av.0.46±0.01) in Bangaram. Inter annual comparison of silicate showed a slightly highest mean during 2014-15periods (0.48µM/L) (Fig.4.9).

4.3.5 Ammonia-nitrogen

In 2013-14, Kavaratti lagoon recorded ammonia values ranging from 0.36-0.37µM/L (av.0.366±0.01) during premonsoon, 0.351-0.356 µM/L (av.0.352±0.01) in monsoon and 0.4-0.41µM/L (av.0.406±0.01) in postmonsoon. In Kalpeni values were 0.35µM/L in monsoon and 0.42µM/L in postmonsoon. In Minicoy, the values were 0.37-0.38 µM/L(av.0.375±0.01) in monsoon and 0.42-0.43µM/L (av.0.425±0.01) in postmonsoon. Spatially, Minicoy recorded a comparatively higher concentration and Kavaratti being the lowest. Seasonally, postmonsoon recorded highest values and the lowest value was recorded during monsoon. While during 2014-15, values fluctuated from 0.38-0.39µM/L (av.0.383±0.01) in Kavaratti, 0.37- 0.39µM/L(av.0.38±0.01) in Agatti and 0.38-0.4µM/L (av.0.39±0.01) in Bangaram. Inter annual comparison of ammonia did not show any significant variation (Fig.4.10).

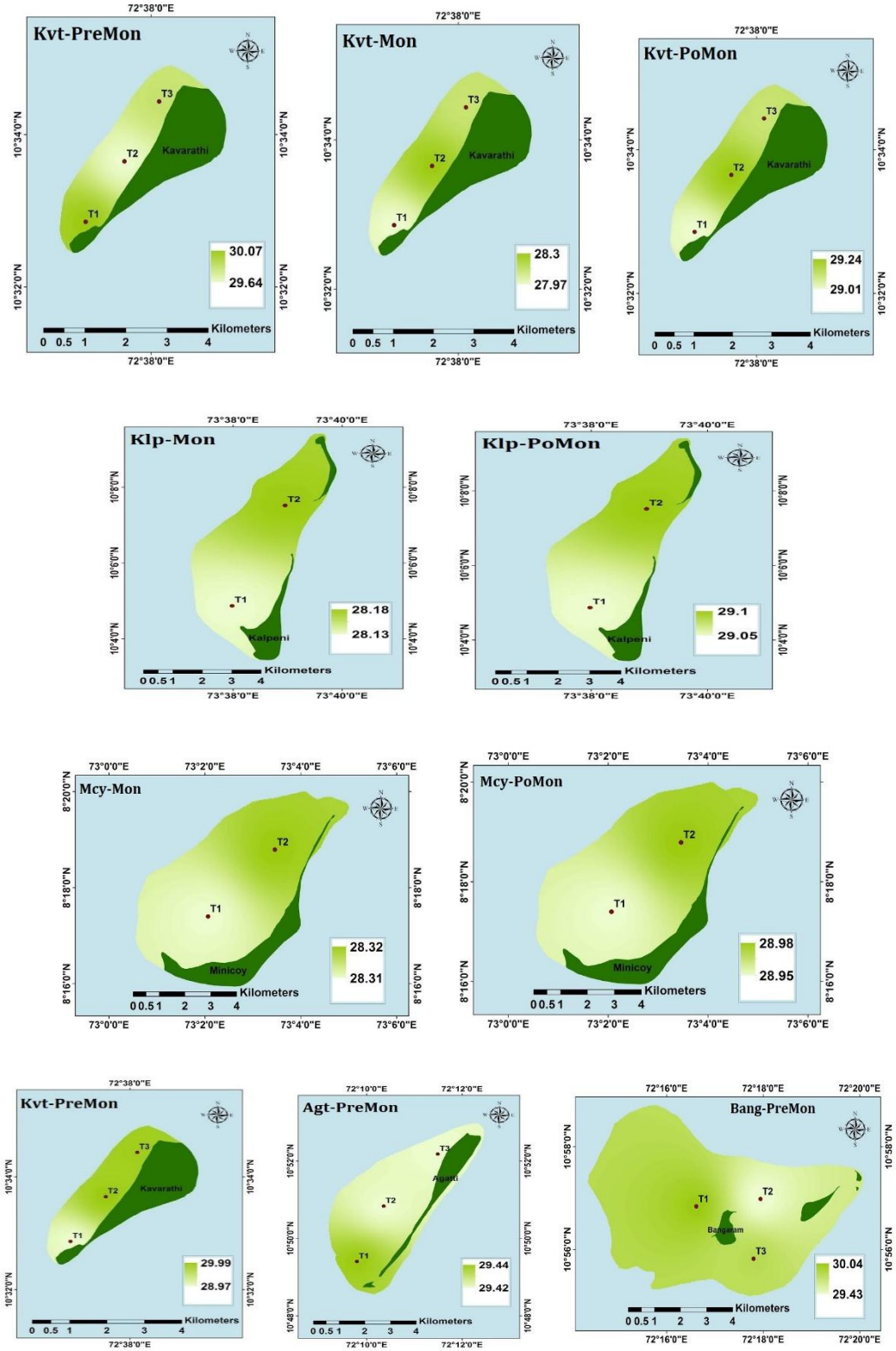


Fig.4.2 Seasonal variation of SST at lagoon stations of five different islands during 2013-15

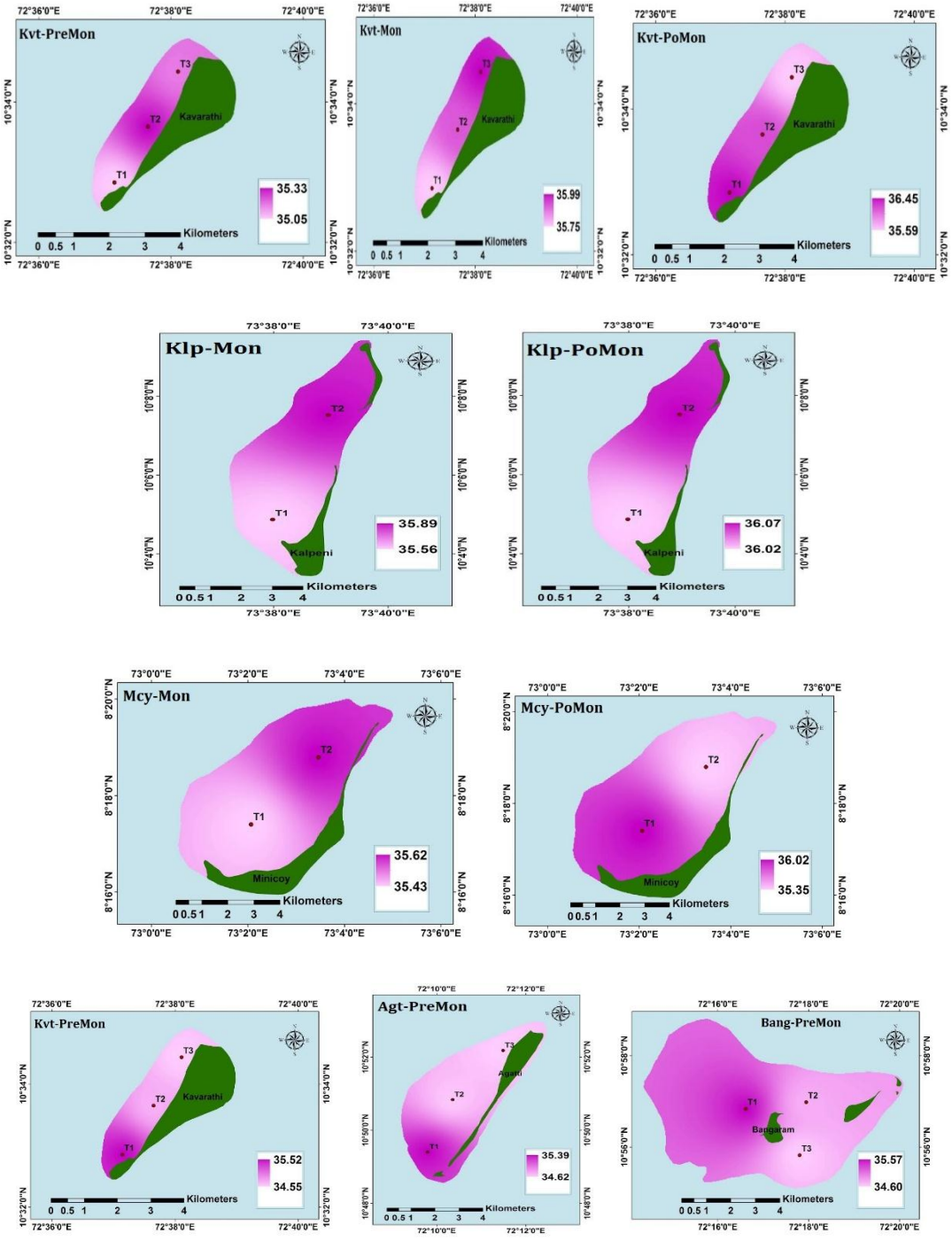


Fig.4.3 Seasonal variation of SSS at lagoon stations of five different islands during 2013-15

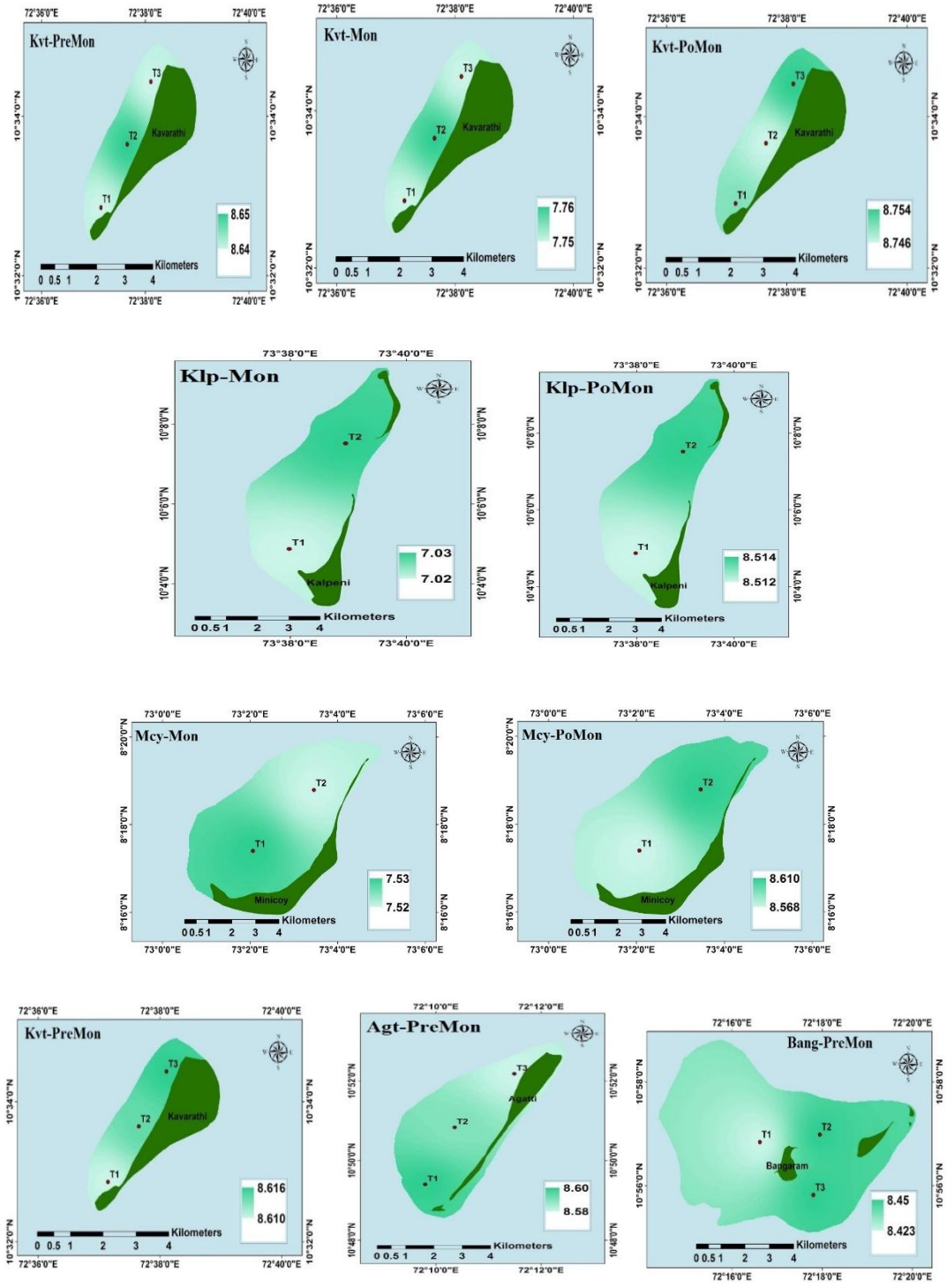


Fig.4.4 Seasonal variation of pH at lagoon stations of five different islands during 2013-15

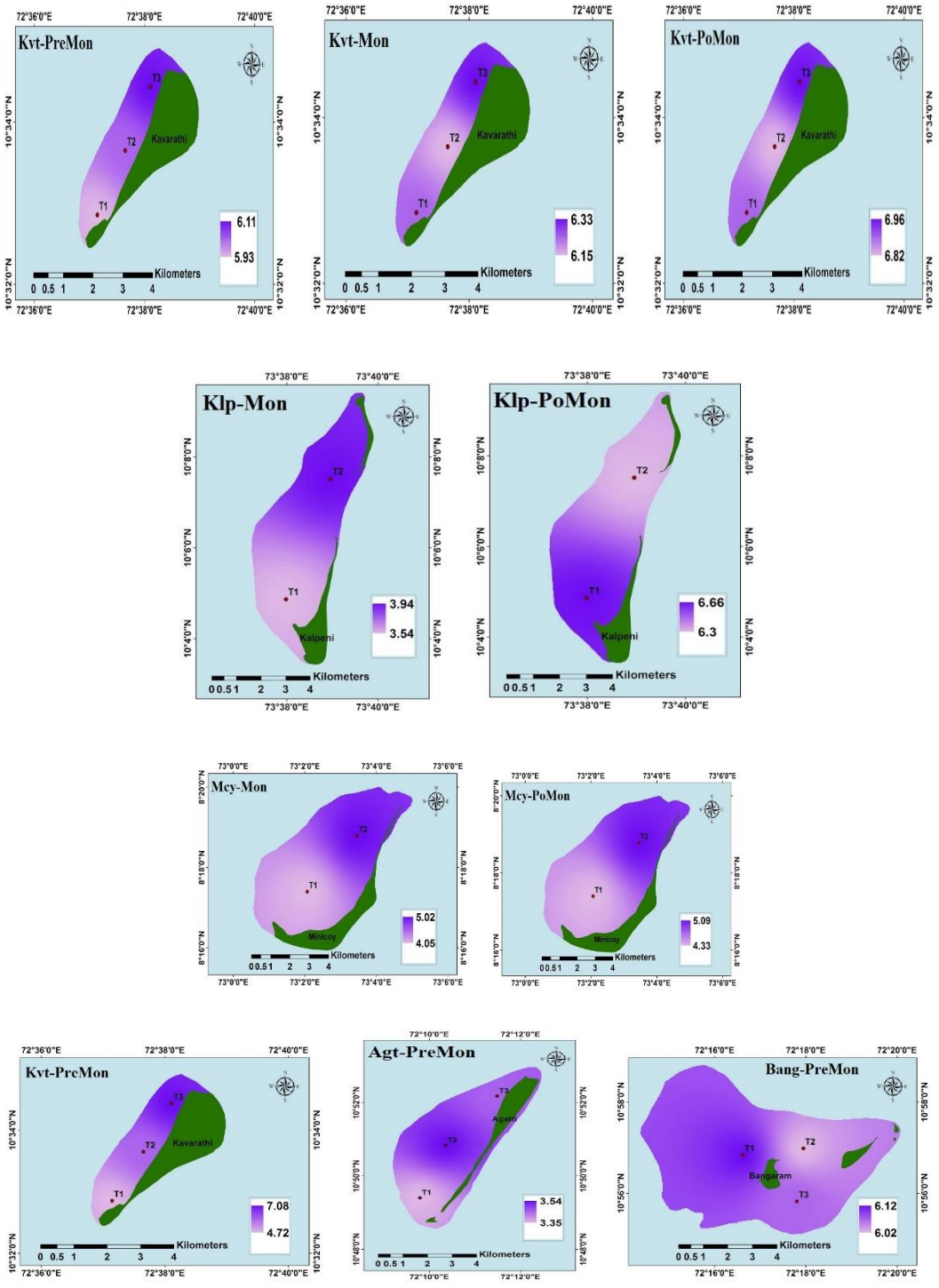


Fig.4.5. Seasonal variation of DO at lagoon stations of five different islands during 2013-15

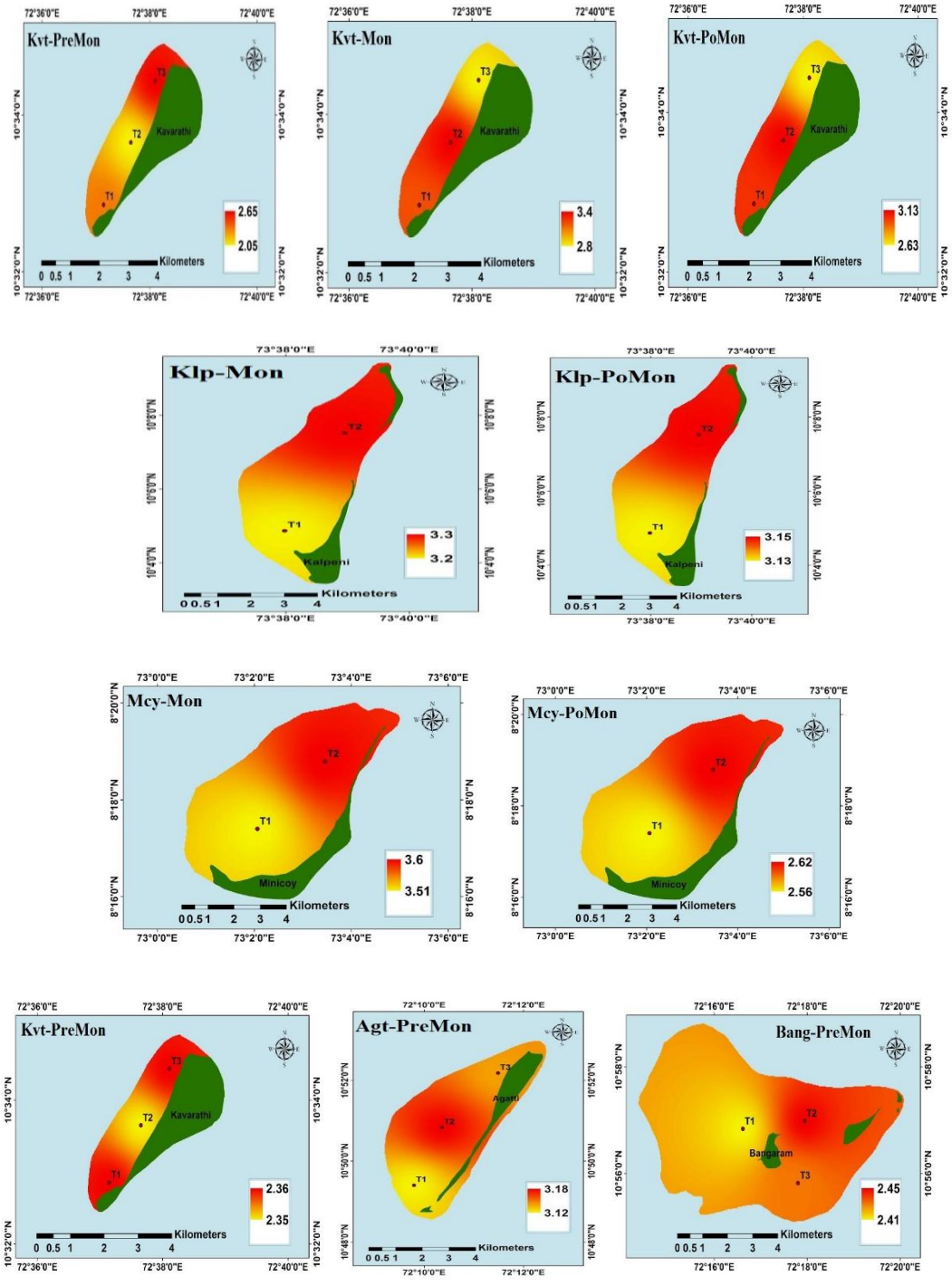


Fig.4.6. Seasonal variation of nitrate at lagoon stations of five different islands during 2013-15

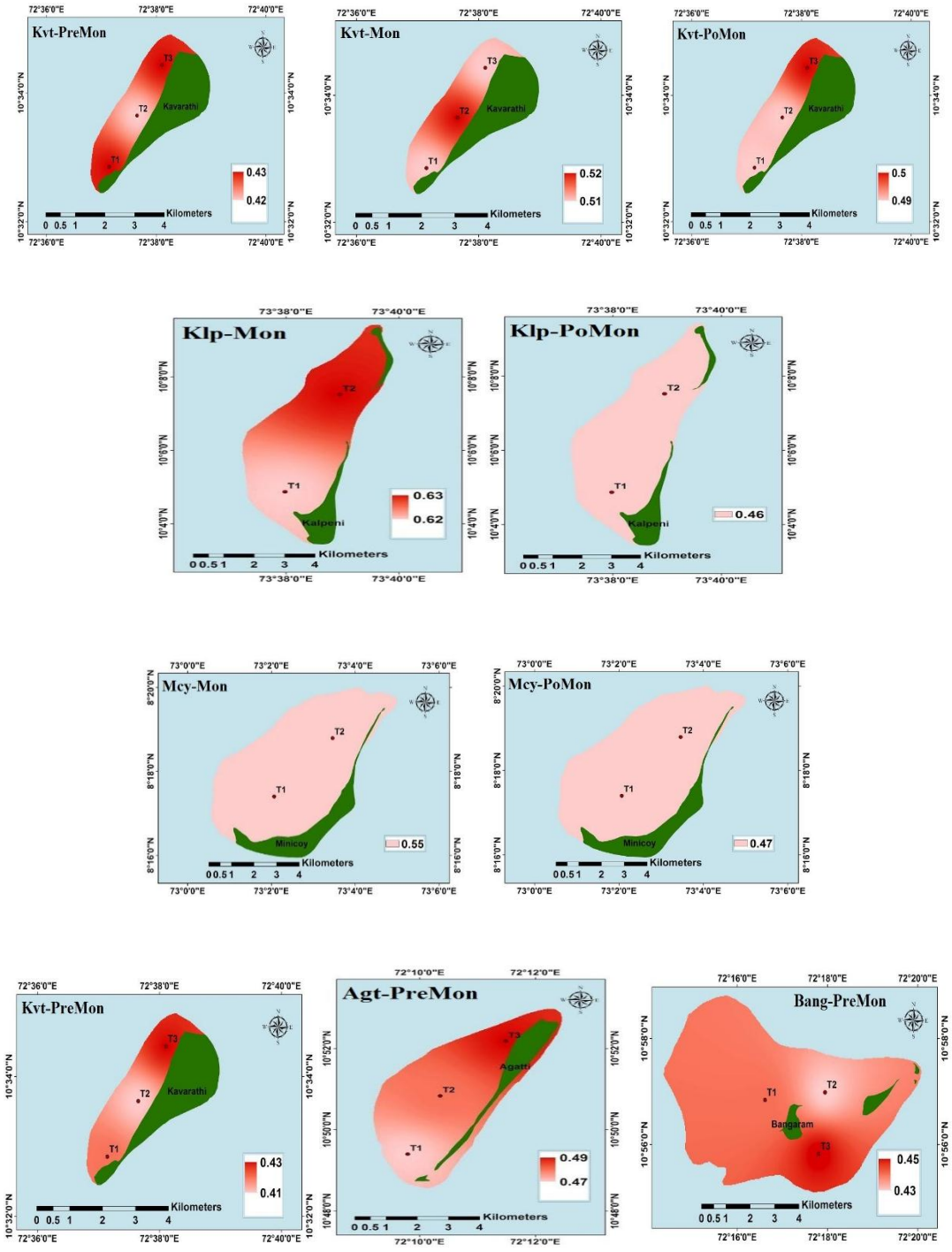


Fig.4.7 Seasonal variation of nitrite at lagoon stations of five different islands during 2013-15.

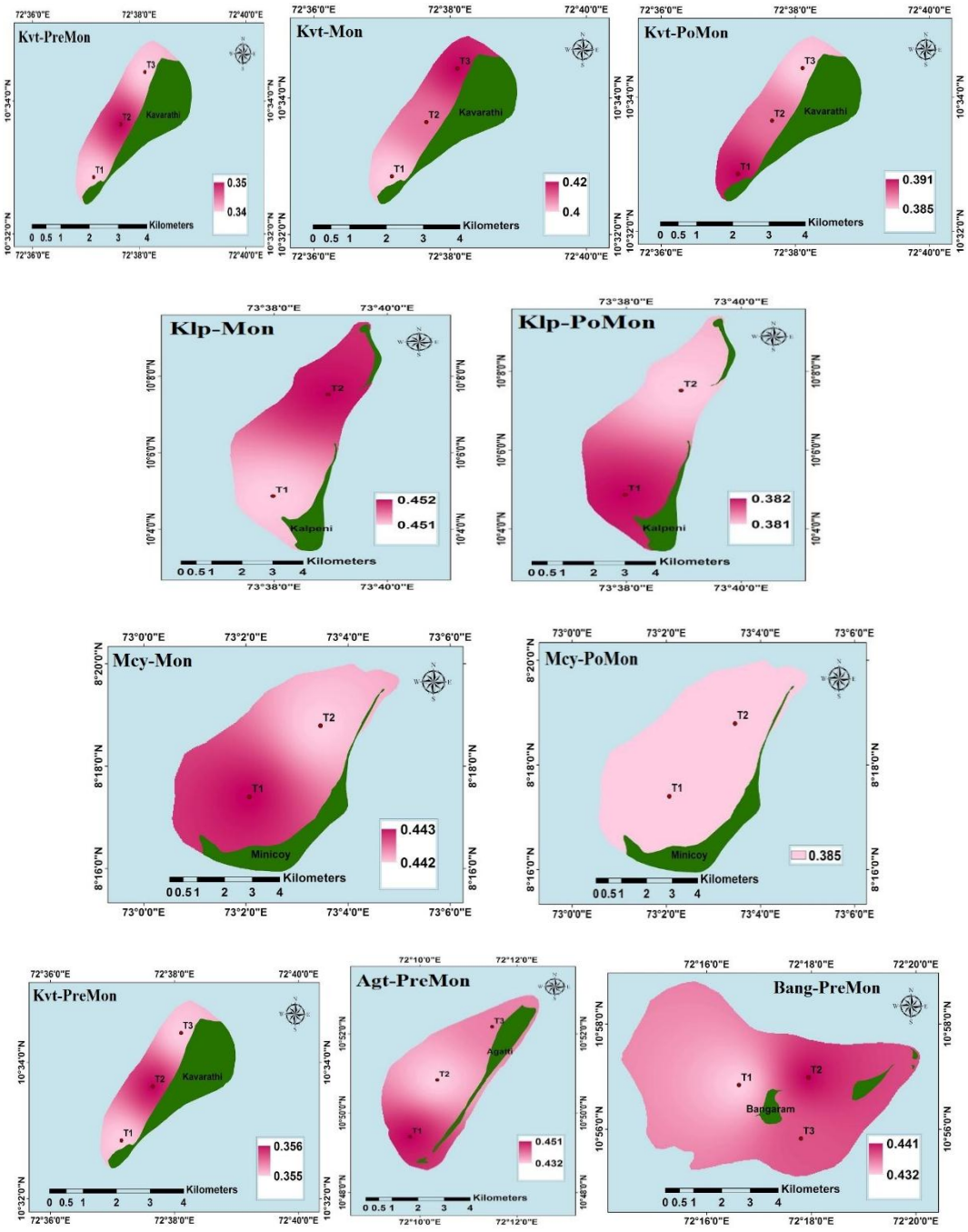


Fig.4.8. Seasonal variation of phosphate at lagoon stations of islands during 2013-2015

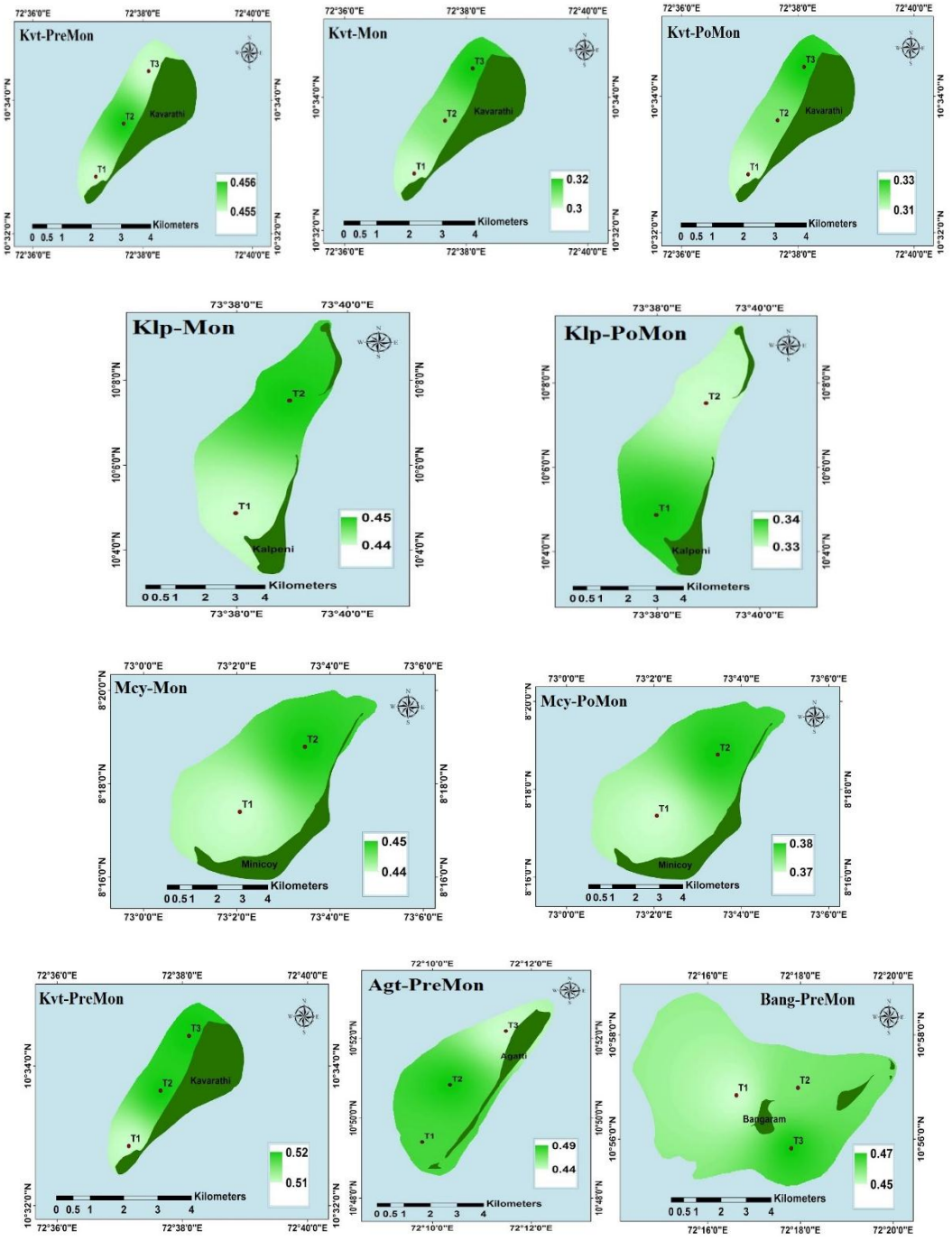


Fig.4.9. Seasonal variation of silicate at lagoon stations of islands during 2013-2015

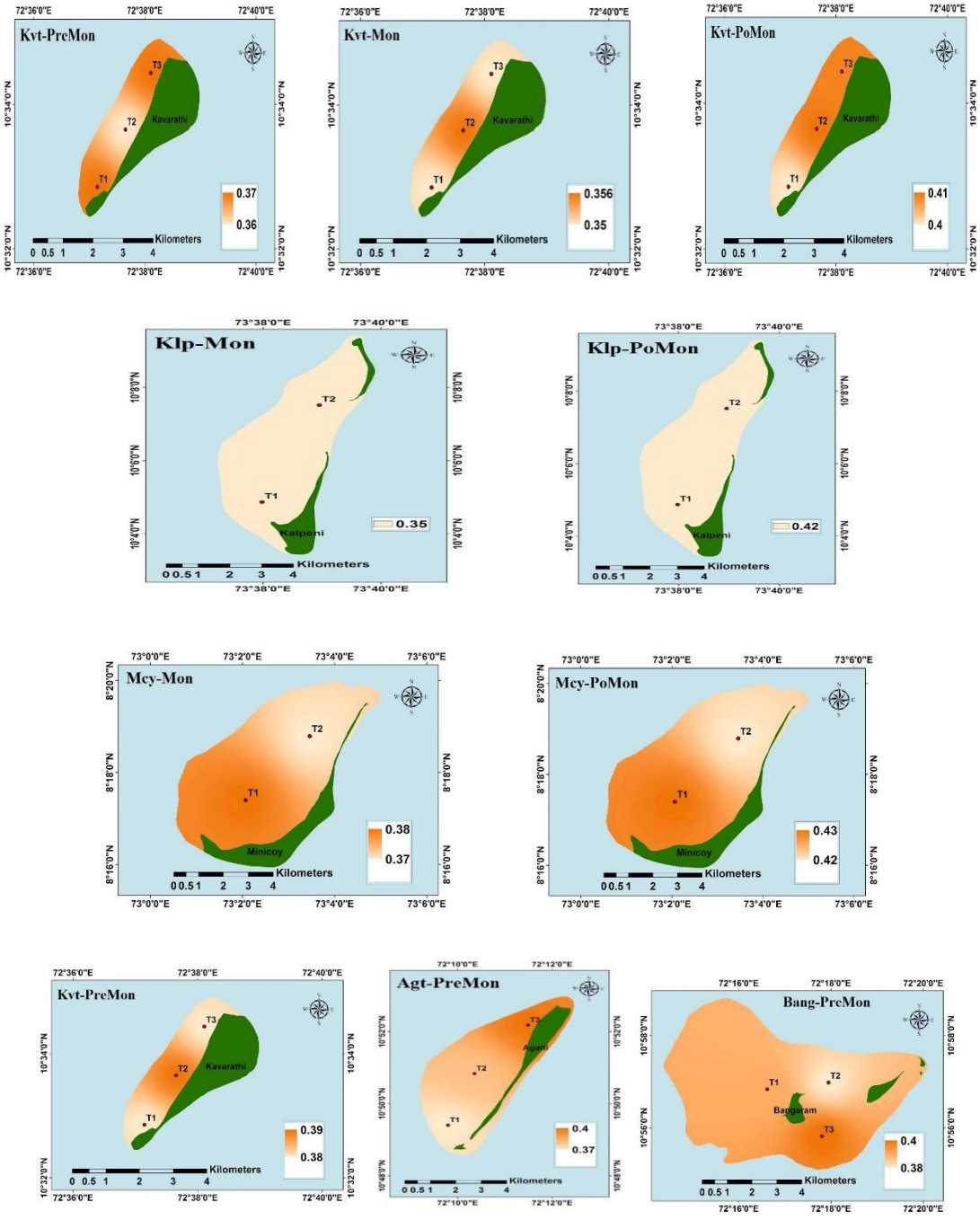


Fig.4.10 Seasonal variation of Ammonia at lagoon stations of islands during 2013-2015

Table.1. ANOVA of SST in Lakshadweep islands during the study period.

Dependent Variable: SST

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.114[a]	14	.008	9.573	.000
Intercept	871.886	1	871.886	1.026E6	.000
Season	.108	2	.054	63.247	.000**
Area	.002	4	.001	.604	.666
Season * Area	.004	8	.001	.639	.734
Error	.013	15	.001		
Total	872.013	30			
Corrected Total	.127	29			

** Variation is significant at 1% level (p≤ 0.01)

Table.2. ANOVA of SSS in Lakshadweep islands during the study period.

Dependent Variable: SSS

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.034[a]	14	.002	5.357	.001
Intercept	1065.767	1	1065.767	2.334E6	.000
Season	.030	2	.015	32.416	.000**
Area	.004	4	.001	2.307	.106
Season * Area	.000	8	5.333E-5	.117	.998
Error	.007	15	.000		
Total	1065.808	30			
Corrected Total	.041	29			

** Variation is significant at 1% level ((p≤0.001)

Table.3. ANOVA of pH in Lakshadweep islands during the study period.

Dependent Variable: pH

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.262[a]	14	.019	175.438	.000
Intercept	245.502	1	245.502	2.302E6	.000
Season	.234	2	.117	1.096E3	.000**
Area	.014	4	.003	32.547	.000**
Season * Area	.014	8	.002	16.703	.000**
Error	.002	15	.000		
Total	245.766	30			
Corrected Total	.264	29			

** Variation is significant at 1% level (p≤0.001)

Table.4. ANOVA of Dissolved oxygen in Lakshadweep islands during the study period

Dependent Variable: DO

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.526[a]	14	.109	5.457	.001
Intercept	160.730	1	160.730	8.045E3	.000
Season	.224	2	.112	5.618	.015
Area	1.074	4	.269	13.442	.000**
Season * Area	.228	8	.028	1.425	.264
Error	.300	15	.020		
Total	162.557	30			
Corrected Total	1.826	29			

** Variation is significant at 1% level (p≤0.001)

4.4 Chlorophyll a

Chlorophyll a values of Kavaratti fluctuated between 0.49-0.52mg/m^3 (av.0.51±0.01) in premonsoon, 0.45-0.46mg/m^3 (av.0.456±0.005) in monsoon and 0.52-0.55mg/m^3 (av.0.533±0.015) in postmon soon 2013-14. But in Kalpeni, chlorophyll a values ranged from 0.67-0.68mg/m^3 (av.0.675±0.007) in monsoon season and 0.15-0.16mg/m^3 (av.0.155±0.0075) in postmonsoon period.

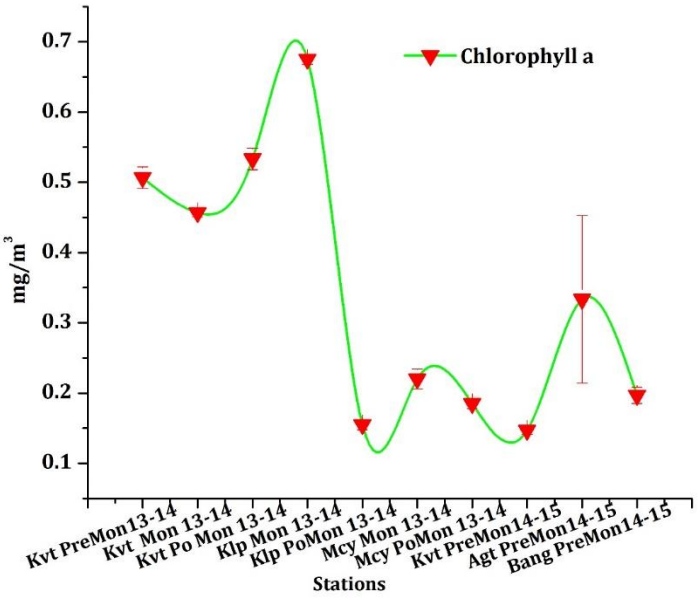


Fig.4.11 Seasonal variation of Chlorophyll a at lagoon stations of islands during 2013-2015

In Minicoy chlorophyll a values fluctuated between 0.21-0.23mg/m^3 (av.0.22±0.004) in monsoon and 0.18-0.19mg/m^3 (av.0.185±0.007) in postmonsoon. However, during pre-monsoon season 2014-15, Kavaratti showed chlorophyll a values of 0.14-0.15mg/m^3 (av.0.146±0.005) Agatti showed 0.25-0.47mg/m^3 (av.0.333±0.119) and Bangaram showed 0.19-0.21mg/m^3 (av.0.196±0.011). Kavaratti lagoon showed the minimum value and a maximum at Agatti lagoon. Inter annual comparison of chlorophyll a showed the highest mean seasonal values during 2013-14 periods.

4.5 Physical parameters of Minicoy open ocean stations

The physico-chemical variables prevailing such as temperature, salinity, and dissolved oxygen were typical of open sea conditions. Sea surface temperatures (10m depth) in the open ocean waters was 30.42°C between 8°12N and 8°24N that slightly decreased as the depth increased. Average SST was found to be 29.32°C at 50m, 25.18°C at 100m, 17.77°C at 150m, 14.56°C at 200m, 13.35 at 250m and 12.33°C at 300m. Depth wise SST variations is given in Fig.4.12.Seas surface salinity (SSS) were found to be 33.76psu at 8°12N that gradually increased as the depth increased (Fig.4.13). Average SSS was 34.63 psu at 50m, 35.59 psu at 100m, 35.24 psu at 150m, 35.14psu at 200m, 35.21psu at 250m and 35.25 psu at 300m. Surface dissolved oxygen (DO) values ranged from 4.32 ml/L (S4) to 4.43 ml/L (S17). Depth wise DO concentrations are given in the Fig.4.14. Average DO value was 4.38 ml/L at 50m,1.43 ml/L at 100 m, 0.006 ml/L at 150m,0.15 ml/L at 200m,0.39 ml/L at 250m and 0.55 ml/L at 300m.Sea water density values ranged from 20.60 (S1) to 21.01(S18).Depth wise density variations are given in Fig.4.15.

The average sea water density was 23.28 kg/m^3 at 50m,27.26 kg/m^3 at 100m, 32.06 kg/m^3 at 150m, 35.36 kg/m^3 at 200m, 38.29 kg/m^3 at 250 m and 41.08 kg/m^3 at 300m.The summer hydrography of open ocean zones of Minicoy did not exhibit a uniformity which may be due to precipitation during the season. Hence, the MLD (Mixed Layer Depth) defining criteria were based on density variation rather than temperature or salinity. Therefore, the MLD was shallow (20m).

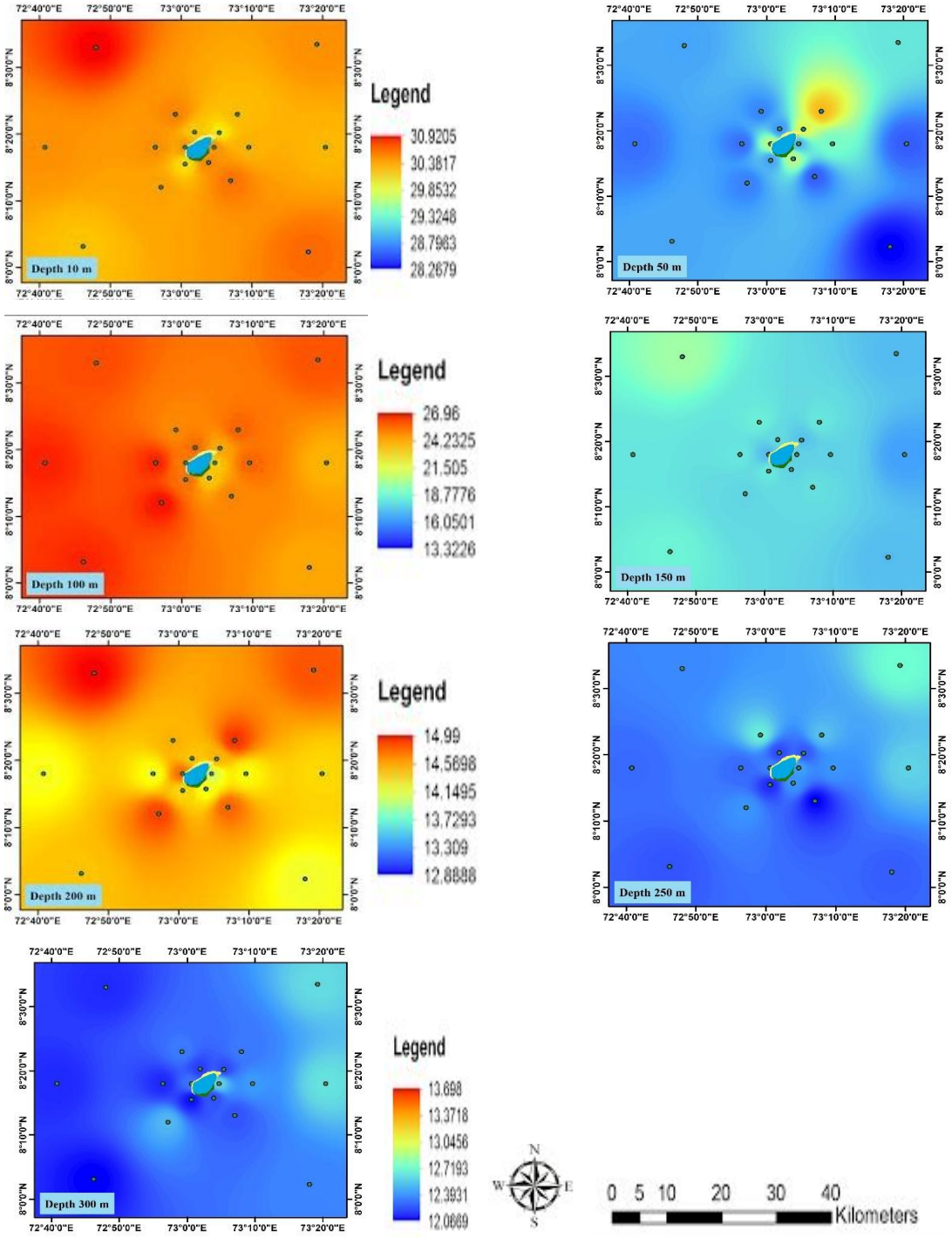


Fig.4.12 Depth wise variation of SST at Minicoy open ocean during March 2015

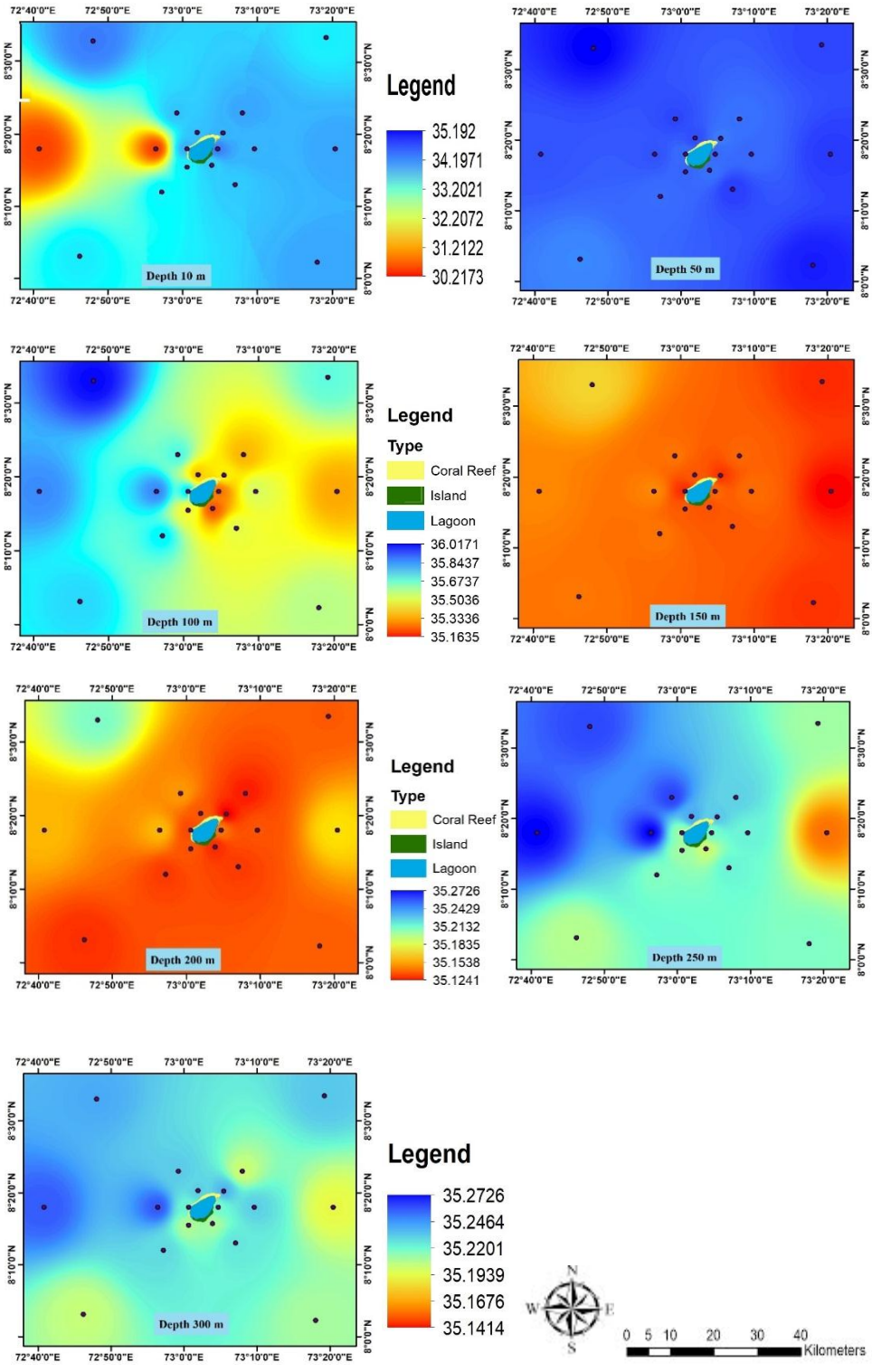


Fig.4.13 Depth wise variation of SSS at Minicoy during premonsoon 2015

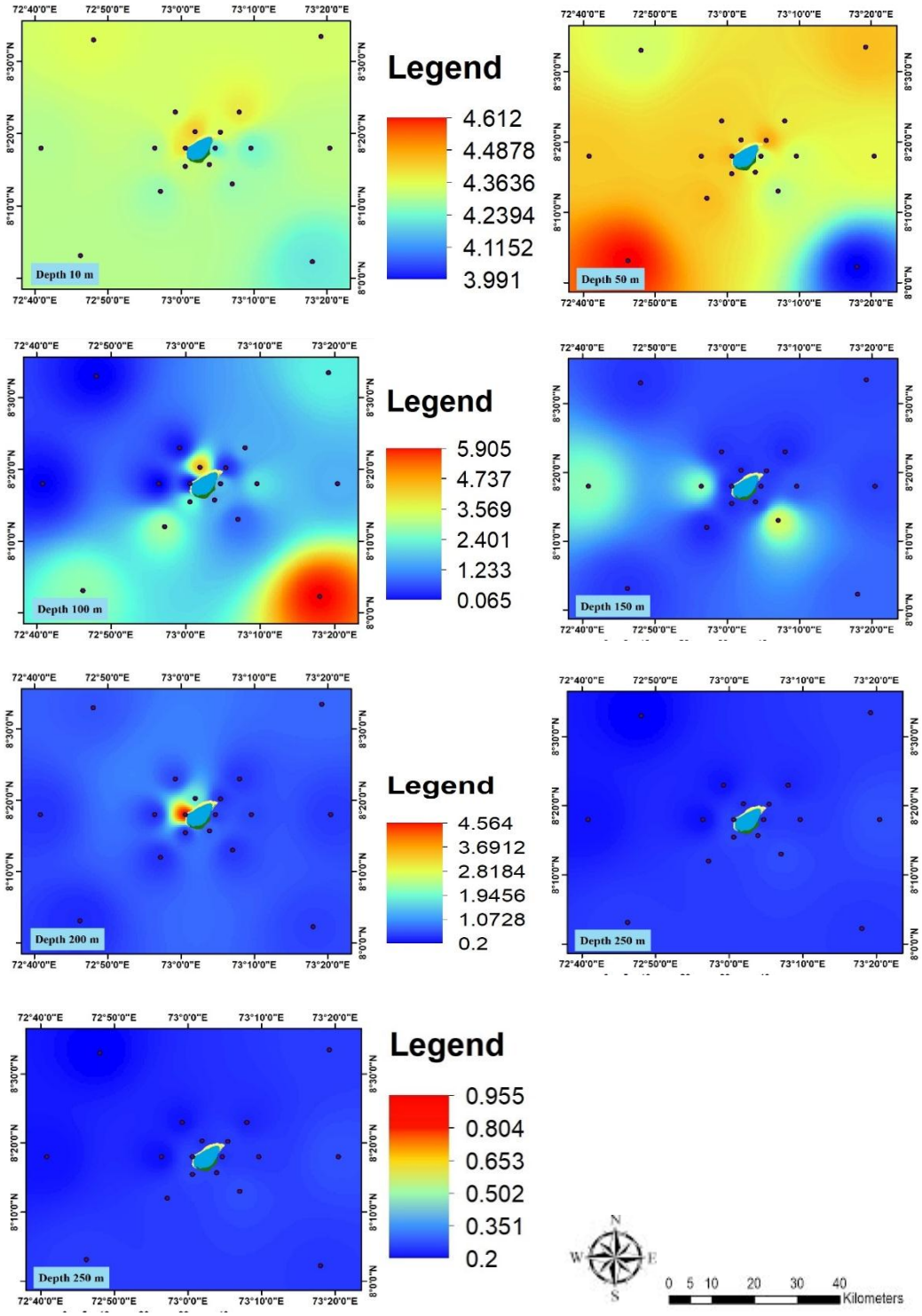


Fig.4.14 Depth wise variation of DO at Minicoy during premonsoon 2015

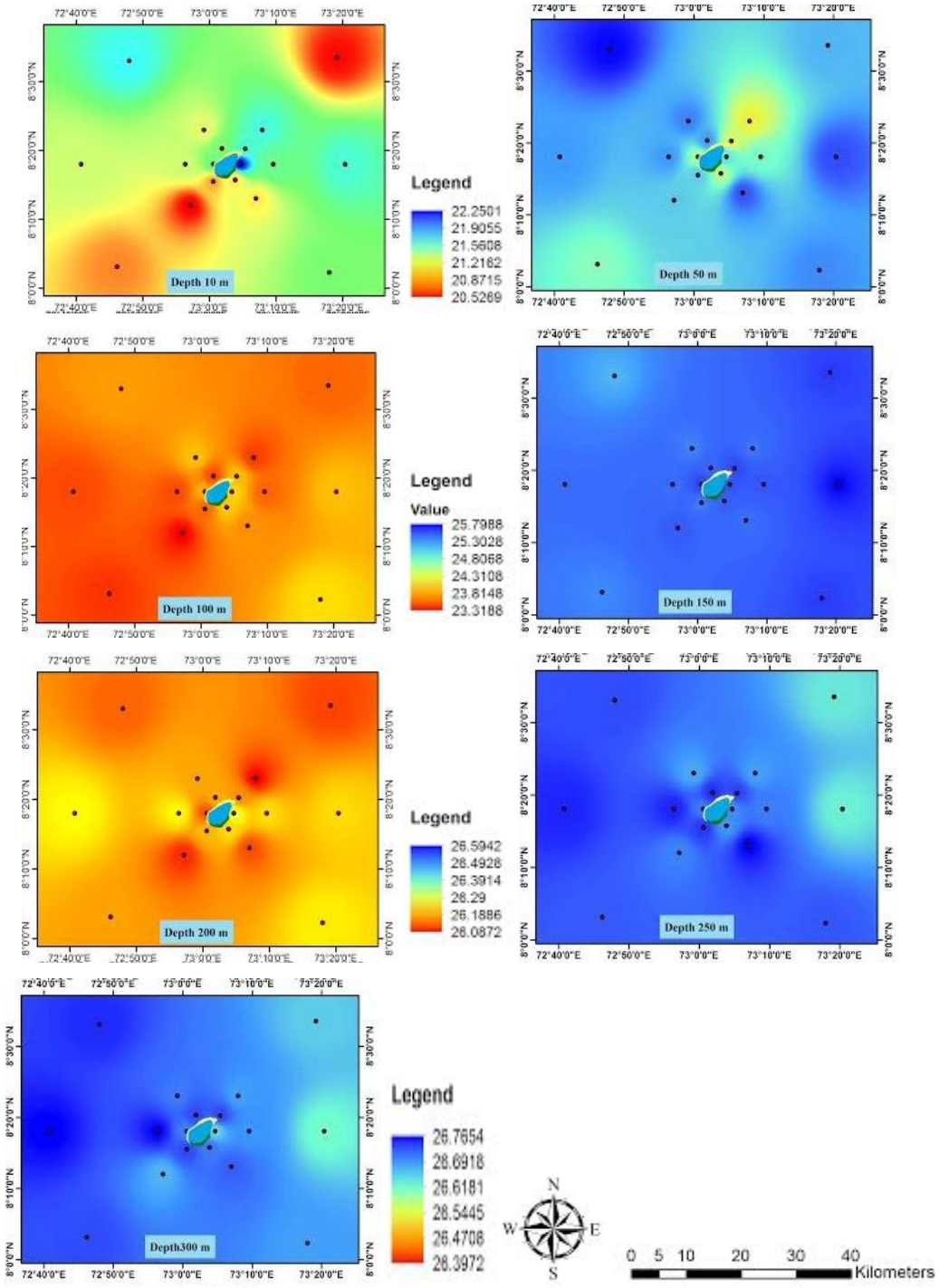


Fig.4.15 Depth wise variation of density at Minicoy during premonsoon 2015

4.6 Principal Component Analysis (PCA)

4.6.1 Principal Component Analysis (PCA) in Kavaratti lagoon

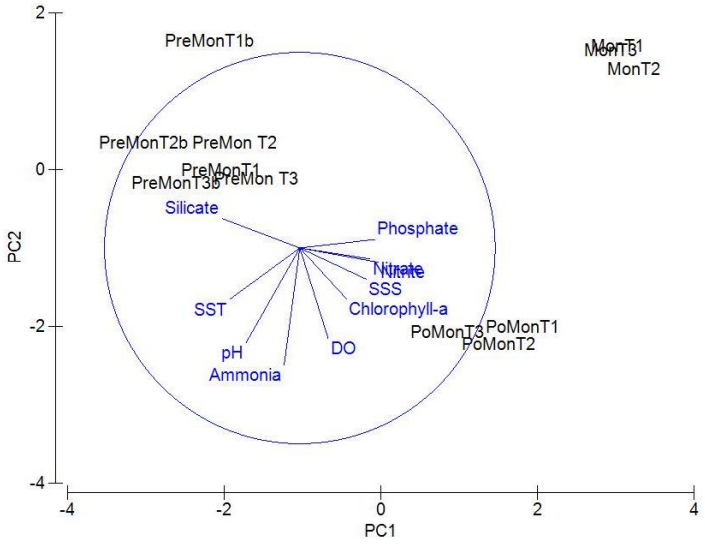


Fig.4.16 PCA of water quality parameters in Kavaratti lagoon

Table 10 Table of PCA analysis in Kavaratti lagoon

PC	Eigen values	% variation	Cum.%variation
1	5.95	66.2	66.2
2	1.99	22.1	88.3
3	0.543	6.0	94.3
4	0.241	2.7	97.0
5	0.227	2.5	99.5

Variable	PC1	PC2	PC3	PC4	PC5
SST	0.386	-0.169	-0.050	**-0.458**	-0.050
SSS	-0.368	-0.258	0.114	-0.308	-0.361
pH	0.280	**-0.505**	0.152	-0.150	-0.112
DO	-0.175	**-0.460**	**-0.844**	0.089	0.183
Nitrate	-0.364	-0.044	0.248	-0.276	**0.820**
Nitrite	**-0.404**	-0.060	0.017	-0.057	-0.118
Phosphate	-0.392	0.039	0.068	**0.484**	-0.219
Silicate	0.391	0.120	-0.081	**0.410**	0.275
Ammonia	0.064	**-0.646**	**0.420**	**0.427**	0.108
Chlorophyll a	0.239	-0.260	**0.676**	**-0.430**	0.030

The first five principal components showed 99.5% variance. For the first two principal components eigen values were greater than one. Therefore the first

two components are most significant. In Kavaratti first principal component was negatively correlated to nitrite. Second principal component was negatively correlated to pH, DO and ammonia. The third axis was correlated to ammonia, chlorophyll a and negatively correlated to DO. The fourth component was correlated to phosphate,silicate and ammonia. It was negatively correlated to SST and chlorophyll a. While the fifth axis was correlated to nitrate (Fig.4.16 and Table 10.).

4.6.2 Principal Component Analysis (PCA) in Kalpeni lagoon

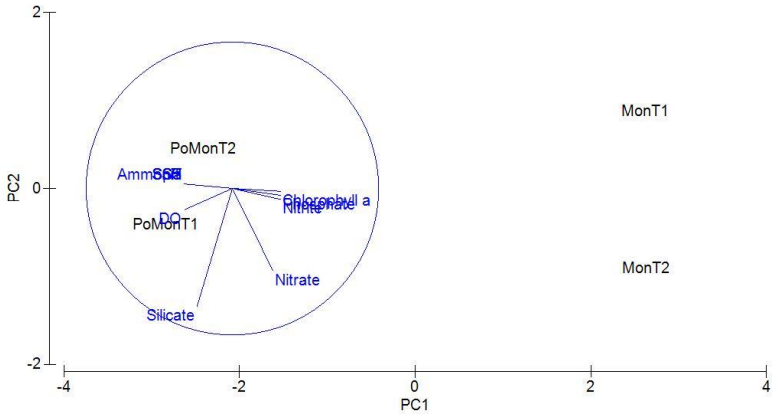


Fig.4.17.PCA of water quality parameters in Kalpeni lagoon

Table .11 Table of PCA analysis in Kalpeni lagoon

PC	Eigen values	% variation	Cum.%variation
1	8.21	91.3	91.3
2	0.653	7.3	98.5
3	0.134	1.5	100.0

Variable	PC1	PC2	PC3
SST	-0.348	0.033	-0.160
SSS	-0.348	0.033	-0.160
pH	-0.348	0.033	-0.160
DO	-0.346	-0.143	-0.099
Nitrate	0.294	**-0.566**	**-0.766**
Nitrite	0.348	-0.077	0.112
Phosphate	0.348	-0.049	0.174
Silicate	-0.257	**-0.804**	**0.509**
Ammonia	-0.348	0.033	-0.160
Chlorophyll a	0.329	-0.019	-0.150

The three principal components showed 100 % variance. Only the first principal component showed eigen values greater than one which makes it more significant. In Kalpeni, second principal component was negatively correlated to nitrate and silicate. The third axis was correlated to silicate and negatively correlated to nitrate (Fig.4.17, Table 11

4.6.3 Principal Component Analysis (PCA) in Minicoy lagoon

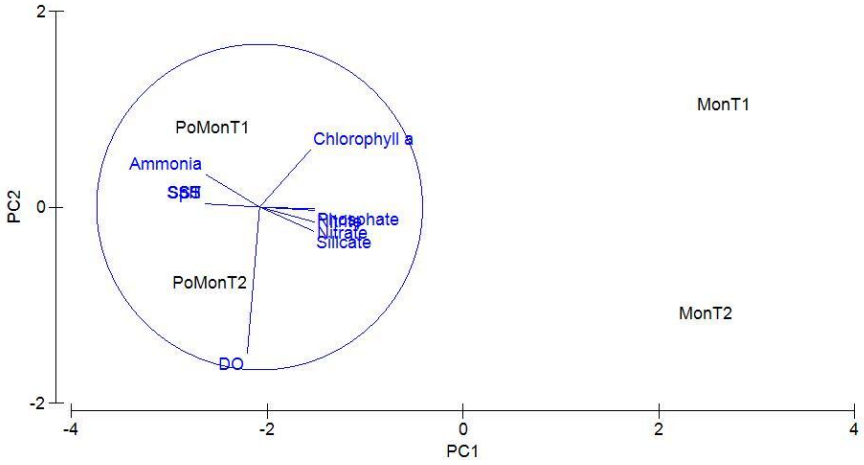


Fig.4.18 PCA of water quality parameters in Minicoy lagoon

Table 12 Table of PCA analysis in Minicoy lagoon

PC	Eigen values	% variation	Cum.%variation
1	7.98	88.7	88.7
2	1.02	11.3	100.0
3	6.98	0.0	100.0
Variable	**PC1**	**PC2**	**PC3**
SST	0.354	0.029	-0.192
SSS	0.354	0.029	-0.192
pH	0.354	0.029	-0.192
DO	0.059	**0.977**	0.158
Nitrate	-0.354	0.049	**0.436**
Nitrite	-0.354	-0.029	0.192
Phosphate	-0.354	-0.039	-0.097
Silicate	-0.352	0.110	**-0.427**
Ammonia	0.349	-0.164	**0.667**
Chlorophyll a	0.311	0.350	**0.793**

All three principal components showed 100% variance with eigen values were more than one. So all are significant. In Minicoy, second axis was correlated to DO and third axis to nitrate and ammonia and chlorophyll a. It was negatively correlated to silicate. (Fig.4.18 and Table.12)

4.6.4 Principal Component Analysis (PCA) in Agatti lagoon

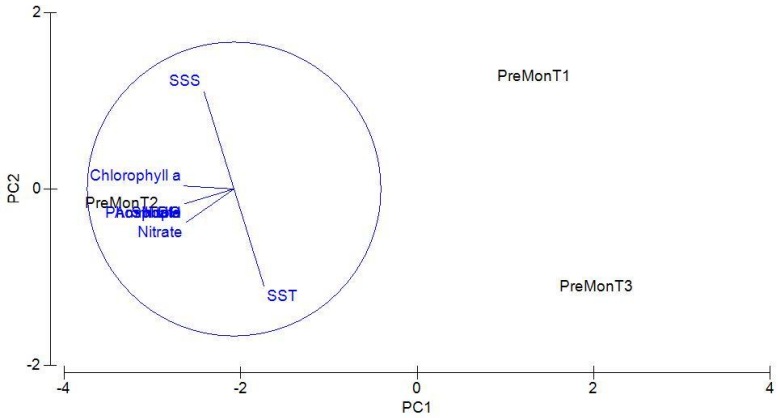


Fig. 4.19 PCA of water quality parameters in Agatti lagoon

Table 13 Table of PCA analysis in Agatti lagoon

PC	Eigen values	% variation	Cum.%variation
1	7.56	84.0	84.0
2	1.44	16.0	100.0

Variable	PC1	PC2
SST	0.217	**-0.668**
SSS	-0.217	**0.668**
pH	-0.361	-0.098
DO	-0.361	-0.098
Nitrate	-0.350	-0.226
Nitrite	-0.361	-0.098
Phosphate	-0.361	-0.098
Silicate	-0.361	-0.098
Ammonia	-0.361	-0.098
Chlorophyll a	-0.342	0.021

First two principal components showed 100% variance. For both the components the eigen values were more than one. So both are significant. In Agatti,second axis was correlated to SSS and negatively correlated to SST (Fig.4.19 and Table. 13)

4.6.5 Principal Component Analysis (PCA) in Bangaram lagoon

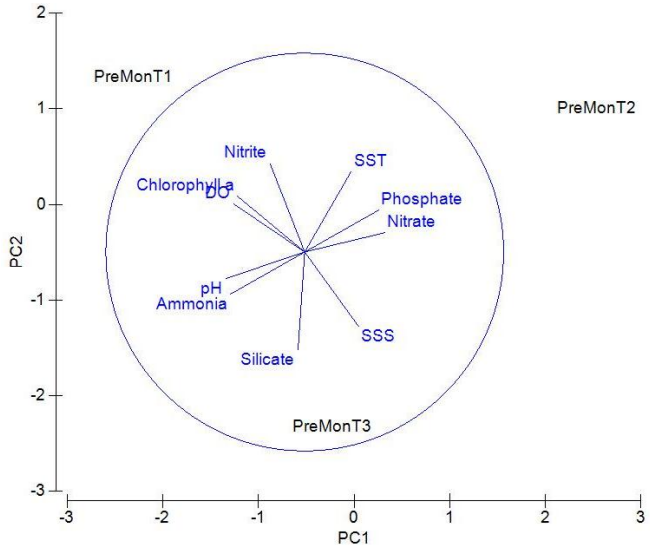


Fig. 4.20 PCA of water quality parameters in Bangaram lagoon

Table 14 Table of PCA analysis in Bangaram lagoon

PC	Eigen values	% variation	Cum.%variation
1	5.36	59.6	59.6
2	3.64	40.4	100.0

Variable	PC1	PC2
SST	0.336	0.329
SSS	0.179	**-0.477**
pH	**-0.432**	0.008
DO	-0.300	0.377
Nitrate	**0.430**	-0.047
Nitrite	-0.065	**0.518**
Phosphate	**0.427**	0.081
Silicate	-0.156	**-0.489**
Ammonia	**-0.427**	-0.081
Chlorophyll a	-0.339	0.281

The two principal components showed 100% variance with eigen values were more than one.So both were significant. In Bangaram, first axis was correlated to nitrate, phosphate and ammonia. It was negatively correlated to pH.The second component was correlated to nitrite and negatively correlated to SSS and silicate (Fig.4.20 and Table.14).

4.6.6 Principal Component Analysis (PCA) in Minicoy open ocean

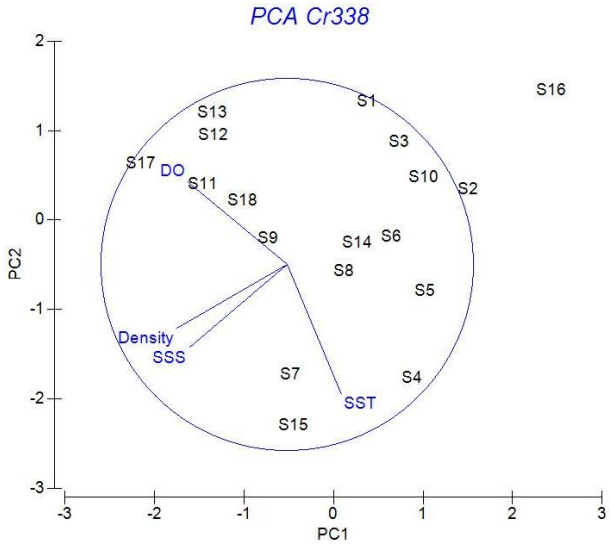


Fig.4.21 PCA of water quality parameters in Minicoy open ocean

Table 15 Table of PCA analysis in Minicoy open ocean

PC	Eigen values	% variation	Cum.%variation
1	1.45	36.2	36.2
2	1.2	30.0	66.2
3	0.712	17.8	84.0
4	0.639	16.0	100.0

Variable	PC1	PC2	PC3	PC4
SST	0.290	**-0.696**	**0.540**	-0.373
SSS	**-0.525**	**-0.447**	**-0.587**	**-0.424**
DO	**-0.535**	**0.444**	**0.508**	**-0.509**
Density	**-0.595**	-0.344	0.326	**0.650**

The four principal components showed 100% variance. For the first two principal components eigen values were greater than one. Therefore the first two components are most significant. In Minicoy open ocean, first principal component was negatively correlated to SSS,DO and density. Second principal component was correlated to DO and negatively correlated to SST and SSS. The third axis was correlated to SST,DO and negatively correlated to SSS. The fourth component was correlated to density. It was negatively correlated to SSS and DO (Fig.4.21, Table 15).

4.7 Discussion

The physicochemical and biological characteristics of various islands of Lakshadweep have been surveyed from different studies (James, 1989; Koya, 2000; Vargis, 2005). Sea surface temperature is of prime importance to distribution of organisms as each species promulgate best within an optimum temperature range. Goswami, 1979 reported that the SST (Sea Surface Temperature) in Kavaratti remained higher throughout the study periods (29.7˚C-31.9˚C) which was comparable to that of the present study having values ranging from 28.13C˚-29.86˚C. These high values may be accredited to the shallow depth as well as low energy region in the lagoon. Clansen *et al* (1975) opined that, coral reef growth occurs at an optimum water temperature between 25˚C and 29˚C and flourishes at water temperature ranging from 17˚C to 34˚C which very well agrees with that observed during the present study. Reports of Robin *et al* (2012) with SST value of 28.55˚C also corroborates the present study.

Eventhough the SST values of all the lagoons of selected islands in the current study displayed a considerable demarcation in the premonsoon season during the first year (30.04˚C-30.38˚C) than that of monsoon (27.97˚C-28.31˚C) and post monsoon (28.53˚C-29.01˚C), the second year showed only a slight variation with values of 29.43˚C-29.91˚C (premonsoon), 28.30˚C-28.90˚C (monsoon) and 28.67˚C-29.24˚C (postmonsoon). Nevertheless, the average seasonal value of SST of various islands of Lakshadweep exhibited a marked variation which in turn points to the significant role of sustained precipitation during monsoon contributing to the hydrography of Lakshadweep lagoons.

Prabhakaran (2008) opined on the influence of the tidal mixing and wind stirring in areas away from the shore of Minicoy lagoon. He also mentioned on the shoreward speed of the cold waters with which they are unable to penetrate as such into the lagoon and the tendency of the low frequency currents that mixes up the horizontal waters. Further in Kalpeni, SST values showed a significant ($p \leq 0.01$) positive correlation with SSS, pH, DO, silicate, ammonia, chlorophyll a and negative correlation with nitrite, nitrate and phosphate. Whereas in Minicoy lagoon, there emerged a significant ($p \leq 0.01$) positive correlation of SST with SSS, pH, DO,

ammonia and a negative correlation with nitrite, nitrate, silicate, phosphate and chlorophyll a. Prabhakaran (2008) observed a negative correlation between SST and phosphate in Minicoy lagoon which was in congruence to the present study in Minicoy and Kalpeni lagoon that was significant at ($p \leq 0.01$ level). In agreement to the normal scenario a strong inverse correlation evolved between SST and rainfall significant ($p \leq 0.01$) as observed in the study.

However in Minicoy open ocean zones, SST were ~30.42°C and SSS 33.76psu. Patil and Ramamirtham (1963) made a detailed study on the summer hydrography of Laccadive offshore waters. Jayaraman *et al*(1960) and Muraleedharan and Prasannakumar (1996) have examined both coastal and open ocean upwelling during south west monsoon season of the Arabian Sea upwelling as a part of Indian Joint Global Ocean Flux studies (JGOFS) program where an SST value ranging from 23°C-26°C and salinity value of 35.1ppt-36.2ppt was reported.

The records of Patil and Ramamithram (1963) from Lakshadweep offshore waters indicate that the sea surface temperature was quite high during the period and it varied between 28°C and 29°C.He also opined that, the north north-western region generally exhibits warmer water while slightly cold water existed in the south western region and reported MLD (Mixed Layer Depth) of 65-80m. Jyothibabu (2004) during spring inter monsoon and summer monsoon from BoB(Bay of Bengal) observed SST ranging from 28.6°C-30.25°C and SSS between 32.8psu-34.3psu with minimum spatial variability. They also reported warmer and low saline waters in the offshore region providing stratified surface layers which resulted in thin mixed layer 30-60m.

Sabu *et al* (2015) has reported MLD of 17m from Northern BoB during early winter monsoon. A warmer SST (29.2°C) which gradually decreased towards south and a low saline water (29-32.4psu) which gradually increased resulted in non-uniformity of salinity and temperature distribution. The same trend was observed during the present study where temperature decreased and salinity increased as depth increased with a shallow MLD of 20m.

Jyothibabu *et al* (2015) from southern BoB during summer monsoon reported MLD of 28m at 8°N latitude, SST of 28.85°C and SSS of 34.22ppt which

was comparable with the present study at Minicoy. Karnan *et al* (2017) from Alappuzha coast (south west coast of India) reported a warmer ocean temperature (30°C) during premonsoon (summer) period with a drop of water temperature at subsurface layers and a high surface salinity of 34.3 psu with an increase in subsurface layers (34.6) which was in agreement with the present study where the temperature decreased and salinity increased in subsurface layers with a shallow MLD of 20m.However, Lathika (2015) reported MLD of ~36m along the northern regions (22°N) that shoaled up to 18m along 21°N from North Eastern Arabian Sea. She reported SST of 26°C and SSS 36.5psu.

The hydrobiology of the Minicoy lagoon along with a comparative study of all the lagoons of Lakshadweep was carried out by Girijavallabhan (1989) during January-March when a maximum SST of 30°C to 35°C were observed. They also observed that throughout the day and night, the temperature remained above 30°C. A similar trend in SST was also reported by Koya (2000) and Vargis (2005). Prabhakaran (2008) documented a range of 26°C-31.2°C SST values from the same lagoon. All these values were comparable with that of the present study.

Varadhachari *et al* (1974) too reported SST ranging from 26.7°C-30°C, SSS of 34.4ppt-35.8ppt and density of 21.3 to 23.3kg/m^3 from west coast of India which was comparable to the present study. Way back in December 1982, Gangadhara Rao and R.Jayaraman in one of the Indian Ocean Expedition (IIOE) cruises in the Arabian Sea, reported an upwelling at the Minicoy open ocean region and depicted the reason as the presence of diverging current systems. They also reported SST of 28°C which was comparatively colder in the sense that present study at Minicoy open ocean zones was carried out during April when SST would obviously be higher. Stephen (1991) recorded a sea surface temperature of 29°C from south west and south east India Coast. Madhupratap *et al* (1996) and Prasannakumar *et al* (2002) also reported surface temperatures of ≤ 24°C along northern Arabian Sea.

Lathika *et al* (2013) has attempted to describe the vertical distribution of SST as well as nutrients of south eastern Arabian Sea during spring inter monsoon (early April) and have reported SST values of 26°C. Jyothibabu *et al* (2013)

observed a surface temperature values of 25.45°C to 34.47°C around the south eastern part of the Indian Ocean thus in analogous with the present result. Similar results of 30.78°C during premonsoon, 28.51°C during monsoon and 27.9°C during post monsoon was reported by Asha *et al* (2016) along the south west coast of India. Similarly Lathika (2015) reported SST values of 24.3°C to 26.8°C along the northern Arabian Sea which was in accordance with the present study. Jagadeesan (2015) reported SST values ranging from 30.31°C (premonsoon), 29.64°C (monsoon) and 26.55°C (postmonsoon) from Gulf of Mannar (which opens into Arabian Sea) and values of 31.47°C (premonsoon), 30.29°C (monsoon) and 25.45°C (postmonsoon) from Palk Bay(PB) (which opens into BoB).The values reported from both GoM and PB was comparatively higher when compared to that of present study at Lakshadweep lagoons and open ocean zones. Stephen *et al* (2013) reported SST values of 31.2°C and 25.7°C during premonsoon and postmonsoon respectively form Mumbai coast, west coast of India. A more recent study on the coastal upwelling along the southwest coast of India (Karnan *et al*., 2017) reported an SST of 30.6°C-31°C (premonsoon) and 26.7°C-27.1°C (monsoon) which were in agreement with our present study.

Atoll lagoons are habitats generally fed by saline water from the adjacent sea and receive freshwater inputs mainly from rainfall. Lagoons whose only freshwater supply is from rainfall commonly become hyperhaline (also known as supersaline) (Bamber, 2010) that is also seen in the present study where the salinity values ranged from 35.53ppt and 36.13ppt. A general decrease in salinity was exhibited by all islands during premonsoon season which may be due to the influence of the flow of low saline water of Bay of Bengal, which joins the northward flowing equatorial Indian Ocean water and flows as a northward surface current along the west coast of India, as opined by Pankajakshan and Ramaraju (1987).

A similar salinity distribution (32ppt) was documented by Gangadhhararao and Jayaraman (1982) from Minicoy open ocean area. Stephen (1991) recorded a salinity of 35ppt from India Coast. Jyothibabu *et al* (2012) along the south east coast of Indian Ocean reported 28.9ppt to 35.39ppt salinity values. Stephen *et al* (2014) reported SSS values of 28.21ppt and 24.71ppt during premonsoon and postmonsoon

respectively form Mumbai coast, west coast of India. Lathika (2016) also observed SSS values ranging 35.5ppt to 36.5ppt in the northern Arabian Sea during spring inter monsoon (early April). However higher salinity during present study when compared to that reported by Jagadeesan (2015) from GoM(Gulf of Mannar) during premonsoon (33ppt), monsoon (9.35ppt) and post monsoon (9.32)and PB(Palk Bay) premonsoon (30.44ppt),monsoon(34.9) and postmonsoon (28.9ppt)might be due to the general Indian Ocean current pattern prevailing during the particular period. Stephen (1991) recorded a salinity of 35ppt from India Coast. Recently Karnan *et al* (2017) also reported a salinity of 34.25ppt-34.3ppt (premonsoon) and 33.6ppt-34.ppt (monsoon) along south west India coast.

A salinity range of 27 to 35ppt was reported by Vargis (2005) and 31.15 to 35.48ppt by Prabhakaran (2008) in Minicoy lagoon. Further, Qasim and Sankaranarayanan (1970) reported that the high salinity in the lagoon may be ascribed to the unidirectional flow of seawater towards the entrance of the lagoon which in turn is created by the heavy surf breaking across the reef. The same can also be due to the fresh water influx during south west monsoon season (June to September) which consecutively could be from precipitation. As per the records, another mystifying factor for high saline conditions is water loss due to evaporation in all lagoons. Hyperhaline conditions results due to minimal replenishment of water but an input of fully strength sea water will trim down salinity in these conditions. SSS showed a maximum of 33.6ppt at southern part and comparatively low saline water (29ppt to 32.4ppt) was observed in the northern part by Sabu *et al* (2015) from northern BoB during early winter monsoon. Isohalines was visible below 30m depth and salinity increased with depth. During the present study in Kalpeni a strong positive correlation significant at $p \leq 0.01$ evolved between SSS with SST, pH, DO, silicate, ammonia, chlorophyll a and a significant ($p \leq 0.01$) negative correlation with nitrate, nitrite and phosphate. While in Minicoy, SSS was positively correlated at $p \leq 0.01$ with SST, pH, DO, ammonia and negatively correlated ($p \leq 0.01$) with nitrate, nitrite, phosphate, silicate and chlorophyll a.

In the present study, the observation of minimum spatial variability of SST during premonsoon season of open ocean surface layers could be linked to the

maximum availability of solar radiation and as an indication of warming of surface layers between winter and summer (Varkey *et al*.,1996).Whereas SSS distribution in general showed a peculiar pattern in which coastal region (lagoon stations) witnessed comparatively high saline waters (35.53ppt-36.13ppt) and pockets of low saline waters in the open ocean stations (33.76ppt-34.88ppt).Such peculiar feature were previously reported from many studies in various parts of Indian ocean and adjoining coasts by several scientists (Murty *et al.,*1968*;* Shetye *et al.,*1991; Sanil Kumar *et al.,*1997; Shetye *et al.,* l993; Jyothibabu, 2004).The reason depicted here was due to influence of circulation as well as warm and low saline waters in the oceanic regions that provide stratified surface layers which in turn lead to shallow MLD observed along most of the oceanic regions.

In recent years, inorder to understand the importance of ocean currents in structuring its biophysical aspects has been an upturn of our scientific interest. The ocean currents in and around the Indian Ocean had been well documented over the last several decades. The role of ocean currents in its hydrography which in turn structures the zooplankton community are very crucial (Jyothibabu *et al*., 2008). In a marine pelagic food web, the significant role played by the zooplankton in transferring organic carbon from the phytoplankton and bacteria to higher trophic levels have been well depicted in various research papers. Due to their short generation times, zooplankton serves as a measure of biological productivity and responds to any subtle changes in physical chemical and biological parameters in their surroundings (Jagadeesan *et al*., 2013; Anger, 2003; Beaugrand, 2004; Bonnet and Frid, 2004; Queiroga and Blanton, 2004).

Open ocean monsoon currents links with the coastal circulation by the currents along the eastern and western coasts of India. During the Northeast monsoon (November to January) when the sea level starts rising (December) at the south west coast of India, the EICC (East India Coastal Current) which is equator ward, carries the low saline waters from the northern BoB (Bay of Bengal) to the south and feed the westward flowing Winter Monsoon Current (WMC). After EICC turning around the southern tip of Sri Lanka, a branch of WMC (Winter Monsoon Current) carries the low saline BoB waters northward and feed the West India Coastal Current (WICC) along the west coast of India. During this time, EICC and

WICC maintain continuous flow from the northern BoB to the northern Arabian Sea which in turn forms a circular high (by early January) to the east of Lakshadweep islands (LH)(Shetye and Gouveia, 1998; Shetye, 1999; Shenoi, 2010). Consequently occurring high saline surface waters of north eastern Arabian Sea due to "Lakshadweep high" (Shetye *et al*.,1993; Shankar *et al*.,2002) have many biological implications (Jyothibabu *et al*.,2008; Jagadeesan *et al*.,2013) .

During the onset of Southwest Monsoon (June to September), sea level starts dropping at the south west coast of India. Then the WICC (West India Coastal Current) which is equator ward flows southward carrying the high saline Arabian Sea waters and feeds the eastward flowing SMC (Summer Monsoon Current).This turns around Sri Lanka and one of its branch feed northward (poleward)flowing EICC along the south east coast of India. During this time, the surface current at the east coast of Sri Lanka is equator ward (Shanker *et al.,*1997). Consequently, a circular low forms to the east of Lakshadweep islands (LL) in July-August. All these observations suggests that the formation of high (low) off southwest India during the northeast (southwest) monsoon is one of the demonstration of annual cycle linked to Indian coastal currents and southern Arabian Sea circulation along with it's vital role on configuring the biophysical aspects of a marine system.

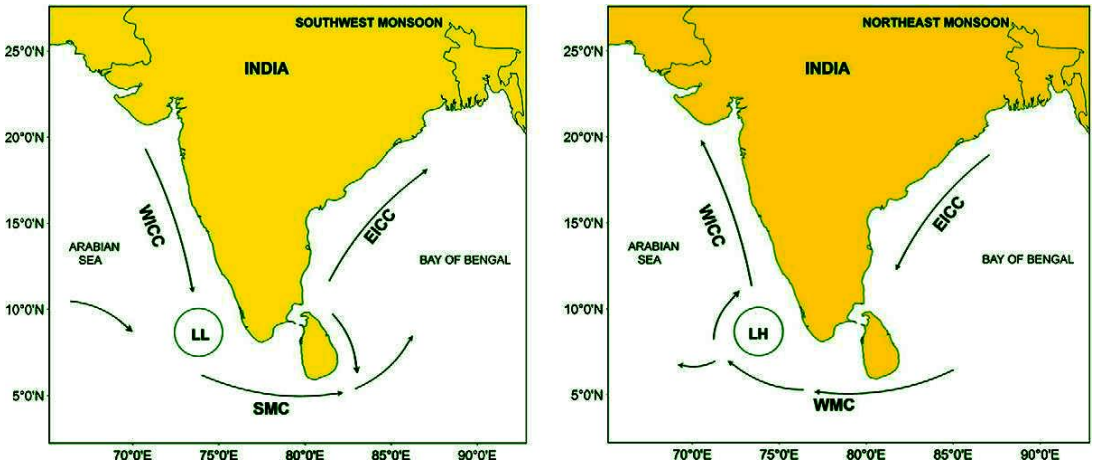


Fig.4.22 Seasonal reversal of ocean currents around Lakshadweep high(January) and low (July).Source: Jagadeesan *et al*., 2013;Shankar and Shetye,1997.WICC – West India coastal Current, LL – Lakshadweep Low, LH – Lakshadweep High, SMC – Summer Monsoon Current, WMC – Winter Monsoon Current, EICC – East India Coastal Currents

As discussed on SST and SSS, the seasonal pattern of salinity distribution in the lagoon as well as open ocean zones are in general agreement with the ocean circulation around the Indian subcontinent. During the North east monsoon (post monsoon) period, the southward EICC which brings saline waters from northern BoB that enters the west coast of India and northern Arabian Sea (Lakshadweep islands). The surface salinity data for the North East monsoon period or post monsoon period shows significantly higher values in island waters (35.69 to 36.09ppt) (Lakshadweep high). These values were comparatively higher to that reported during previous studies (Jagadeesan *et al*.,2013;Rao *et al.,*2011) who reported the influence of current patterns of Indian Ocean on hydrography and zooplankton abundance. This can be supported by the low amount of rainfall received in Lakshadweep Sea during that particular period (59.3mm to 78.5mm) when compared to the northern BoB (80mm-100mm) which in turn has prompted an increase the salinity values of northern Arabian Sea. The seasonal pattern of SST distribution in the Lakshadweep waters which showed significantly higher values during North east monsoon period was also in general agreement with previous studies (Jagadeesan *et al*.,2013; Rao *et al.,*2011).The spring intermonsoon (premonsoon) being the transition phase between North east monsoon and South west monsoon, the northeasterly winds prevalent in the northern BoB translate into weak currents (Jagadeesan *et al*.,2013; Shankar *et al.,* 2002). A salinity value of 33.36 psu prevalent in open ocean zones of Minicoy during the premonsoon (spring intermonsoon) was concordant with that of Jagadeesan *et al* (2013) who recorded a similar salinity value of 33.6psu in the GoM (Gulf of Mannar) whose physical entities are more close to that of AS (Arabian Sea). He also pinpointed the occurrence of a higher seasonal SST value (30.29°C) which was in agreement with that of Minicoy open ocean zones SST value (30.42°C).Thus a substantial impact of ocean circulation on the hydrography of island waters subsequently will have an effect on its zooplankton distribution which is well discussed in chapter 5.

Owing to the susceptibility of high organic content in lagoon water, phytoplankton blooms occur frequently whose photosysnthetic activity results in the reduction of carbon dioxide and a concomitant rise in pH. This can bring about a slight alkaline nature which can also be due to calcium and carbonate deposits

particular to coral reef ecosystems. pH being an important factor in regulating the rates of phosphorus release from sediments, when present below 5 or above 8.6 in water is detrimental or lethal to aquatic organisms which prefer values between 6.7 and 8.4. Patil and Ramammirtham (1963) reported pH varying between 8.30-8.35 from Lakshadweep. In Kavaratti lagoon, pH of water ranged from 8.01-8.8 (Robin *et al.*, 2012) and in Minicoy lagoon pH was 7.38 (Prabhakaran *et al*.,2008) which was in agreement with the present study. Temporal variation as well as spatial variation of pH were significant in all the islands as clearly indicated by the ANOVA results. Further a positive correlation of pH significant at $p \leq 0.01$ with SST, pH, DO, ammonia and a negative correlation with nitrite, nitrate phosphate, silicate and chlorophyll a were observed in Minicoy .While in Kalpeni a significant $p \leq 0.01$ correlation existed with SST,SSS, DO, silicate, ammonia and chlorophyll a and a negative correlation with other inorganic nutrients.

Dawes (1988) opined that polar seas, due to their lower temperatures and salinities, contain about twice amount of oxygen as tropical waters. As the lagoon ecosystems are net autotrophic and release oxygen into the water column, dissolved oxygen is usually high. During the present study, DO values fluctuated between 3.45 to 6.89 mg/L and there existed a significant variation of DO between the islands and seasons. Pervasiveness of saturated condition of dissolved oxygen value could be owed to the active photosynthesis by seaweeds as well as sea grasses (Radhika *et al*., 2014b; Robin *et al*., 2012).In the present study in Lakshadweep, a slightly higher DO (6.89mg/L) observed during postmonsoon season. This may be attributed to higher primary production occurring in the ocean surface during this period as well as higher oxygen solubility in colder and less saline water. However studies from various parts of Arabian Sea depicted above, mentioned parameter peak values in monsoon period. (Qasim *et al*., 1969; Haridas *et al*.,1973; Pillai *et al*.,1975; Jyothibabu *et al*.,2006; Madu *et al*.,2007; John, 2009; Haridevi, 2013).

A DO value of 5.3mg/L from open ocean waters of Indian West coast was also documented by Stephen (2000).Fluctuations in DO concentrations below 40m depth was clearly depicted in BoB by Sabu *et al* (2015) corresponding with thermo-haline oscillations that showed a sharp decrease from 4.8ml/L at 40m to

0.8ml/L at 65m and 100m depth encountered a DO value of 2ml/L. Stephen (1991) recorded DO value of 4.2 to 4.5 ml/L from south west coast of India. A similar DO value of 3.93ml/L (premonsoon) and 5.07ml/L(postmonsoon) was reported by the same author from Mumbai coast , west coast of India.

Prabhakaran (2008) encountered a minimum DO value of 1.46ml/L during extremely low tides in Minicoy lagoon. He opined that since Minicoy being a restricted area with active tidal influxes, the amount of DO could be mainly contributed by the photosynthetic activity of macrophytes such as seagrass and seaweeds present in the lagoon. Paul and Ramamirtham (1963) reported a DO value of 4.3-4.6ml/L from offshore Laccadive (Lakshadweep) waters. Present observations are contrary to the findings of Jayaraman *et al* (1960) in the continental waters off Cochin in that DO value was found to be high 6.10 and 5.00 ml/L due to the stirring action of the prevailing winds. However lower values ranging from 0.90 to 5.35ml/L has been encountered during the very same study at 10m and 20m depth depicting a reason that the forces leading to upwelling appear to be fairly strong pushing up the dense, oxygen-poor waters (Jayaraman *et al*.,1960).Indeed, this seems to be contrary to the present study observations from open ocean waters of Minicoy where fairly high and constant DO (4ml/L) was observed in almost all stations. Gangadhararao and Jayaraman (1982) reported DO value of 3-4 ml/L from open ocean waters of Minicoy which was comparable with that of the present study. However still higher values (7.81ml/L) of DO was reported in open ocean waters of Indian Ocean by Jagadeesan (2015).Vargis (2005) recorded a value of 2.33-4.35ml/L from Minicoy island. Robin *et al* (2012) and Prabhakaran (2008) could find a positive correlation between pH and DO from Kavaratti and Minicoy respectively. DO values showed significant ($p \leq 0.01$) positive correlation with SST,SSS, pH, silicate, ammonia, chlorophyll a and negative correlation with nitrite, nitrate phosphate in the present study in Kalpeni. While in Minicoy, DO values exhibited significant ($p \leq 0.01$) positive correlation with SST,SSS, pH, DO, ammonia and negative correlation with nitrite, nitrate phosphate silicate and chlorophyll a..

One of the major intra and inter interactions of marine coastal systems is cycling of the primary nutrients such as nitrogen and phosphorus. The incongruity

on the existence of coral reef communities where nutrient concentrations are low as opined by Prabhakaran (2008) has already been corroborated by Hatcher and Hatcher(1981) who proposes on the non-dependency of lagoon coral reef and its associated fauna on the surrounding oceans for the input of organic nitrogen along with its generating and retaining capacity of available nitrogen depending on its structure and season which in turn is influenced by its benthic floral communities. An essential role in growth and overall functioning of an organism is taken up by the nutrients. Coastal nutrient distribution is determined by the tidal flow, freshwater flow and seasons (Damodaran *et al*., 2010).

Nitrite being an intermediate compound produced by the oxidation of ammonia to nitrate or by the reduction of nitrate is by and large present in lower concentrations in marine water than other forms of combined inorganic nitrogen. Dawes (1988) established that nitrite (NO_2) in the oceanic water ranges from 0.01 to 3µg at/l and 0.1 to 50 µg at/l in neritic waters. Previously recorded nitrite values in Lakshadweep by Vargis (2005) and Prabhakaran (2008) in Minicoy lagoon ranged from 0.17-2.5µg at/l and 0.17-2.28 µg at/l respectively. On the other hand Sanilkumar (2009) recorded a bit higher values ranging from 0.736µM/L to 12µM/L from various estuarine and coastal regions of south west coast of Indian Ocean. These higher value of nitrite is attributed to denitrification, oxidation and reduction of ammonia and nitrate and excretion of planktonic organisms that increases nitrite concentration in sea water (Govinadswami *et al.,* 2000). Anyhow, the values recorded by Robin *et al* (2012) from Kavaratti waters (0.46-0.48µM/L) and also from previous literatures also agreed with the presently recorded values of nitrite from various islands of Lakshadweep (0.43-0.63 µM/L). Webb and Weibe (1975) discoursed that closely coupled reactions of ammonia (to nitrite) and nitrite (to nitrate) oxidation would lead to relatively low levels of nitrite. Anyhow nitrite exhibited a positive correlation ($p \leq 0.05$) with nitrate at Kavaratti. In Minicoy, nitrite was positively correlated ($p \leq 0.01$) with nitrite, silicate, phosphate, chlorophyll a and negatively correlated with ammonia, SSS, SST, pH and DO. Whereas in Kalpeni, nitrite was positively correlated ($p \leq 0.01$) with nitrate, phosphate, chlorophyll a and negatively correlated with SST,SSS,pH,DO, silicate and ammonia. When Robin *et al* (2012) from Kavaratti observed a positive

correlation between NO_2 and NO_3, neither correlation was observed by Prabahkaran (2008) in Minicoy lagoon.

Nitrate, the micronutrient controlling primary production in euphotic surface layers is considered to be the most abundant and thermodynamically stable form of combined nitrogen. Kioike and Sorenson (1988) suggested on the seasonal trends of denitrification being determined mostly by nitrate availability which in turn is controlled by rates of nitrification. The importance of nitrogen in various forms, it's cycling and variability has very well been documented by previous authors (Carpenter and Capone, 1983; Sathyanarayana *et al*., 1992 and Koya, 2000).

The average nitrate nitrogen concentration recorded during the present study was 3.03µM/L in the first year and 2.65 µM/L in the second year. These values were consistent with that of Robin *et al* (2012) who gave an ecological assessment of Kavaratti waters of Lakshadweep. However Sanalkumar (2009) encountered with a wide range of values for nitrate starting from a minimum of 0.725 to 44.9µM/L from various estuarine stations of south west coast of India. On the other hand, he also reported nitrate values from various coastal stations (3.04 to 3.13) which totally agreed with the present study in Lakshadweep islands. Vargis (2005) and Prabhakaran (2008) recorded values ranging from 0.13µg at/l to 3.75µg at/l from Minicoy lagoon which too were in accordance with the present study. The higher values when compared may be due to oxidation of ammonia (Grasshoff *et al.,* 1999) along with the fact that coastal upwelling increases nitrate concentration. Recent studies by Sarangi (2011) explained that the nutrient supply in the Arabian Sea is mainly due to the seasonal upwelling processes. Lower nitrate values were reported by Sahu *et al* (2012) and Anu (2015) in coastal waters of South East coast of India. Jyothibabu *et al* (2015) reported nitrate values ranging from 0.01-0.96 µM/L from BoB during summer monsoon which was fairly low when compared to Lakshadweep waters. However, Gopinath (2002) could find out a positive correlation of nitrate with organic carbon (r=0.995) in Minicoy lagoon.While Prabhakaran (2008) from Minicoy, Sanalkumar (2009)from South west coast of Indian ocean and Robin *et al* (2012) from Kavaratti waters could not find a correlation. A positive correlation with nitrite significant at 1% level, with

phosphate significant at 5% level and a negative correlation with SST was recorded during the study period. Nitrite exhibited a positive correlation ($p \leq 0.05$) with nitrate at Kavaratti. In Minicoy, nitrate was positively correlated ($p \leq 0.01$) with nitrite, silicate, phosphate, chlorophyll a and negatively correlated with ammonia. Whereas in Kalpeni, nitrate was positively correlated ($p \leq 0.01$) with nitrite, phosphate, chlorophyll a and negatively correlated with SST, SSS, pH, DO, silicate and ammonia. Whereas, Robin *et al* (2012) from Kavaratti observed a positive correlation between NO_2 and NO_3, neither correlation was observed by Prabahkaran (2008) in Minicoy lagoon.

Inorganic phosphate concentration being a limiting factor in coastal marine ecosystems is by and large determined by biological activities (Harrison *et al*., 1990; Pardo *et al*., 1998). As it has already been reported by Nair (1990) and Kleeberg (2002) that the surface sediment release or trap phosphate depends on the concentration of overlying waters since microbial reactions make available with the reactive phosphorus in global phosphorus cycle. Anyhow, the lower concentration of inorganic phosphate (0.34µM/L) in Lakshadweep waters irrespective of the seasons has very well been substantiated by D'Elia and Weibe (1990) who observed commonly a low phosphate concentration in reef areas. These values observed in various lagoons of Lakshadweep islands also corroborates very well with those reported from Minicoy by Prabhakaran (2008) and other areas of Indian Ocean (Johannes *et al*., 1983b; Rayner and Drew, 1984; Wafar *et al*., 1985).Jyothibabu *et al* (2015) reported phosphate values ranging from 0.05-0.08µM/L from BoB during summer monsoon which was fairly low when compared to present study. Sabu *et al* (2015) also recorded similar lower phosphate values (0.1-0.2 µM/L) from BoB during early winter monsoon. In Minicoy, phosphate was positively correlated ($p \leq 0.01$) with nitrite, nitrate, silicate, phosphate, chlorophyll a and negatively correlated with SST,SSS,pH DO and ammonia. Whereas in Kalpeni, phosphate was positively correlated ($p \leq 0.01$) with nitrite, nitrate and negatively correlated with SST,SSS,pH,DO, silicate, ammonia and chlorophyll a.

Coral reef organisms being more calcareous than siliceous, silicon is not an essential element for most reef flora and fauna. Due to this reason itself, minor

focus has been perceived on silicon dynamics of coral reefs and associated ecosystems. However silicon is essential for the cell wall formation of diatoms. During the present study, premonsoon recorded highest values whereas the lowest value was recorded during the postmonsoon. The spatio-temporal distribution of silicate observed in the present study was similar to the observations from earlier works (D'Elia and Weibe, 1990; Vargis, 2005; Prabhakaran, 2008; Sanalkumar,2009; Robin *et al*.,2012). Observations of Jyothibabu *et al* (2015) recorded 0.21-1.14µM/L which was comparable to that of the present study. In Kalpeni, silicate values were positively correlated ($p \leq 0.01$) with SST, SSS, pH, DO, chlorophyll a and negatively correlated with nitrite, nitrate, silicate, phosphate and ammonia. In Minicoy also the same pattern was followed.

Fairly low value of ammonia was recorded in the present study that owed to its increased uptake by the phytoplankton community which prefers it over nitrate in certain environmental factors. Seasonally, postmonsoon recorded highest values and the lowest value was recorded during monsoon. Previous works in the same region (D'Elia and Weibe,1990;Vargis,2005; Prabhakaran,2008; Sanalkumar, 2009; Robin *et al*., 2012) also corroborated the observations in the present study. A positive correlation emerged with pH at $p \leq 0.01$ significance with SST, SSS, pH, DO and negative correlation with nitrite, nitrate, silicate, phosphate and chlorophyll a.

A comparative richness of nutrients in the present study might be owing to the incursion of domestic sewage input, leaching from land vegetation and coir spinning industries situated along the coast and increased utilization by macrophytes and low retention by the sandy substratum contributing to pervasiveness of low nutrients during other seasons (Neudecker,1987; Radhika *et al*.,2014b).The oligotrophic nature of Lakshadweep waters is very well substantiated by the absorbance even at very low concentrations of inorganic phosphorus by the coral containing zooxanthellae (D'Elia, 1988). The growth and development of corals is greatly affected by the availability of nutrients.

Chlorophyll 'a' being the primary and predominant photosynthetic pigment of phytoplankton, it acts as an index providing the primary production potential of an aquatic system upon which the biodiversity, biomass and carrying capacity of system

depends (Strickland, 1960; Masson and Peña, 2009; Goela et al., 2014; Jeffrey and Mantoura, 1997).Pelagic primary production is attributed to phytoplankton which in turn can be directly related to chlorophyll a concentration and that can be inversely linked up with zooplankton or secondary productivity. During the course of study, the chlorophyll a concentrations of lagoons waters generally exhibited lower values (0.15-0.68 mg/m^3) than those reported by Robin *et al* (2012) who recorded values of 0.58-0.86 mg/m^3 from Kavaratti waters. The same trend was reported by Devassy and Goes (1991) from Mauritius. Studies by Robin *et al* (2012) proved that low chlorophyll concentration with less nutrient concentration could be used to predict the trophic state of Kavaratti waters. As a good indicator of phytoplankton dominance, values of chlorophyll in a lagoon less than 2.5mg/m^3 could be termed as oligotrophic. Hence, in the present study it can be established that Lakshadweep lagoon waters are oligotrophic as the pigment concentration was below 1mg/m^3. Further statistical analysis by Robin *et al* (2012) depicted a positive correlation between chlorophyll a with phytoplankton standing crop and nutrient concentration. In the present study, chlorophyll a showed significant ($p \leq 0.01$) positive correlation with inorganic nutrients and negative correlation with inorganic phosphate in Kalpeni lagoon. While in Minicoy lagoon, chlorophyll a exhibited a significant ($p \leq 0.01$) positive correlation with nitrate, nitrite, silicate, phosphate and a significant ($p \leq 0.01$) negative correlation with SST, SSS, pH, DO and ammonia. While in Kavaratti lagoon, chlorophyll a showed a significant ($p \leq 0.05$) correlation with nitrite.

Distribution of surface chlorophyll *a* from south to north in the Lakshadweep Sea during south west monsoon season showed a value of 2.23-4.62 mg/m^3 by Balachandran *et al* (1997).These very high concentrations of chlorophyll a when compared to the present study may be due to the highly productive nature of south west monsoon season and prevalence of rich phytoplankton biomass. It has been already proved by various authors that upwelling together with the large influx of nutrient rich river water into the Arabian Sea attributes to this high productivity. However high pockets of chlorophyll a increased towards areas of deeper zones (50-100 m) depth along the Lakshadweep waters (Balachandran *et al*.,1997) which is due to the movements of enriched upwelled waters away from the coast (Laevastu

and Hela, 1970). This might be another reason of a lower chlorophyll a concentration during the present study where the maximum depth was 4-5m. Seasonal variability is also another reason in which the lowest chlorophyll a concentration was observed during spring inter monsoon season (premonsoon). High chlorophyll a values ranging from 0.89- 18.86 mg/m^3 during postmonsoon of 1976 period and 1.4 to 15.4 mg/m^3 for premonsoon of 1978 period have been reported from the waters of Lakshadweep Sea (Bhattathiri *et al.,* 1978).

Prasanna kumar *et al* (2000) recorded chlorophyll a values of 0.04-0.05 mg/m^3 during spring intermonsoon, 0.10-0.35 mg/m^3 during fall intermonsoon, 0.09-1.34 mg/m^3 during summer monsoon and 0.03-0.80 mg/m^3 during winter monsoon from central and eastern Arabian Sea which are in general agreement with the present study. The present study recorded much lower chlorophyll a values during the premonsoon (spring intermonsoon) of 2014-15 which was in congruence with that of Prasanna kumar *et al* (2000). This is because the Arabian Sea being a tropical basin, during spring intermonsoon, the main heating season, availability of surface water nutrients controls the biological production since light is not a limiting factor in this season. Vertical mixing and upward transport of subsurface nutrients gets inhibited by the warm and highly stratified upper ocean under the influence of peak insolation together with light winds. Since there is no source of nutrients from lateral advection, open ocean circulation at this period is weak and zonal which in turn leads to rapid utilization of available nutrients making the production nutrient limiting. The surface chlorophyll a in the central Bay of Bengal increased from 0.06 mg/m^3 in the south to 0.28 mg/m^3 in the north and in the Arabian Sea, it varied from 0.32 to 1.12 mg/m^3 in the study conducted by Prasannakumar *et al* (2002) during summer monsoon. Madhuprathap *et al* (2003) reported chlorophyll a value of 0.26 mg/m^3 during summer monsoon season along northern BoB.

The chlorophyll a pigment concentration derived from the studies of Prasannakumar *et al* (2004) from BoB during winter monsoon corroborated with the present study and was also consistent with nitrate distribution. The relatively high nitrate levels is a clear indication that the enhanced chlorophyll is associated with the nutrient injection via advection of the Bay of Bengal waters. Prasanna

kumar *et al* (2007) also reported a chlorophyll a value of 0.13 mg/m^3 during fall intermonsoon season along the northern BoB. Muraleedharan *et al* (2007) documented chlorophyll a value as 0.14 mg/m^3 during summer monsoon along northern BoB while Jyothibabu *et al* (2008) reported summer monsoon chlorophyll a value of 0.2 mg/m^3 along the same region.

Peak chlorophyll a values ranging from 8 mg/m^3 -22.7 mg/m^3 were reported from south eastern Arabian Sea during summer monsoon by Lathika *et al.,* 2013. Suface nitrate concentration was also consistent with chlorophyll a increase that totally agreed with the present study. The values of chlorophyll a obtained from different lagoons of Lakshadweep was fairly close to those found in waters of Great Barrier reefs of Australia (0.06-0.24 mg/m^3) by Jeffrey (1968).Chlorophyll a values recorded by Qasim *et al* (1972) from Kavaratti lagoon was in general agreement with that of the present study observation. Honey *et al* (2014) articled comparatively higher chlorophyll a values (0.91mg/m^3-1.72 mg/m^3) from Port Blair Bay and Mahatma Gandhi Marine National Park of Andaman islands. These higher biological production in Andaman islands is attributed primarily to the rich mangrove and coral reef resources as opined by Gopinathan and Rajagopalan (1983) and Pillai (1983).

Prasannakumar *et al* (2010) articled surface chlorophyll a values ranging from 0.06 to 0.21mg/m^3 during spring intermonsoon,0.06 to 0.28 mg/m^3 during summer monsoon,0.13 to 0.77 mg/m^3 during fall intermonsoon and 0.12 to 0.28 mg/m^3 during winter monsoon along the central and western boundary of BoB. Sabu *et al* (2015) reported chlorophyll a value of 0.2 mg/m^3 during the winter season from northern BoB. Jagadeesan *et al* (2013) reported average chlorophyll a concentrations of 0.87 to 0.92mg/m^3 during spring intermonsoon, 0.76 to 1.6 mg/m^3 during summer monsoon and 0.75 to 1.8 mg/m^3 during north east monsoon. These values were slightly higher but comparable with the present study observations. Jyothibabu *et al* (2013) documented chlorophyll a values from BoB during summer monsoon ranging from 0.1-0.6 mg/m^3 which was comparable to the present study.

Chlorophyll a values from south eastern Arabian Sea was articled by Karnan *et al* (2017) during premonsoon and south west monsoon seasons. The values ranged from 0.93 to 2.73 mg/m^3 during premonsoon and 5.78 to 6.02 mg/m^3 during south west monsoon season and was comparatively higher to the present study. However peak chlorophyll values in south west monsoon season than premonsoon (spring inter monsoon) is the clear indication of coastal upwelling that prevailed during south west monsoon season in the study conducted by Karnan *et al*., 2017.

To summarize, the tropical basins of Arabian Sea and Bay of Bengal experiences large hydrological imbalances on an annual scale. This can be owed to the intense evaporation in the Arabian Sea leading to fresh water loss on an annual scale and reverse condition in BoB which receives massive quantities of fresh water due to precipitation and river run off. Besides this, the seasonally reversing circulation which was discussed earlier, in turn creates highs and lows in and around Lakshadweep Sea. It generates a hydrological imbalance by exchanging water masses between the Arabia Sea and Bay of Bengal that have a huge implication in terms of physicochemical and biological changes.

Principal Component Analysis (PCA) was carried in order to find out the environmental parameters influencing the study area. PCA of hydrography data of Kavaratti extracted two factors (principal component) with eigen values >1.The composite variables captured 99.5% of the variation. PC1 explained 66.2% of the total variance which was significantly contributed by nitrite (eigen value 5.95).PC2 explained 88.3% of the total variance which was significantly contributed by pH, ammonia and DO (eigen value 1.99).PCA of Kalpeni extracted one (first) principal component with eigen values >1.PCI explained 91.3% of the total variance which was contributed by SST,SSS, and pH (eigen value 8.21).PCA of Minicoy extracted three principal components with eigen values >1. PCI explained 88.7% of the total variance which was contributed by nitrate, nitrite, and phosphate(eigen value 7.98).PC2 explained 100% variance which was significantly contributed by DO(eigen value 1.02) and PC3 explained 100% variance which was significantly contributed by ammonia and nitrate (eigen value 6.98). The second component with strong loading value for DO (0.997) may be due to higher oxygen solubility in

colder and less saline water besides higher primary production. Whereas a positive loading towards nitrate (0.436) could be attributed to the coastal upwelling that increases nitrate concentration. Whereas PCA of Agatti extracted two principal components with eigen values >1.PC1 explained 84% variance which was contributed by DO, nitrate, nitrite (eigen value 7.56).PC2 explained 100% variance which was significantly contributed by SST and SSS (eigen value 1.44).PCA of Bangaram extracted two principal components with eigen values >1. PC1explained 59.6 of total variance which was significantly contributed by pH, nitrate, phosphate and ammonia (eigen value 5.36) and PC2 explained 100% variance which was significantly contributed by nitrite and silicate (eigen value 3.64).In Bangaram, the first principal component showed positive loadings for nitrate (0.430) and phosphate(0.427) while the second component showed positive loadings for nitrite (0.518).In Minicoy open ocean, the second component showed positive loading with DO (0.444).From the PCA analysis of water quality data, the first principal component reveals DO, nitrate, nitrite and phosphate as the significant loading factors.

Chapter 5

Mesozooplankton abundance and community structure of Cyclopoid copepods

Contents

5.1 Introduction

Zooplankton includes a categorization spanning a variety of organisms with size range 20µm-20mm including copepods, fish eggs, fish larvae, small hydromedusae, older stages of crustacean plankton and meroplanktonic larval forms. In a marine pelagic food web, zooplankton plays a significant role in transferring organic carbon from the phytoplankton and bacteria to higher trophic levels. Due to their short generation times, zooplankton serves as a measure of biological productivity and responds to any subtle changes in physical chemical and biological parameters in their surroundings. The use of mesozooplankton as reliable bio-indicators of ecosystem health is due to the fact that they are being strongly influenced by climatic changes. Hence, to understand the bio-physical processes that structures the marine ecosystems, spatio-temporal distribution of mesozooplankton is thus crucial.As opined by Tranter and George (1972), zooplankton represents the major food source of the coral reef community. Existence of zooplankton community, the major secondary producers are directly or indirectly influenced by the environmental conditions. The abundance of species in the sea is sustained by the lagoon along with a resident population and thus maintaining a high biodiversity hotspot. Zooplankter in a coral reef ecosystem plays an important role in the health of an aquatic ecosystem as they serve as food for corals, other invertebrates and reef fishes. As copepods forms the most significant secondary producers, their variation could also account for the geographical and seasonal variations of the mesozooplankton community (Uye *et*

al., 2000; Gaonkar *et al*., 2010). Dynamics of their population also greatly influences the reproductive and recruitment success of pelagic fish community (Conover *et al*., 1995; Beaugrand *et al*., 2003; Gonçalves *et al.,* 2015).

Seasonal analysis of the mesozooplankton biomass and abundance pattern (with special reference to copepods) and cyclopoid community structure from Lakshadweep lagoons Kavaratti (Kvt), Kalpeni (Klp),Minicoy (Mcy), Agatti (Agt) and Bangaram (Bang) and open sea stations are detailed in this chapter.

5.2 Mesozooplankton Abundance and Biomass of lagoon stations

In Kavaratti island during 2013-14, the biomass varied from 0.04 to 0.13 ml/m^3 (av.0.08± 0.05ml/m^3) in premonsoon season, 0.01-0.05ml/m^3 (av.0.03± 0.02ml/m^3) during monsoon and 0.02ml/m^3 to 0.14ml/m^3 (av.0.06±0.06ml/m^3) during postmonsoon (Fig.5.1).In Kalpeni during 2013-14, the biomass did not show any marked variation in monsoon (0.01ml/m^3) but in post-monsoon it ranged from 0.01 to 0.02 ml/m^3 (av.0.015±0.01ml/m^3) (Fig.5.2). In Minicoy lagoon during 2013-14 monsoon, the value ranged between 0.02 to 0.03ml/m^3 (av.0.025± 0.01ml/m^3). In post monsoon the biomass did not showed any variation (0.02 ml/m^3) (Fig.5.3).During 2014-15 pre-monsoon in Kavaratti, there was no variation in biomass and remained the same in all the transects (0.01ml/m^3) (Fig.5.4). In Agatti biomass varied from 0.02 ml/m^3-0.04ml/m^3 (av.0.03±0.01ml/m^3) with an average of 0.03±0.01ml/m^3 (Fig.5.5).In Bangaram 2014-15, the biomass exhibited marked variation from 0.06ml/m^3 to 0.09 ml/m^3 (av.0.07±0.02ml/m^3) during pre-monsoon season(Fig.5.6).

The major mesozooplankon obtained from different coral lagoons of Lakshadweep Sea were conveniently grouped into calanoid copepods, cyclopoid copepods, harpacticoid copepods and other groups. The total abundance of mesozooplankton in Kavaratti lagoon varied among the transects and ranged between 46800 to 64600 No/100m^3 (av. 57833 ±9637 No/100m^3) during pre-monsoon, 14500 to 24300 No/100m^3 (av.19067 ±4937 No/100m^3) during monsoon and 84500 to 147500 No /100m^3 (av.111200 ±32579 No/100m^3) during postmonsoon in 2013-14. Abundance of mesozooplankton was found to be the highest in the postmonsoon and the least in monsoon in the first year (Fig.5.1). In Kalpeni during 2013-14, the abundance was comparatively lower when compared to

Kavaratti and ranged between 738 to 815No/100m^3 (av.777±54 No/100m^3) (monsoon) and 12950 to 14822No/100m^3 (av.13886±1324No/100m^3) (post monsoon). Post monsoon season exhibited a higher abundance than that in monsoon (Fig.5.2).The total abundance of mesozooplankton in Minicoy also showed a comparatively prominent variation ranging from 2018 to 2472No/100m^3 (av.2245± 321No/100m^3) in monsoon and 20776 to 22239 No/100m^3(av.21508±1034 No/100m^3) in postmonsoon 2013-14. A seasonal comparison of Minicoy mesozooplankton revealed a higher abundance in post monsoon (Fig.5.3).

However during the second year, abundance from Agatti, Bangaram and Kavaratti was calculated in the premonsoon. But during 2014-15 in Kavaratti, abundance of mesozooplankton was comparatively lower than that of the first year and ranged from 1345 to 2288No/100m^3 (av.1893±490No/100m^3) (Fig.5.4).Pre-monsoon of the first year exhibited comparatively higher abundance than that in second year in Kavaratti. Agatti showed variation in abundance ranging from 2531 to 3217No/100m^3 (av.2892±344No/100m^3) (Fig.5.5). Meanwhile, Bangaram also showed a higher abundance ranging from 3888 to 5542No/100m^3 (av.4967±935 No/100m^3) (Fig.5.6). Bangaram was found to be highly abundant during premonsoon 2014-15 followed by Agatti and Kavaratti.

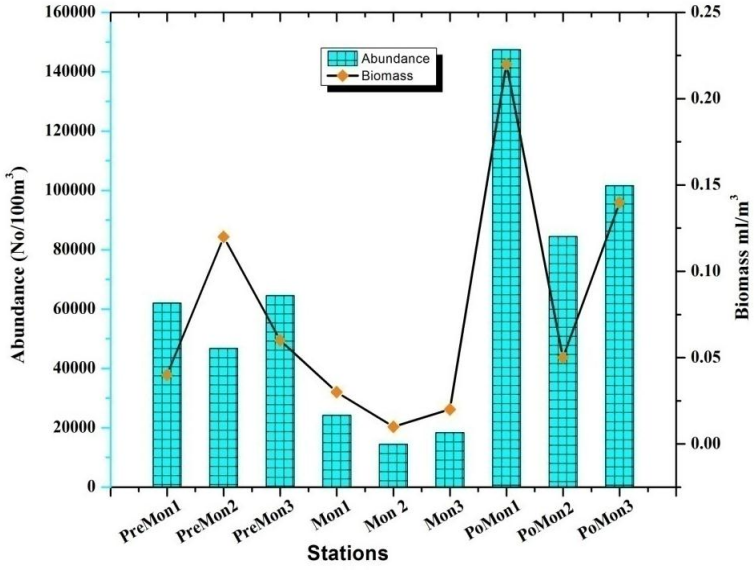


Fig. 5.1 Trasect wise variation in Abundance and biomass of zooplankton in lagoon stations of Kavaratti during 2013-14

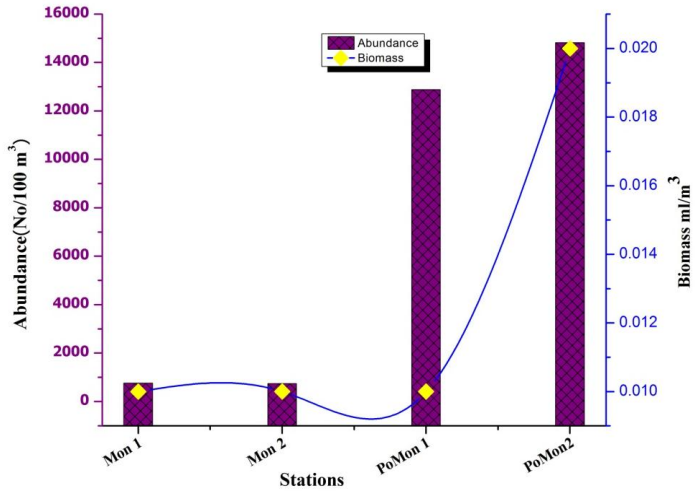


Fig.5.2 Transect wise variation in abundance and biomass of zooplankton in lagoon stations of Kalpeni during 2013-14

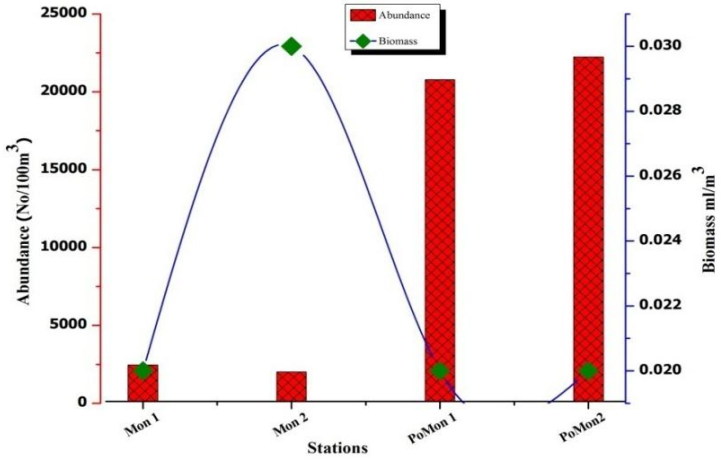


Fig. 5.3 Transect wise variation in abundance and biomass of zooplankton in lagoon stations of Minicoy during 2013-14

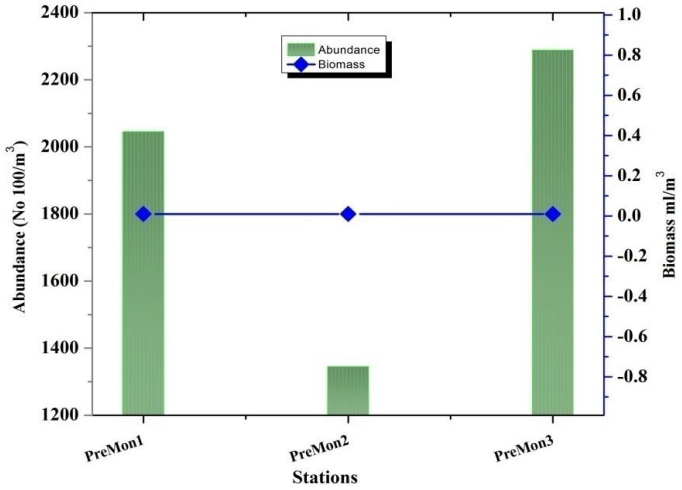


Fig.5.4 Transect wise variation in abundance and Biomass of zooplankton in lagoon stations of Kavaratti during 2014-15

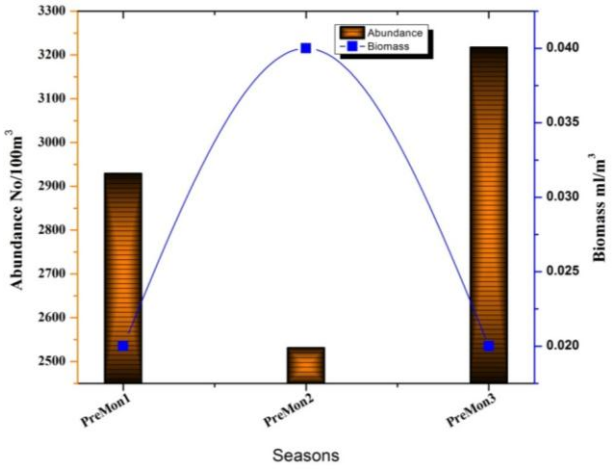


Fig.**5.5** Transect wise variation in abundance and biomass of zooplankton in lagoon stations of Agatti during 2014-15

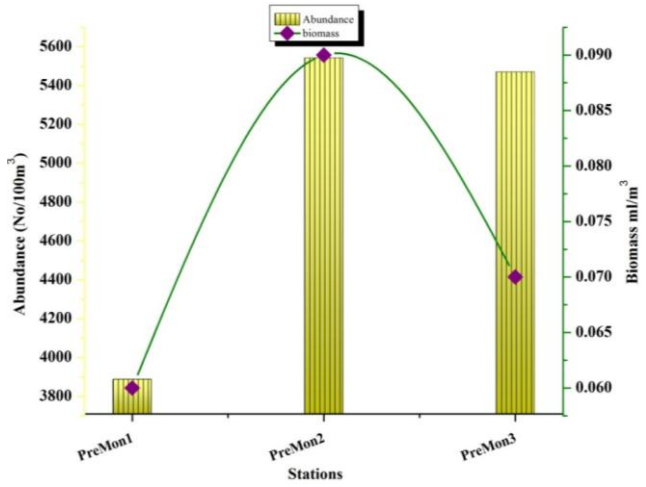


Fig. 5.6 Transect wise variation in abundance and biomass of zooplankton in lagoon stations of Bangaram during 2014-15

5.3 Mesozooplakton abundance and biomass of open ocean stations

In Minicoy open ocean stations, the biomass varied from 0.02 ml/m^3 to 0.11ml/m^3 (av.0.07±0.03ml/m^3) in premonsoon season with an average value of 0.03 ml/m^3**.**The total abundance of mesozooplankton from Minicoy open ocean varied among the stations and ranged between 2149 (S7) to 15432 No/100m^3 (S10) (av.8989 ±3866No/100m^3) (Fig.5.7).

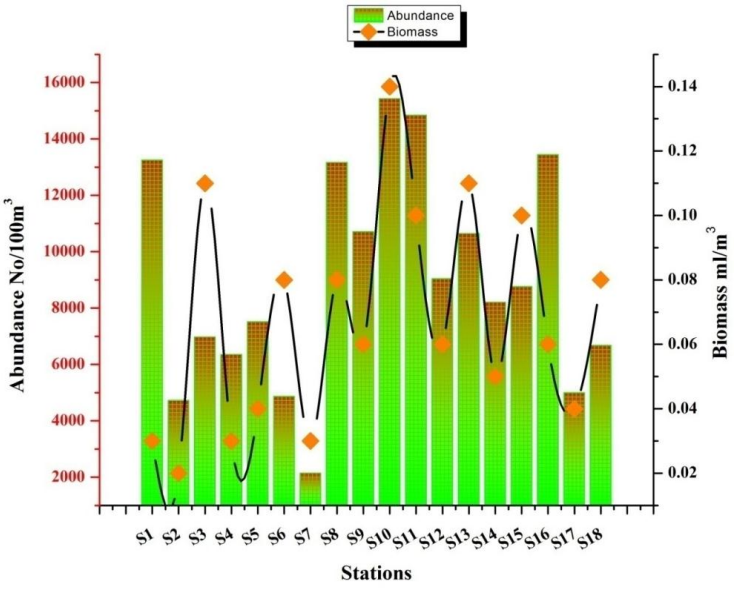


Fig.5.7 Station wise variation in abundance and biomass of zooplankton of open ocean stations in Minicoy during 2015

5.4 Copepod abundance of lagoon and open ocean stations

The total abundance of copepods in Kavaratti lagoon varied among the transects and ranged between 13700 to 56300No/100m^3 (av.40200±23126 No/ 100m^3) during premonsoon, 4900 to 14000 No/ 100m^3 (av.8100 ±5116 No/100m^3) during monsoon and 74800 to 131700No /100m^3 (av.99466 ±29194 No/100m^3) during postmonsoon in 2013-14. Copepod abundance was found to be the highest in the postmonsoon and the least in monsoon in the first year (Fig.5.8a).Among copepods, the abundance of calanoids copepods varied among the transects and ranged between 3100 to 16500 No/ 100m^3 (av.10333 ±6763 No/100m^3) during premonsoon, 3200 to 10000 No/ 100m^3 (av.5533 ±3869 No/100m^3) during monsoon and 57300 to 76200No /100m^3 (av.65366 ±9749 No/100m^3) during postmonsoon while that of harpacticoids abundance ranged between 3600 to 9400 No/100m^3 (av.7433±3320 No/100m^3) during premonsoon, 100 to 200 No/ 100m^3 (av.133 ±58 No/100m^3) during monsoon and 1200 to 6100 No/100m^3 (av.3466 ±2470No/100m^3).Cyclopoids dominated the copepod community during premonsoon and calanoids dominated monsoon and postmonsoon seasons. Harpacticoids showed the least dominance in all the seasons in Kavaratti 2013-14 (Fig.5.8b). In Kalpeni during 2013-14, copepod abundance was comparatively lower when compared to Kavaratti and ranged between 306 to 339 No/100m^3 (av.323±23

No/100m^3) (monsoon) and 544 to 678No/100m^3 (av.611±95No/100m^3) (post monsoon). Post monsoon season exhibited a higher abundance than that of monsoon (Fig.5.9a).In this, calanoids copepods dominated the monsoon season with an abundance ranging between 246 to 257 No/100m^3 (av.252±8 No/100m^3) while harpacticoids displayed the least abundance ranging between 6 to 8 No/100m^3 (av.7±1 No/100m^3).On the contrary during post monsoon season, abundance of calanoids copepods varied among the transects and ranged between 140 to 148 No/100m^3 (av.144±6No/100m^3) and that of harpacticoids ranged between 250 to 271 No/100m^3 (av.260±14No/ 100m^3).Post monsoon season of Kalpeni witnessed the abundance of cyclopoids in T1(coral area) and harpacticoids in T2 (lagoon area) (5.9b).The copepod abundance in Minicoy also showed a comparatively prominent variation ranging from 752 to 888No/100m^3 (av.820±96No/100m^3) in monsoon and 13185 to 13773 No/100m^3 (av.13479±416No/100m^3)in postmonsoon 2013-14 (Fig.5.10a).A seasonal comparison of Minicoy copepods revealed a higher abundance in post monsoon. Amidst copepods, the abundance of calanoids copepods ranged between 159 to 179 No/ 100m^3 (av.169 ±14 No/100m^3) during monsoon and 3600 to 4210 No/ 100m^3 (av.3905 ±431 No/100m^3) during postmonsoon. While harpacticoids abundance ranged between 18 to 21 No/ 100m^3 (av.19.5±2No/ 100m^3) during monsoon and 510 to 620 No/ 100m^3 (av.565±77No/100m^3) during post monsoon. Cyclopoid copepods dominated the copepod community followed by calanoids and the least by harpacticoids in Minicoy in the first year (5.10b)

However during the second year, copepod abundance from Agatti, Bangaram and Kavaratti was calculated in the premonsoon. But during 2014-15 in Kavaratti, abundance of copepods were comparatively lower than that of the first year and ranged from 278 to 1349 No/100m^3 (av.797±553No/100m^3) (Fig.5.11a).During premonsoon season 2014-15,within copepods, the abundance of calanoids copepods ranged between 210 to 790 No/ 100m^3 (av.479 ±292 No/100m^3) and that of harpacticoids ranged between 9 to 26 No/ 100m^3 (av.16±8No/100m^3).Calanoids dominated the copepod community followed by cyclopoids and harpacticoids in Kavaratti (Fig.5.11b).Agatti showed variation in abundance ranging from 635 to 822 No/100m^3 (av.743 ±97 No/100m^3) (Fig.5.12a).Meanwhile, Bangaram also showed a higher abundance ranging from 542 to 1961 No/100m^3 (av.1350±730 No/100m^3). Bangaram was found to be highly abundant during premonsoon 2014-15 followed

by Kavaratti and Agatti (Fig.513a).In Agatti, calanoid copepod abundance ranged from 335 to 416 No/100m^3 (av.387 ±45 No/100m^3) and abundance of harpacticoids copepods ranged from 1No/100m^3 to 56 No/100m^3 (av.20 ±30 No/100m^3).Agatti copepod community witnessed the dominance of calanoids and least by harpacticoids (Fig.5.12b).While in Bangaram, calanoid copepod abundance ranged from 320 to 851 No/100m^3 (av.666 ±299 No/100m^3) and abundance of harpacticoids copepods ranged from 9 to 178 No/100m^3 (av.66±96 No/100m^3). Here, the copepod community was dominated by cyclopoids in T1 while T2 and T3 was dominated by calanoids. Harpacticoids formed the least abundant copepod in all the transects of Bangaram (Fig.13b).In Minicoy open ocean, the total abundance of copepods varied among the stations and ranged between 1219 (S7) to 6828 No/100m^3(S11) (av.3728±1828 No/100m^3) (Fig.5.14a). Among copepods, the abundance of calanoids copepods ranged between 691 (S17) to 6558 No/ 100m^3 (S8) (av.2985 ±1834 No/100m^3) and harpacticoids abundance ranged from 16 (S1) to 1008 No/ 100m^3 (S17) (av.43 ±23 No/100m^3).However, copepod community was dominated by calanoids in all the stations followed by cyclopoids and harpacticoids being the least (5.14b).

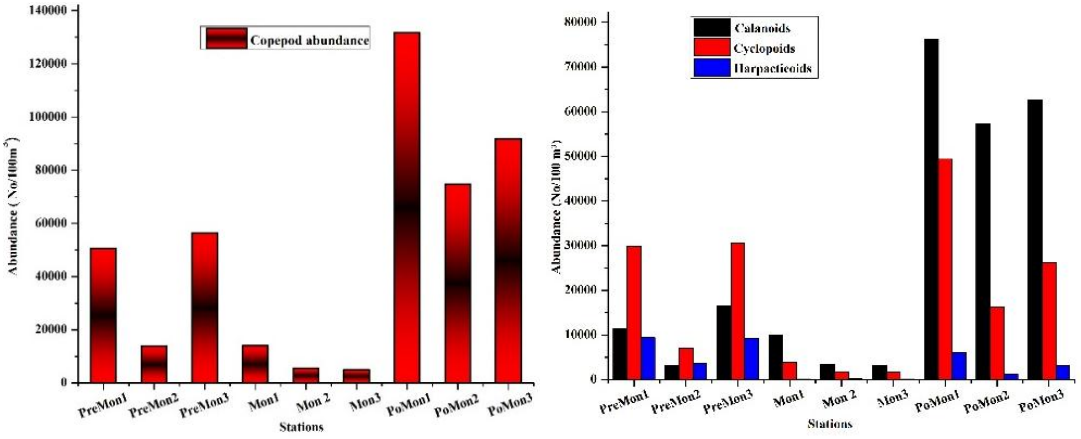


Fig.5.8 a and b. Transect wise variation in abundance of copepods in lagoon stations of Kavaratti during 2013-14

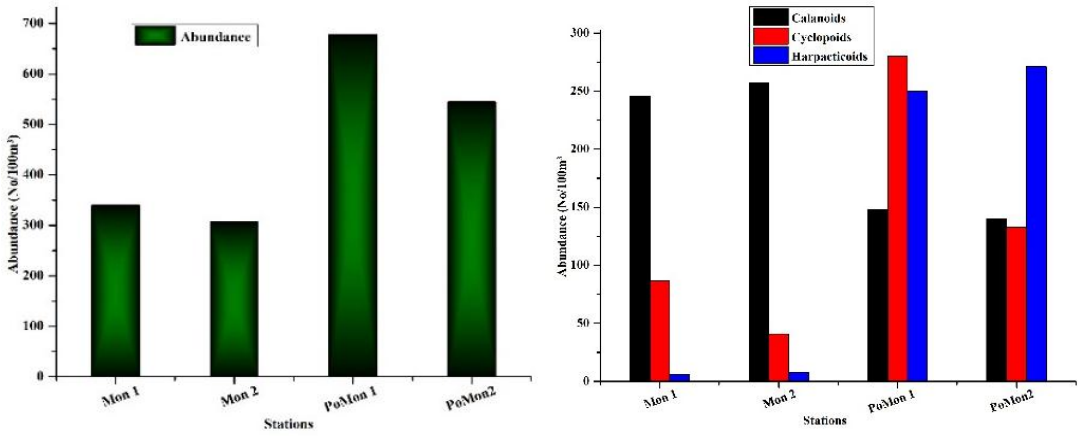


Fig. 5.9 a and b. Transect wise variation in abundance of copepods in lagoon stations of Kalpeni during 2013-14

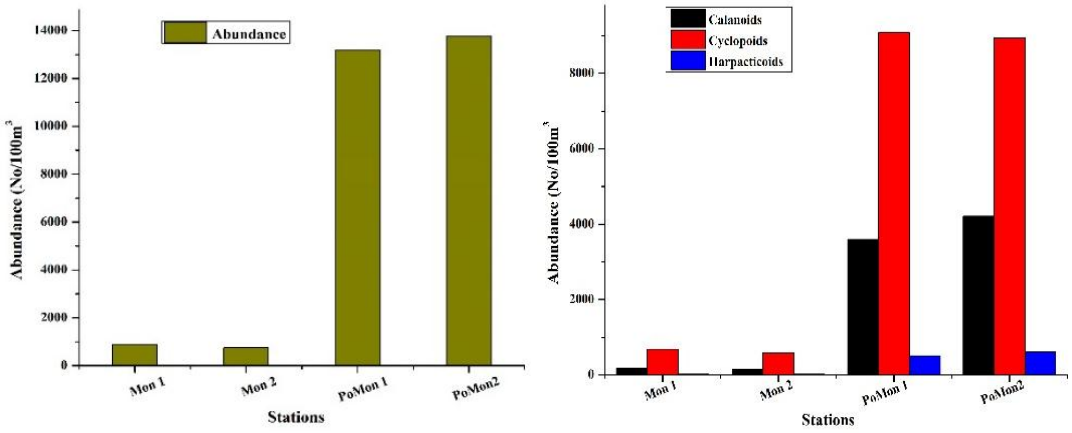


Fig. 5.10 a and b. Transect wise variation in abundance of copepods in lagoon stations of Minicoy during 2013-14

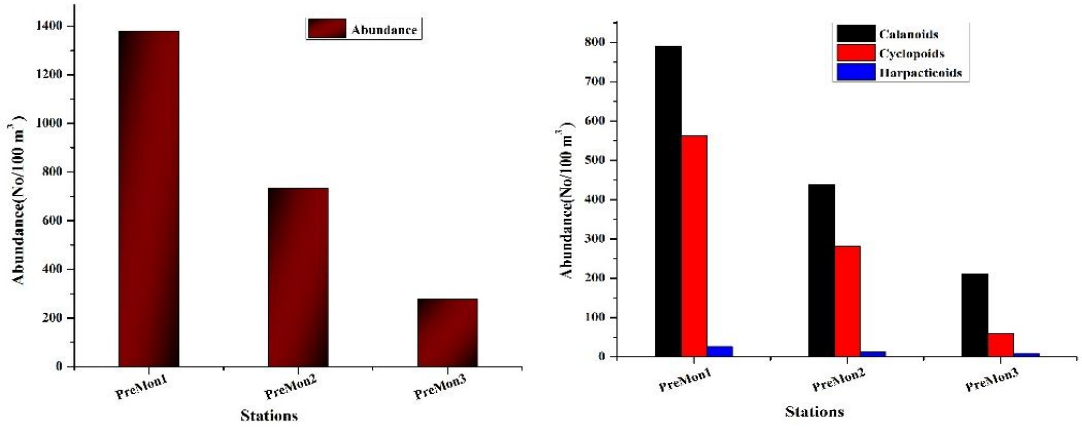


Fig.5.11 a and b. Transect wise variation in abundance of copepods in lagoon stations of Kavaratti during 2014-15

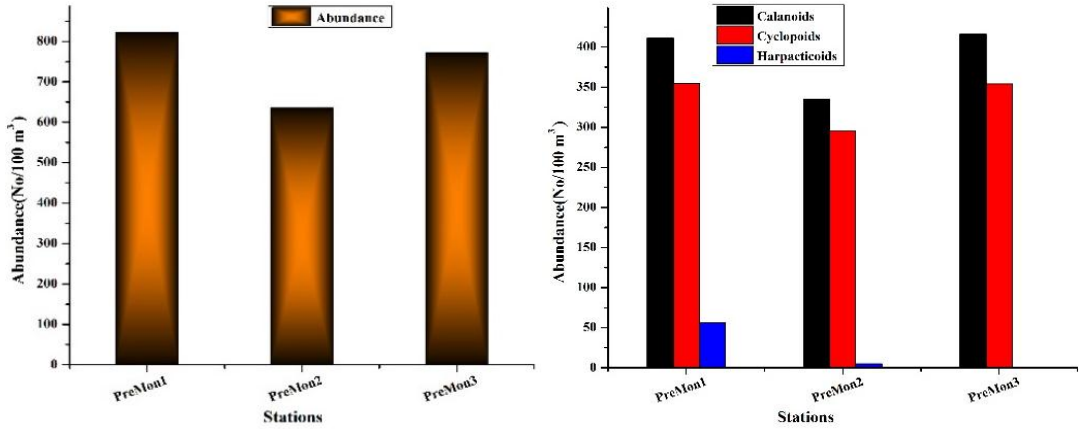


Fig. 5.12 a and b. Transcect wise variation in abundance of copepods in lagoon stations of Agatti during 2014-15

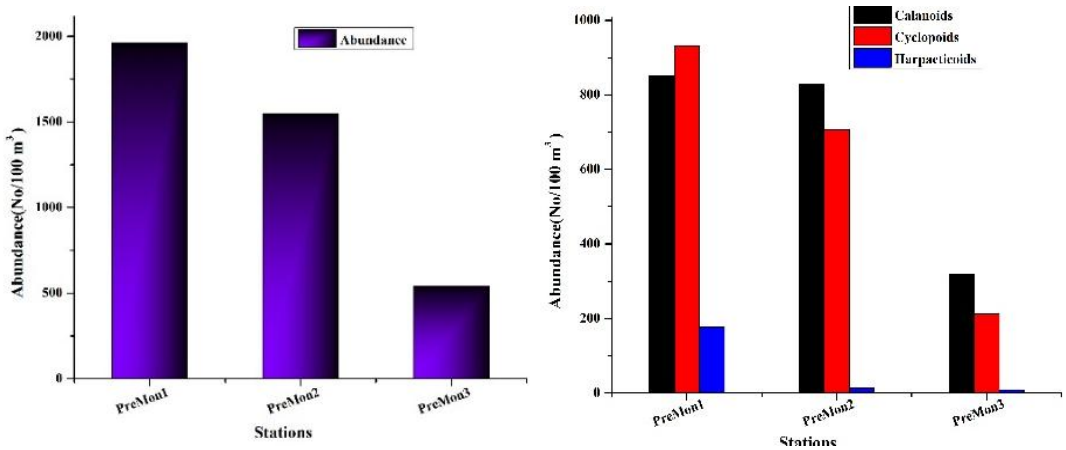


Fig. 5.13 a and b. Transcect wise variation in abundance of copepods in lagoon stations of Bangaram during 2014-15

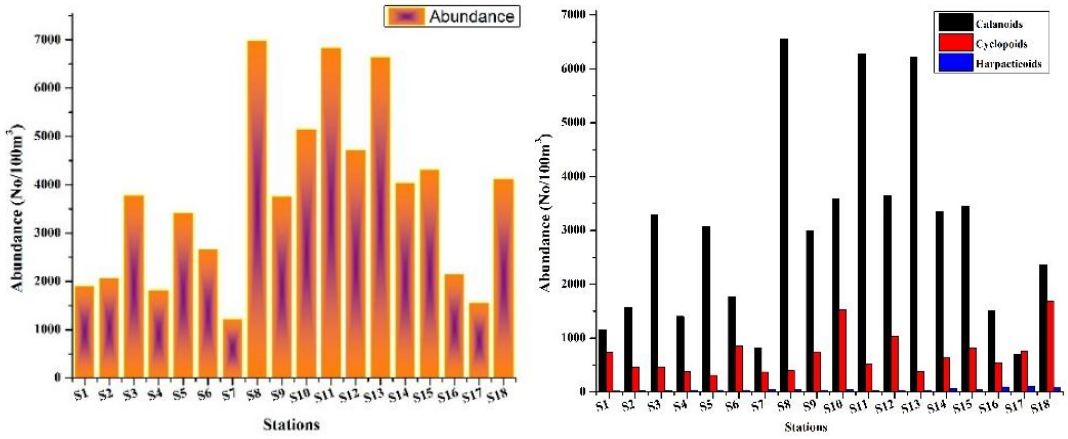


Fig. 5.14 a and b. Transcect wise variation in abundance of copepods in lagoon stations of Minicoy open ocean zones during 2015

5.5 Cyclopoid abundance and diversity from lagoon stations

Twenty five cyclopoid species belonging to eight genera and three families were identified during premonsoon, twenty three species during monsoon and thirty four species during postmonsoon in Kavaratti 2013-14 (Table 1).

Total abundance of cyclopoid copepods varied among stations and ranged between 7000 to 30500 No/100m^3 (av.22433±13370No/100m^3) in premonsoon, 1600 to 3900 No/100m^3 (av.2433±1274No/100m^3) in monsoon and 16300 to 49400 No/100m^3 (av.30633±16990 No/100m^3) (Fig.5.15). *Farranula* (300 to 11900 No/100m^3) was the most abundant cyclopoid genus irrespective of all seasons. *Oncaea* was observed to be the least abundant genus (3400No/m^3) and genus *Dioithona* being absent during premonsoon and monsoon (Fig.5.16**)**.The most species rich family observed during premonsoon in Kavaratti was Corycaedae (> 20spp.) followed by Oithonidae (>3spp.) and the least one to be Oncaedae (>2spp.).Family Sapphrinidae was completely absent in Kavaratti lagoon

During premonsoon season, boat channel (T3) witnessed the highest number of species (30500No/100m^3) with numbers ranging from 5600 (*Corycaeus*), 5800 (*Onychocorycaeus*),4900 (*Ditrichocorycaeus*),8300 (*Farranula*),2300 (*Oncaea*) and 3600 (*Oithona*).T3 was followed by T1(coral area)(29800No/100m^3) with numbers ranging from 5500 (*Corycaeus*), 5800 (*Onychocorycaeus*), 5500 (*Ditrichocorycaeus*), 7400(*Farranula*), 2200(*Oncaea*) and 3400 (*Oithona*).The least number of species was witnessed in T2(inner lagoon)(7000 No/100m^3) with numbers ranging from 800 (*Corycaeus*), 1500 (*Onychocorycaeus*),1600 (*Ditrichocorycaeus*), 2000 (*Farranula*),300 (*Oncaea*) and 800 (*Oithona*). Genus *Urocorycaeus* and genus *Dioithona* were completely absent in Kavaratti in premonsoon season (Fig.5.16). In the coral area (T1), the cyclopoid community was characterized by the dominance of the genus *Farranula* which represented 25% followed by *Onychocorycaeus* (20%), *Corycaeus* (19%), *Ditrichocorycaeus* (18%), *Oithona* (11%) and *Oncaea* (7%).The inner lagoon was also dominated by *Farranula (*29%) followed by *Ditrichocorycaeus* (23%), *Onychocorycaeus* (21%), *Corycaeus*(12%) *Oithona* (11%) and *Oncaea* (4%). However, in boat channel (T3) *Farranula* dominated (27%) followed by *Onychocorycaeus* (19%), *Corycaeus* (18%), *Ditrichocorycaeus* (16%), *Oithona* (12%) and *Oncaea* (8**%**) (Fig.5.17).

Whereas in monsoon season, coral area (T1) witnessed the highest number of species (3900No/100m^3) with numbers ranging from 1200 (*Corycaeus*), 400 (*Onychocorycaeus*), 1000 (*Ditrichocorycaeus*), 700(*Farranula*), 300(*Oncaea*) and 300(*Oithona*).T1 was followed by T2 (inner lagoon)(1800No/100m^3) with numbers ranging from 600 (*Corycaeus*), 100 (*Onychocorycaeus*),300 (*Ditrichocorycaeus*),500 (*Farranula*),100 (*Oncaea*) and 200 (*Oithona*). The least number of species was witnessed in T3 (boat channel) (1600 No/100m^3) with numbers ranging from 600 (*Corycaeus*), 400 (*Onychocorycaeus*), 300 (*Ditrichocorycaeus*), 300 (*Farranula*). Genus *Urocorycaeus,* genus *Oithona,* genus *Oncaea* and genus *Dioithona* were completely absent in Kavaratti monsoon season. *Corycaeus* (31%), *Ditrichocorycaeus* (25%) *Farranula* (18%) and *Onychocorycaeus* (10%) predominated in the coral area. T2 was predominated by *Corycaeus* (33%), *Farranula* (28%), *Ditrichocorycaeus* (17%), *Oithona* (11%), *Oncaea* (6%), *Oithona* (11%), *Oncaea* (8%).While in T3, *Corycaeus* (37%) was followed by *Onychocorycaeus* (25%), *Farranula-Ditrichocorycaeus* (19%). However genus *Urocorycaeus*, *Dioithona*, *Oncaea* and *Oithona* showed complete absence of its representatives in boat channel (T3).

During post monsoon, T1 and T2 was dominated by *Farranula* (24% and 29%) whereas T3 by both *Farranula* and *Onychocorycaeus* (21%).The least dominated genus was *Oncaea* in all three transects. In T1, *Farranula* was followed by *Onychocorycaeus* (18%), *Corycaeus* (17%), *Ditrichocorycaeus* (15%), *Oithona* (9%), *Oncaea* (7%). In T3, *Farranula* was followed by *Onychocorycaeus* (21%), *Corycaeus* (19%), *Ditrichocorycaeus* (17%), *Oithona* (8%), *Oncaea* (5%).While in T2, *Farranula* was followed by *Corycaeus* (19%), *Onychocorycaeus* (13%), *Oncaea-Oithona* (7%), *Urocorycaeus* (6%) and the least by *Dioithona* (4%).

The premonsoon cyclopoid community at Kavaratti were devoid of *U.furcifer, U.lautus, O.pumilus, O.paraclevie ,O.venusta, O.scottodiarloi, O.mediterranea, O.macilenta, O.curta, O.nana, O.simplex, D.rigida* and *D.oculata* while the monsoon cyclopoid community showed the absence of *U.furcifer, U.lautus ,O.giesbrechti, O.latus, O.pumilus, O.paraclevie, O.venusta, O.scottodiarloi, O.mediterranea, O.macilenta, O.curta,O.similis, O.nana, D.rigida* and *D.oculata.* The genus *Dioithona* was represented only during postmonsoon. However, premonsoon cyclopoid community was characterized by the high dominance of *O.agilis* and least dominance by *O.latus*; the monsoon cyclopoid community was

dominated by *C.crassiusculus* and least dominated by *D.affinis, C.clausi ,D.subulatus* and *O.brevicornis.* Meanwhile, post monsoon was dominated by *F.gibbula* and the least by *D.affinis, C.clausi ,D.subulatus*, *O.curta* and *O.paraclevie.*

Table.1 Cyclopoid copepod species recorded at Kavaratti during 2013-2014

	Taxa	PreMon	Mon	PoMon
Family Corycaedae				
Genus *Corycaeus*	*Corycaeus crassiusculus*	+++	+	+++
	Corycaeus speciosus	++	+	++
	Corycaeus clausi	++	+	+++
	Corycaeus vitreus	+++	+	+++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	-	-	++
	Urocorycaeus lautus	-	-	+++
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	+++	+	+++
	Onychocorycaeus agilis	+	+	+++
	Onychocorycaeus giesbrechti	+	–	+++
	Onychocorycaeus latus	+++	-	++
	Onychocorycaeus pumilus	-	-	-
	Onychocorycaeus pacificus	++	–	++
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	+	–	++
	Ditrichocorycaeus affinis	++	+	+++
	Ditrichocoryceus dahli	++	+	+
	Ditrichocoryceus tenius	+	+	–
	Ditrichocorycaeus subulatus	+	+	+
	Ditrichocorycaeus lubbocki	+++	+	+++
Genus *Farranula*	*Farranula gibbula*	++	+	+++
	Farranula concinna	+++	+	+++
	Farranula gracilis	++	+	++
	Farranula rostrata	++	+	+++
	Farranula curta	+	+	+++
Family Oncaedae				
Genus *Oncaea*	*Oncaea clevei*	-	-	+++
	Oncaea media	-	-	+++
	Oncaea paraclevie	-	-	+
	Oncaea venusta	-	-	+
	Oncaea scottodicarloi	-	-	+
	Oncaea mediterranea	-	-	+
	Oncaea macilenta	-	-	+++
	Oncaea curta	-	-	+
Family Oithonidae				
Genus *Oithona*	*Oithona similis*	++	-	+
	Oithona brevicornis	++	-	+++
	Oithona plumifera	++	-	+++
	Oithona nana	-	-	++
	Oithona simplex	-	-	++
Genus *Dioithona*	*Dioithona rigida*	-	-	++
	Dioithona oculata.	-	-	-

"+" Denotes presence ,"++" Denotes Less abundant , "+++" Denotes Abundant ,"-" Denotes absence

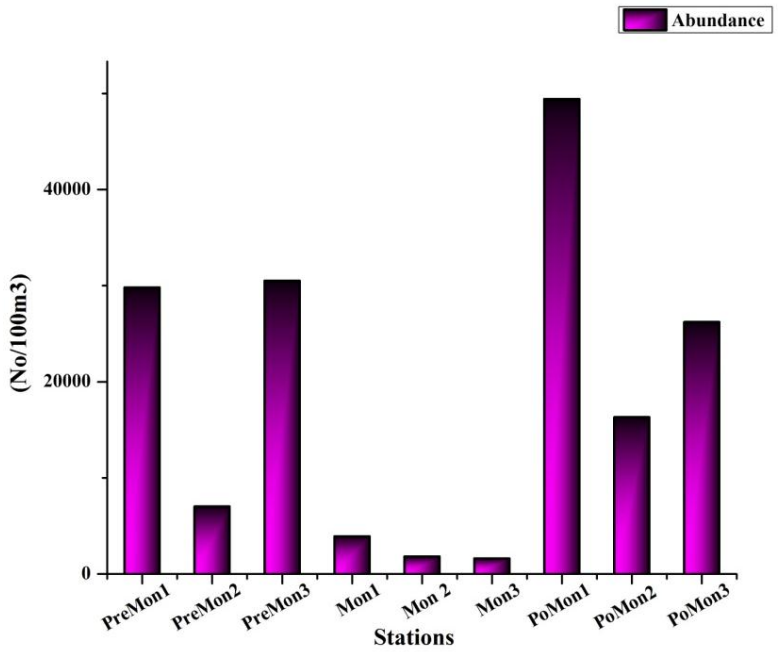


Fig.5.15 Variation in cyclopoid abundance during premonsoon, monsoon and postmonsoon at lagoon stations of Kavaratti 2013-14

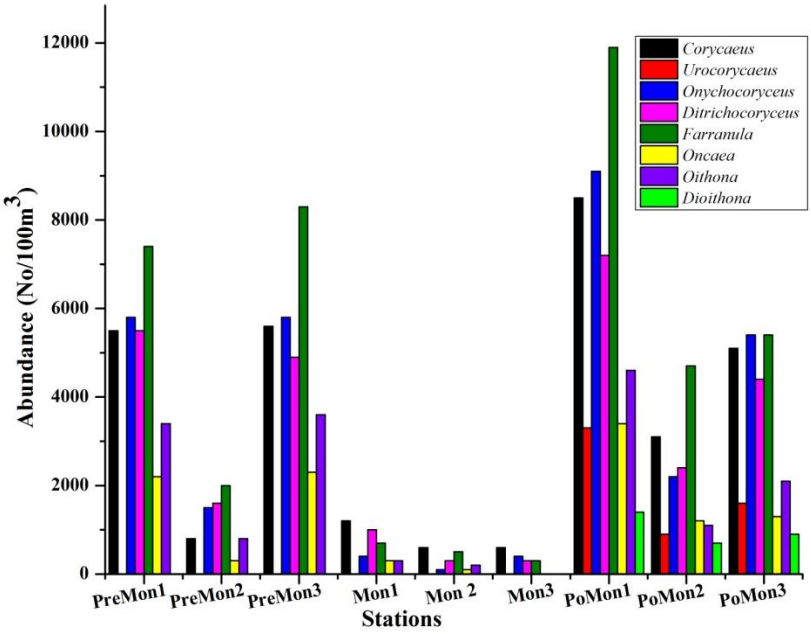


Fig.5.16 Transect wise abundance of major cyclopoid genera during premonsoon, monsoon and postmonsoon at lagoon stations of Kavaratti during during 2013-14.

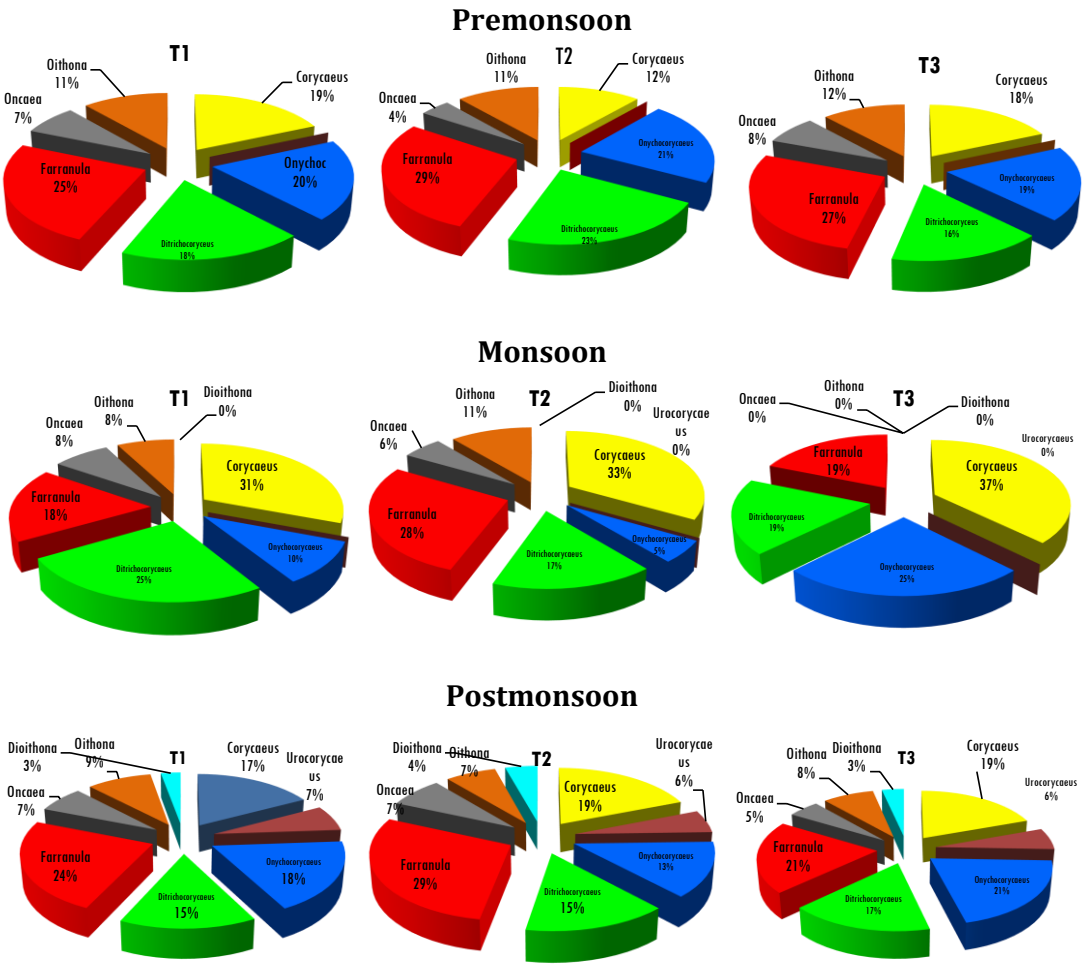


Fig.5.17 Transect wise percentage composition of cyclopoid genus during premonsoon, monsoon and postmonsoon at lagoon stations of Kavaratti 2013-14

In Kalpeni during 2013-14, twenty seven species were identified both in monsoon and postmonsoon season (Table.2).Diversity of species was comparatively less when compared with that of Kavaratti. Total abundance of cyclopoid copepods varied among stations and ranged between 41 to 87 No/ $100m^3$(av.64±33No/$100m^3$) during monsoon and 133 to 280No/$100m^3$ (av.207± 133 No/$100m^3$) during post monsoon (Fig.5.18)**.** The most species rich family observed during premonsoon in Kalpeni was Corycaedae (> 12pp.) followed by Oncaedae (>8spp.) and the least was Oithonodae (>7spp.).Family Sapphrinidae was completely absent in Kalpeni lagoon.In Kalpeni 2013-14,*Oncaea* was the most abundant cyclopoid genus with an average abundance ranging between 26 to 129 No/$100m^3$ followed by and *Ditrichocorycaeus* (23-117No/$100m^3$),

Onychocorycaeus (21 to 39No/100m^3), *Oithona* (16 to 83No/100m^3), *Dioithona* (13 to 43No/100m^3), *Corycaeus* (12 to 18No/100m^3)and *Farranula* (8 to 18No/100m^3) (Fig.5.19).

During monsoon season in Kalpeni, coral area (T1) witnessed the highest number of species (87No/100m^3)with numbers ranging from 9(*Corycaeus*), 9(*Urocorycaeus*),21 (*Onychocorycaeus*), 11 (*Ditrichocorycaeus*), 3 (*Farranula*), 12 (*Oncaea*), 10 (*Oithona*) and 12 (*Dioithona*).T1 was followed by T2 (inner lagoon) (41No/100m^3) with numbers ranging from 3 (*Corycaeus*), 12 (*Ditrichocorycaeus*),5 (*Farranula*),14(*Oncaea*) and 6 (*Oithona*) 1 (*Dioithona*). Meanwhile in postmonsoon season, coral area (T1) witnessed the highest number of species (280No/100m^3) with numbers ranging from 14 (*Corycaeus*), 37 (*Onychocorycaeus*), 67(*Ditrichocorycaeus*), 14 (*Farranula*), 82(*Oncaea*), 57(*Oithona*) and 29 (*Dioithona*).T1 was followed by T2 (inner lagoon) (133No/100m^3) with numbers ranging from 4(*Corycaeus*), 2(*Onychocorycaeus*), 50 (*Ditrichocorycaeus*),4 (*Farranula*) ,47(*Oncaea*) and 26(*Oithona*), 14(*Dioithona*). Genus *Urocorycaeus* was absent in T2. Post monsoon season was found to be more abundant than that of monsoon. During monsoon 2013-14 in Kalpeni, in the coral area (T1), the cyclopoid community was characterized by the dominance of the genus *Onychocorycaeus* (24%) followed by *Dioithona* and *Oncaea* (14%), *Oithona* (12%) and least by *Farranul*a (3%). The inner lagoon also was characterized by the dominance of *Oncaea* (34%) followed by *Ditrichocorycaeus* (29%), *Oithona* (15%), *Farranula* (12%) and the least by *Dioithona* (3%).However during postmonsoon in Kalpeni, the coral area was dominated by *Oncaea* (27%), *Dioithona* (22%) *Oithona* (19%), and the least by *Farranula* and *Corycaeus* (5%). Inner lagoon was also dominated *Ditrichocorycaeus* (34%), followed by *Oncaea* (32%), *Oithona* (18%), *Dioithona* (9%) and the least by *Onychocorycaeus* (1%) (Fig.5.20). At Kalpeni, while monsoon cyclopoid community was characterized by the high dominance of *D.rigida* and least dominance by *D.oculata, O.scottodicarloi, F.gracilis*; the post monsoon cyclopoid community was dominated by *D.dahli* and least dominated by *F.gibbula.*

Table.2 Cyclopoid copepod species recorded at Kalpeni during 2013-2014

		Monsoon	Postmonsoon
	Cyclopoids		
Family Corycaedae			
Genus *Corycaeus*	*Corycaeus crassiusculus*	-	-
	Corycaeus speciosus	-	-
	Corycaeus clausi	++	++
	Corycaeus vitreus	++	+
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	+	-
	Urocorycaeus lautus	-	-
	Onychocorycaeus catus	-	++
Genus *Onychocorycaeus*	*Onychocorycaeus agilis*	++	+++
	Onychocorycaeus giesbrechti	-	-
	Onychocorycaeus latus	+++	-
	Onychocorycaeus pumilus	-	-
	Onychocorycaeus pacificus	+	++
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	-	-
	Ditrichocorycaeus affinis	-	++
	Ditrichocoryceus dahli	++	+++
	Ditrichocoryceus tenius	-	+
	Ditrichocorycaeus subulatus	++	+++
	Ditrichocorycaeus lubbocki	++	++
Genus *Farranula*	*Farranula gibbula*	+	+
	Farranula concinna	+	-
	Farranula gracilis	+	+
	Farranula rostrata	-	++
	Farranula curta	-	-
Family Oncaedae			
Genus *Oncaea*	*Oncaea clevei*	+	+
	Oncaea media	+	+
	Oncaea paraclevie	++	+++
	Oncaea venusta	++	+++
	Oncaea scottodicarloi	+	++
	Oncaea mediterranea	+	+++
	Oncaea macilenta	+	++
	Oncaea curta	++	++
Family Oithonidae			
Genus *Oithona*	*Oithona similis*	+	++
	Oithona brevicornis	+	++
	Oithona plumifera	+	+++
	Oithona nana	+	+
	Oithona simplex	+	-
Genus *Dioithona*	*Dioithona rigida*	++	+++
	Dioithona oculata.	+	++

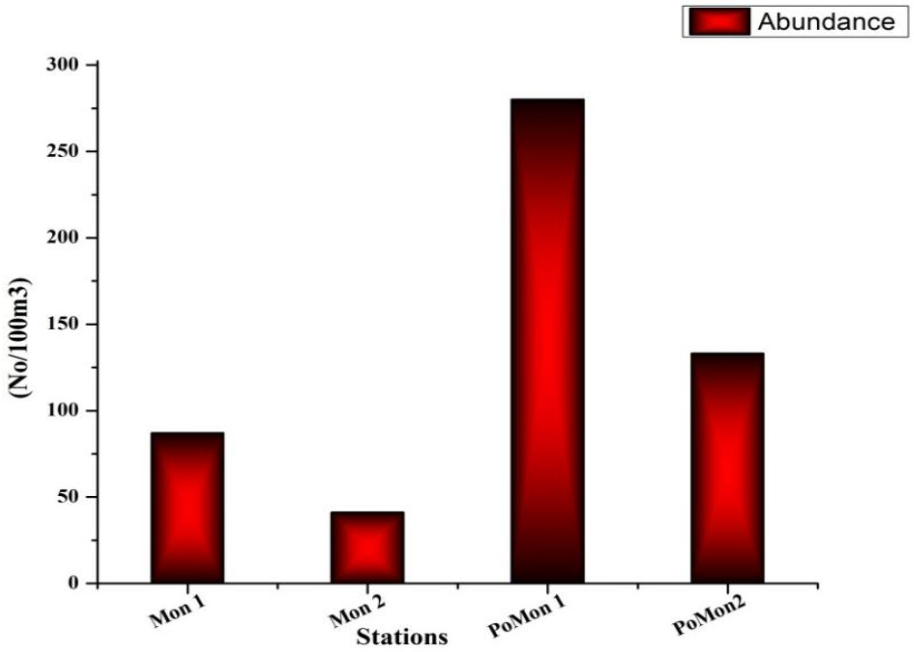


Fig.5.18 Variation in Cyclopoid abundance during monsoon and postmonsoon at lagoon stations of Kalpeni during 2013-14

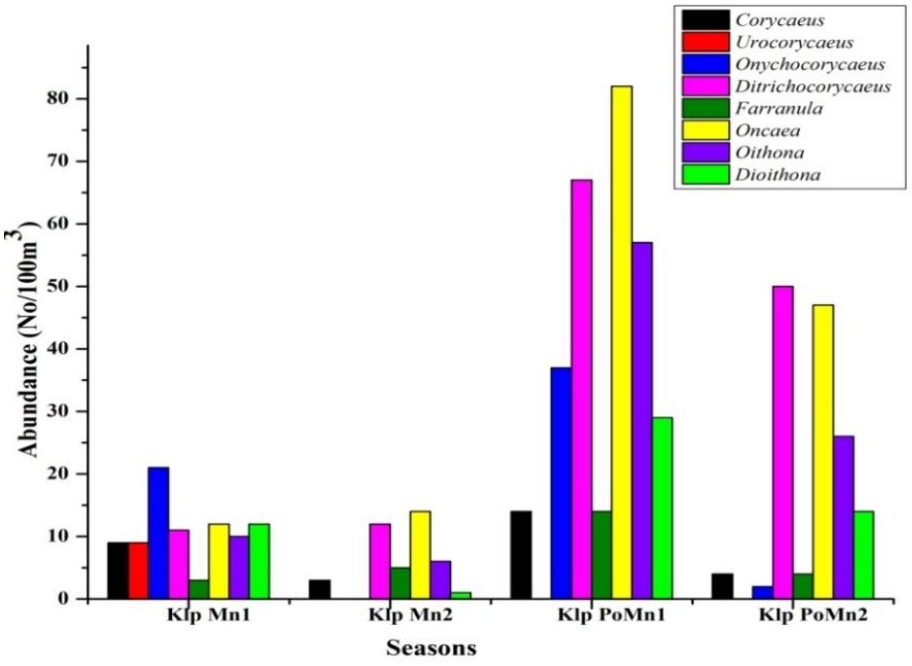


Fig.5.19 Transect wise abundance of major Cyclopoid genera in monsoon and postmonsoon at lagoon stations of Kalpeni during 2013-14.

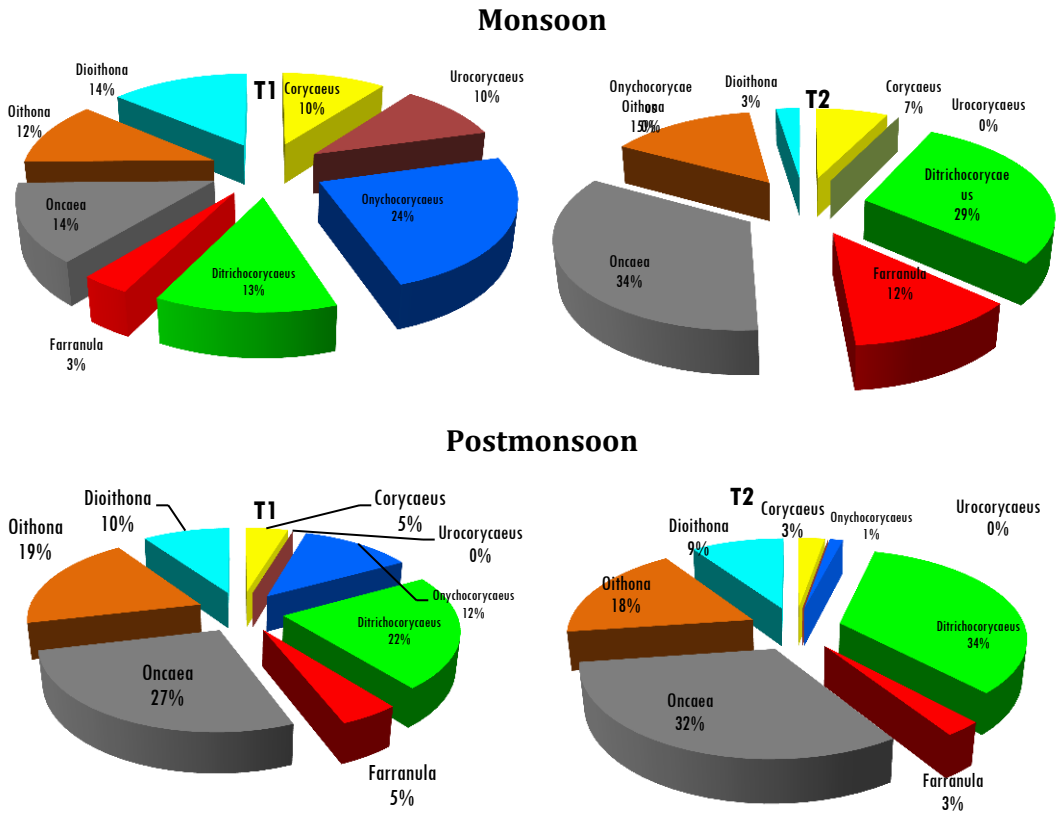


Fig.5.20 Station wise percentage composition of cyclopoid genus in premonsoon, monsoon and postmonsoon at lagoon stations of Kalpeni during 2013-14

In Minicoy 2013-14, thirty five species were identified in monsoon and thirty eight species in postmonsoon season (Table.3). Total abundance of cyclopoid copepods varied among stations and ranged between 575 to 688No/100m^3 (av.632±80No/100m^3) during monsoon and 8943 to 9075 No/100m^3 (av.9009±93 No/100m^3) during post monsoon (Fig.5.21). *Onychocorycaeus* was the most abundant cyclopoid genus with an abundance ranging between 108 to 156 No/100m^3 followed by *Corycaeus* (108 to 156No/100m^3), *Dioithona* (85 to 159 No/100m^3), *Oncaea* (79 to 94 No/100m^3), *Oithona* (76 to 85 No/100m^3), *Ditrichocorycaeus* (65 to 79 No/100m^3), *Dioithona* (55 to 79 No/100m^3), *Farranula* (40 to 78No/100m^3) and the least by *Urocorycaeus* (6 to 19 No/100m^3)(Fig.5.22).

In Minicoy also, postmonsoon season encountered more abundance. When families were compared, it was observed that Corycaedaea family was the most abundant and diverse with 20 spp. Oncaedae family came next with 8spp. followed by Oithonidae with 7spp. *Corycaeus* genus which formed 19% of the total cyclopoids dominated T1 (coral area) community followed by *Oncaea* (19%), *Oithona* (16%),

Onychocorycaeus(15%) *Ditrichocorycaeus* (10%) and *Farranula* (9%). While T2 was dominated by *Corycaeus* and *Oncaea* (18%), *Onychocorycaeus* (17%), *Oithona* (15%), *Farranula* (12%), *Dioithona* and *Ditrichocorycaeus* (9%) (Fig.5.23).

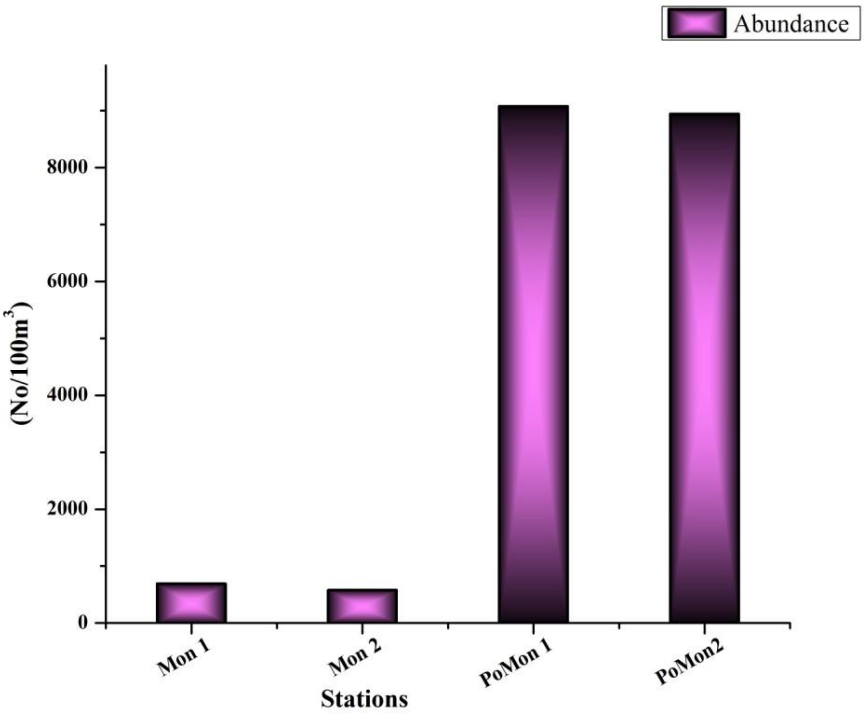


Fig.5.21 Variation in cyclopoid abundance in monsoon and postmonsoon at lagoon stations of Minicoy during 2013-14

Table.3. Cyclopoid copepod species recorded at Minicoy during 2013-2014

		Monsoon	Postmonsoon
	Cyclopoids	T1	T1
Family Corycaedae			
Genus *Corycaeus*	*Corycaeus crassiusculus*	+++	+++
	Corycaeus speciosus	+++	+++
	Corycaeus clausi	++	+++
	Corycaeus vitreus	++	+++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	+	++
	Urocorycaeus lautus	+	+++
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	++	+++
	Onychocorycaeus agilis	++	+++
	Onychocorycaeus giesbrechti	++	+++
	Onychocorycaeus latus	+	+

	Onychocorycaeus pumilus	+	+++
	Onychocorycaeus pacificus	+	+++
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	++	+++
	Ditrichocorycaeus affinis	++	+++
	Ditrichocoryceus dahli	+	++
	Ditrichocoryceus tenius	+	+++
	Ditrichocorycaeus subulatus	-	+
	Ditrichocorycaeus lubbocki	-	+
Genus *Farranula*	*Farranula gibbula*	++	+++
	Farranula concinna	-	+++
	Farranula gracilis	++	++
	Farranula rostrata	+	+++
	Farranula curta	+	+
Family Oncaedae			
Genus *Oncaea*	*Oncaea clevei*	++	+++
	Oncaea media	++	+++
	Oncaea paraclevie	+	+++
	Oncaea venusta	+	+++
	Oncaea scottodicarloi	+	++
	Oncaea mediterranea	++	++
	Oncaea macilenta	+	+++
	Oncaea curta	+	++
Family Oithonidae			
Genus *Oithona*	*Oithona similis*	++	+++
	Oithona brevicornis	+	++
	Oithona plumifera	++	+++
	Oithona nana	+	+
	Oithona simplex	+	++
Genus *Dioithona*	*Dioithona rigida*	++	+++
	Dioithona oculata.	++	+++

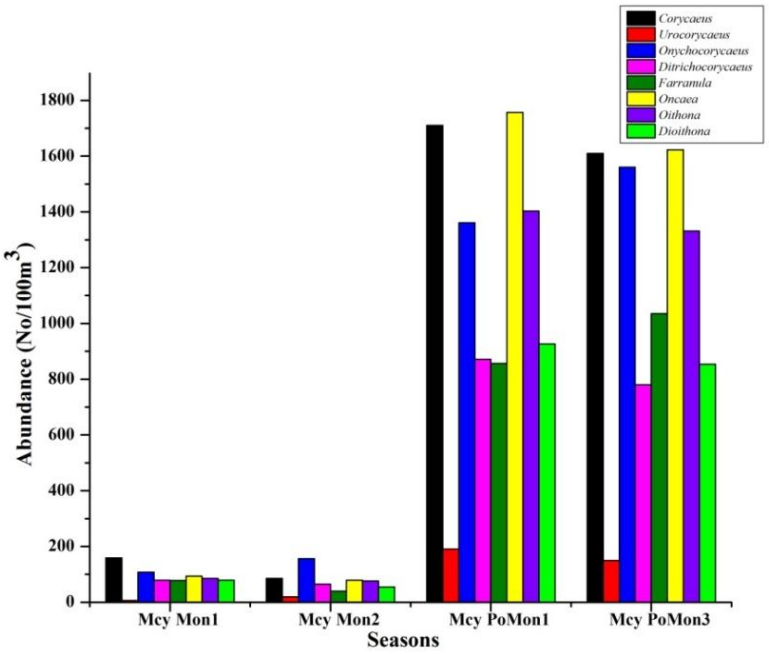


Fig.5.22 Transect wise abundance of major cyclopoid genera in monsoon and postmonsoon at lagoon stations of Minicoy during 2013-14

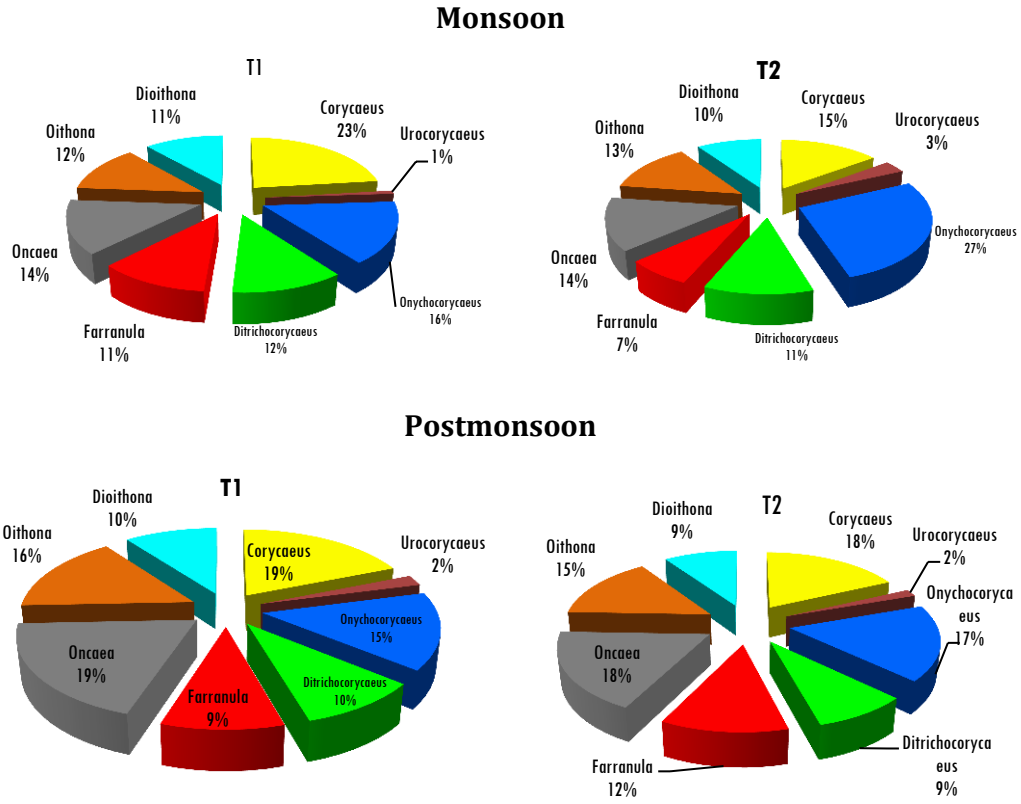


Fig.5.23 Transect wise percentage composition of cyclopoid genus in monsoon and postmonsoon at lagoon stations of Minicoy during 2013-14

In Agatti during 2014-15, thirty seven species were identified in premonsoon season (Table.4). Total abundance of cyclopoid copepods varied among stations and ranged between 295 to 355No/100m^3 (av.335±34no/100m^3) (Fig.5.24). *Oncaea* was the most abundant cyclopoid genus with an abundance ranging between 74 to 82 No/100m^3 followed by *Oithona* (48 to 69 No/100m^3), *Ditrichocorycaeus* (39 to 64 No/100m^3), *Farranula* (45 to 48 No/100m^3), *Onychocorycaeus* (22 to 47No/100m^3), *Corycaeus* (16 to 50No/100m^3) and the least by *Urocorycaeus* (16 to 27 No/100m^3) **(**Fig.5.25). Corycaedaea family was found to be the most abundant and diverse with 22spp.Oncaeadae species was the next diverse genera with 8 spp and Oithonidae being the least (7spp).Here the cyclopoid community in the coral area was characterized by the dominance of the genus *Oncaea* (22%) followed by *Ditrichocorycaeus* (18%), *Oithona* (14%), *Onychocorycaeus* and *Farranula* (13%), *Corycaeus* and *Dioithona* (8%) and *Urocorycaeus* (4%) the least .The inner lagoon was characterized by the dominance of the genus *Oncaea* (28%) followed by *Oithona* (17%), *Farranula* (15%),*Ditrichocorycaeus* (13%), *Onychocorycaeus* (11%) and *Corycaeus*(6%) whereas *Dioithona* (5%) and *Urocorycaeus* (5%) being the least. However in boat channel (T3) also genus *Oncaea* (21%) dominated followed by *Oithona* (19%), *Farranula* (14%) and *Dioithona* the least (8%) **(**Fig.5.26).In Agatti, *Oithona plumifera* dominated the cyclopoid community and *Oncaea media,* the least. However *O.catus* was absent in Agatti lagoon.

Table 4 Cyclopoid copepod species recorded at Agatti during 2014-2015

	Cyclopoids	Premonsoon
Family Corycaedae		
Genus *Corycaeus*	*Corycaeus crassiusculus*	+++
	Corycaeus speciosus	++
	Corycaeus clausi	+
	Corycaeus vitreus	++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	++
	Urocorycaeus lautus	+
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	-
	Onychocorycaeus agilis	+
	Onychocorycaeus giesbrechti	+
	Onychocorycaeus latus	++
	Onychocorycaeus pumilus	++
	Onychocorycaeus pacificus	++
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	++
	Ditrichocorycaeus affinis	++
	Ditrichocoryceus dahli	+++
	Ditrichocoryceus tenius	++
	Ditrichocorycaeus subulatus	+
	Ditrichocorycaeus lubbocki	+++
Genus *Farranula*	*Farranula gibbula*	++
	Farranula concinna	++
	Farranula gracilis	++
	Farranula rostrata	++
	Farranula curta	+
Family Oncaedae		
Genus *Oncaea*	*Oncaea clevei*	++
	Oncaea media	1
	Oncaea paraclevie	+++
	Oncaea venusta	+++
	Oncaea scottodicarloi	+
	Oncaea mediterranea	++
	Oncaea macilenta	+
	Oncaea curta	+
Family Oithonidae		
Genus *Oithona*	*Oithona similis*	++
	Oithona brevicornis	+
	Oithona plumifera	+++
	Oithona nana	+
	Oithona simplex	+
Genus *Dioithona*	*Dioithona rigida*	++
	Dioithona oculata.	++

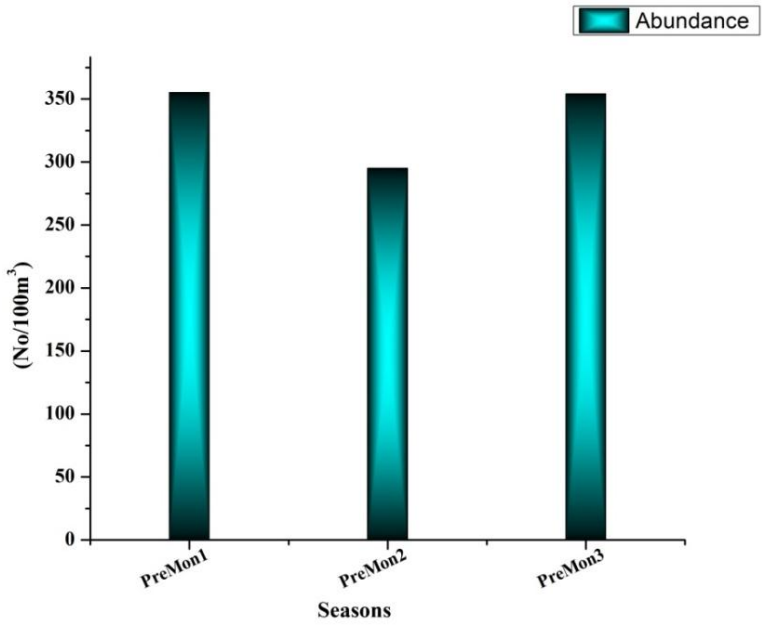


Fig.5.24 Variation in cyclopoid abundance in premonsoon at lagoon stations of Agatti during 2014-15

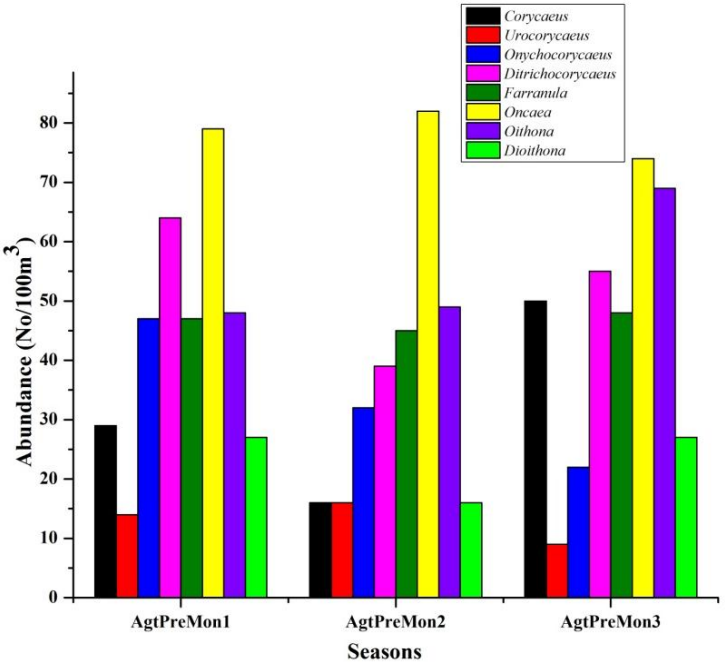


Fig.5.25 Transect wise abundance of major cyclopoid genera in premonsoon at lagoon stations of Agatti during 2014-15

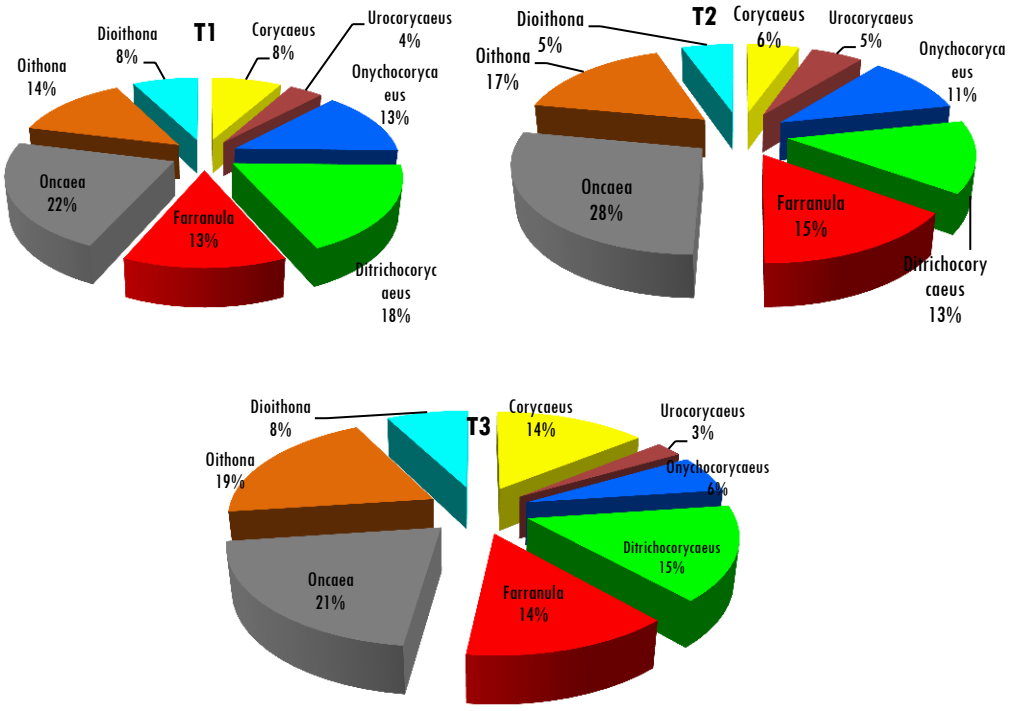


Fig.5.26 Transect wise percentage composition of cyclopoid genus in premonsoon at lagoon stations of Agatti during 2014-15

Total of thirty six species were identified during premonsoon season in Bangaram during 2014-15 (Table.5).Total abundance of cyclopoid copepods varied among transects and ranged between 213 to 932 No/100m^3 (av.617± 368no/100m^3) (Fig.5.27).

Onychocorycaeus was the most abundant cyclopoid genus with an abundance ranging between 47 to 229 No/100m^3 followed by *Ditrichocorycaeus* (22 to 148 No/100m^3), *Farranula* (42 to 126No/100m^3), *Corycaeus*(20 to 129 No/100m^3), *Oncaea* (40 to 117 No/100m^3), *Dioithona* (10 to 48 No/100m^3) and the least by *Urochocorycaeus* (10 to 38 No/100m^3) (Fig.5.28).Corycaedaea family was found to be the most abundant and diverse with 21spp. Oncaeadae species was the next diverse genera with 8 spp and Oithonidae being the least (7spp).

In Bangaram, coral area was characterized by the dominance of the genus *Onychocorycaeus* (25%) followed by *Ditrichocorycaeus* (16%), *Corycaeus* (14%), *Farranula* and *Oncaea* (14%) whereas *Oithona* (10%), *Dioithona* (5%) and

Urocorycaeus (4%) were the least. Inner lagoon (T2) was characterized by the dominance of the genus *Ditrichocorycaeus* (21%), *Onychocorycaeus* (18%), *Farranula* (16%), *Corycaeus* (14%), *Oncaea* (11%), *Oithona* and *Dioithona* (8%) whereas *Urocorycaeus* (4%) was the least. However in boat channel (T3) also genus *Onychocorycaeus* (22%) dominated followed by *Farranula* (20%) *Oncaea* (19%), *Ditrichocorycaeus* (10%), *Oithona* (10%), *Corycaeus* (9%) and *Urocorycaeus* whereas *Dioithona* was the least (5%) (Fig.5.29). *F.gracilis* was the most dominated cyclopoid species and the least being *O.media*,*C.clausi*.However *U.lautus* that were absent in Bangaram.

From Kavaratti 2014-15 during premonsoon period, thirty five cyclopoid species were identified (Table.6**)**.Total abundance of cyclopoid copepods varied among stations and ranged between 59 to 563No/100m^3(av.301±253 No/100m^3) (Fig.5.30).*Onychocorycaeus* was the most abundant cyclopoid genus with an average abundance ranging between 14 - 102 No/100m^3 followed by *Corycaeus* (6 to 108No/100m^3), *Ditrichocorycaeus* (11 to 120No/100m^3), *Oncaea* (3 to 107 No/100m^3), *Farranula* (12 to 56 No/100m^3) and *Oithona* (4 to 22 No/100m^3), *Dioithona* (2 to 25 No/100m^3) and the least by *Urochorycaeus* (1 to 23 No/100m^3) **(**Fig.5.31).Corycaedaea family was found to be the most abundant and diverse with 22spp. Oncaeadae species was the next diverse genera with 6spp and Oithonidae being the least (6spp).Here all the transects was dominated by *Onycochorycaeus* and the least by *Urocorycaeus* (Fig.5.32). *C.speciosus* was the most dominated cyclopoid species and the least being *O.brevicornis*. *O.macilenta, O.similis, O.media* but *F.curta* was absent in Kavaratti during 2014-15.

Table.5 Cyclopoid copepod species recorded in Bangaram during 2014-2015

	Cyclopoids	**Premonsoon**
Family Corycaedae		
Genus *Corycaeus*	*Corycaeus crassiusculus*	+++
	Corycaeus speciosus	+++
	Corycaeus clausi	-
	Corycaeus vitreus	++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	++
	Urocorycaeus lautus	-
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	+++
	Onychocorycaeus agilis	++
	Onychocorycaeus giesbrechti	++
	Onychocorycaeus latus	+++
	Onychocorycaeus pumilus	+++
	Onychocorycaeus pacificus	+++
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	++
	Ditrichocorycaeus affinis	+++
	Ditrichocoryceus dahli	+++
	Ditrichocoryceus tenius	++
	Ditrichocorycaeus subulatus	++
	Ditrichocorycaeus lubbocki	++
Genus *Farranula*	*Farranula gibbula*	+++
	Farranula concinna	++
	Farranula gracilis	+++
	Farranula rostrata	++
	Farranula curta	+
Family Oncaedae		
Genus *Oncaea*	*Oncaea clevei*	++
	Oncaea media	+
	Oncaea paraclevie	++
	Oncaea venusta	+
	Oncaea scottodicarloi	+
	Oncaea mediterranea	+
	Oncaea macilenta	+
	Oncaea curta	++
Family Oithonidae		
Genus *Oithona*	*Oithona similis*	+
	Oithona brevicornis	+
	Oithona plumifera	+++
	Oithona nana	+
	Oithona simplex	+
Genus *Dioithona*	*Dioithona rigida*	+++
	Dioithona oculata.	+

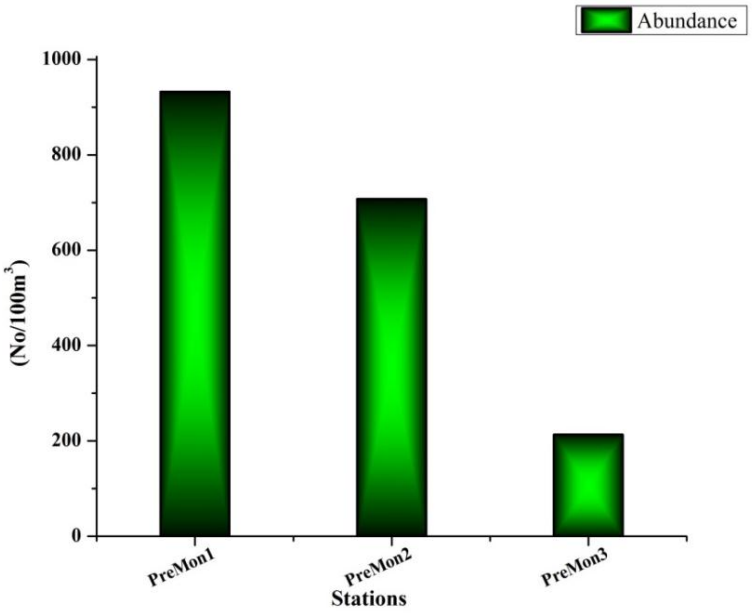


Fig.5.27 Variation in cyclopoid abundance in premonsoon at lagoon stations of Bangaram during 2014-15

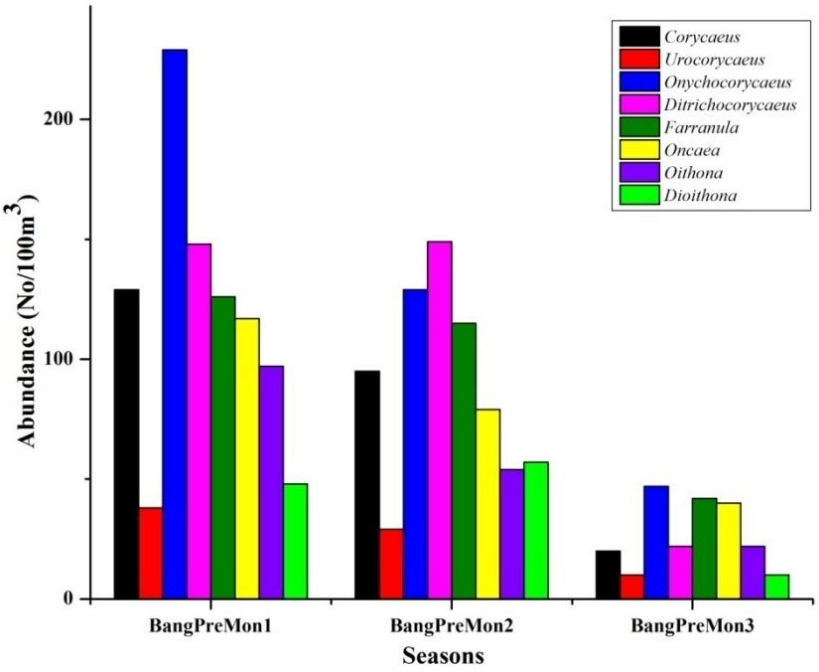


Fig.5.28 Transect wise abundance of major cyclopoid genera in premonsoon at lagoon stations of Bangaram during 2014-15

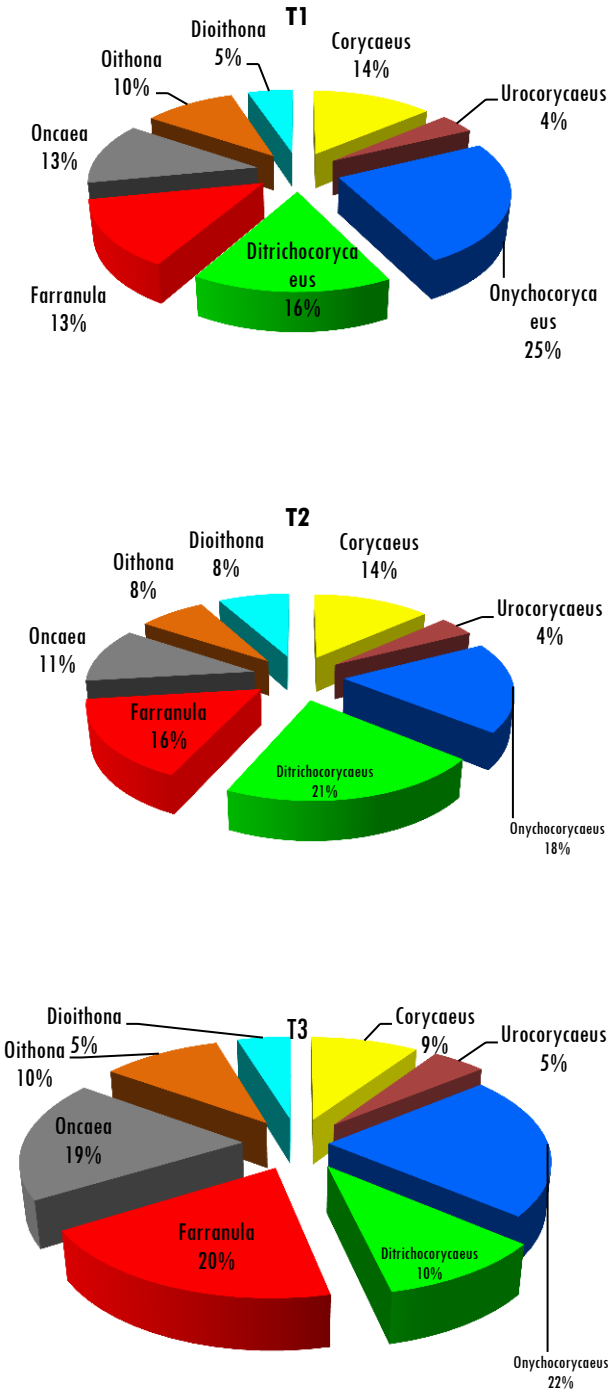


Fig.5.29 Transect wise percentage composition of cyclopoid genus in premonsoon at lagoon stations of Bangaram during 2014-15

Table.6 Cyclopoid copepod species recorded at Kavaratti during 2014-2015.

	Cyclopoids	Premonsoon
Family Corycaedae	*Corycaeus crassiusculus*	++
Genus *Corycaeus*	*Corycaeus speciosus*	+++
	Corycaeus clausi	+
	Corycaeus vitreus	++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	++
	Urocorycaeus lautus	+
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	+
	Onychocorycaeus agilis	+++
	Onychocorycaeus giesbrechti	++
	Onychocorycaeus latus	+
	Onychocorycaeus pumilus	+++
	Onychocorycaeus pacificus	+
Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	+
	Ditrichocorycaeus affinis	++
	Ditrichocoryceus dahli	++
	Ditrichocoryceus tenius	++
	Ditrichocorycaeus subulatus	++
	Ditrichocorycaeus lubbocki	++
Genus *Farranula*	*Farranula gibbula*	++
	Farranula concinna	++
	Farranula gracilis	++
	Farranula rostrata	+++
	Farranula curta	-
Family Oncaedae	*Oncaea clevei*	+
Genus *Oncaea*	*Oncaea media*	-
	Oncaea paraclevie	+
	Oncaea venusta	++
	Oncaea scottodicarloi	++
	Oncaea mediterranea	++
	Oncaea macilenta	-
	Oncaea curta	+
	Oithona similis	-
Family Oithonidae	*Oithona brevicornis*	+
Genus *Oithona*	*Oithona plumifera*	+
	Oithona nana	++
	Oithona simplex	++
Genus *Dioithona*	*Dioithona rigida*	++
	Dioithona oculata.	++

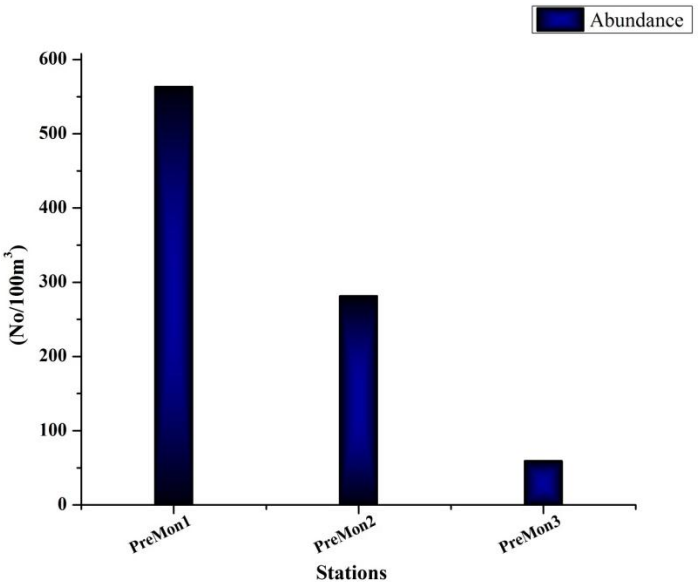


Fig.5.30 Variation in cyclopoid abundance in premonsoon at lagoon stations of Kavaratti during 2014-15

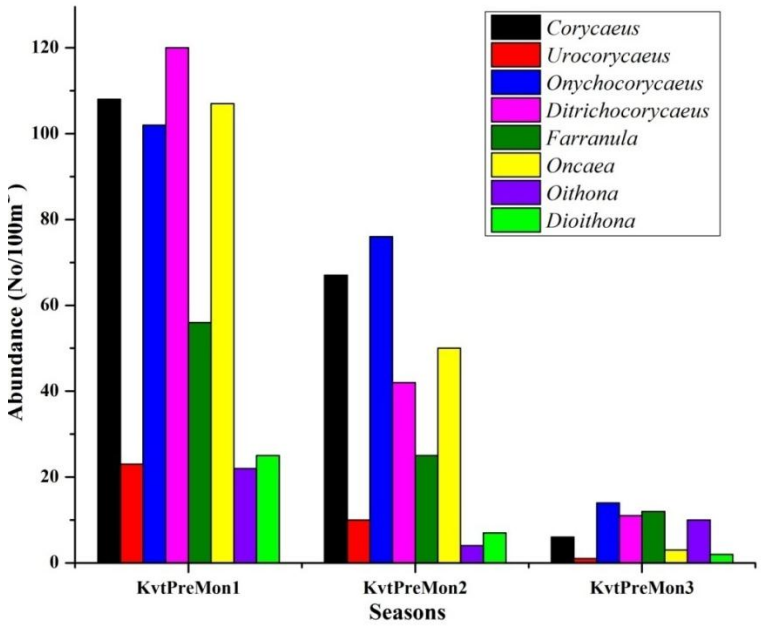


Fig.5.31 Transect wise abundance of major cyclopoid genera in premonsoon at lagoon stations of Kavaratti during 2014-15.

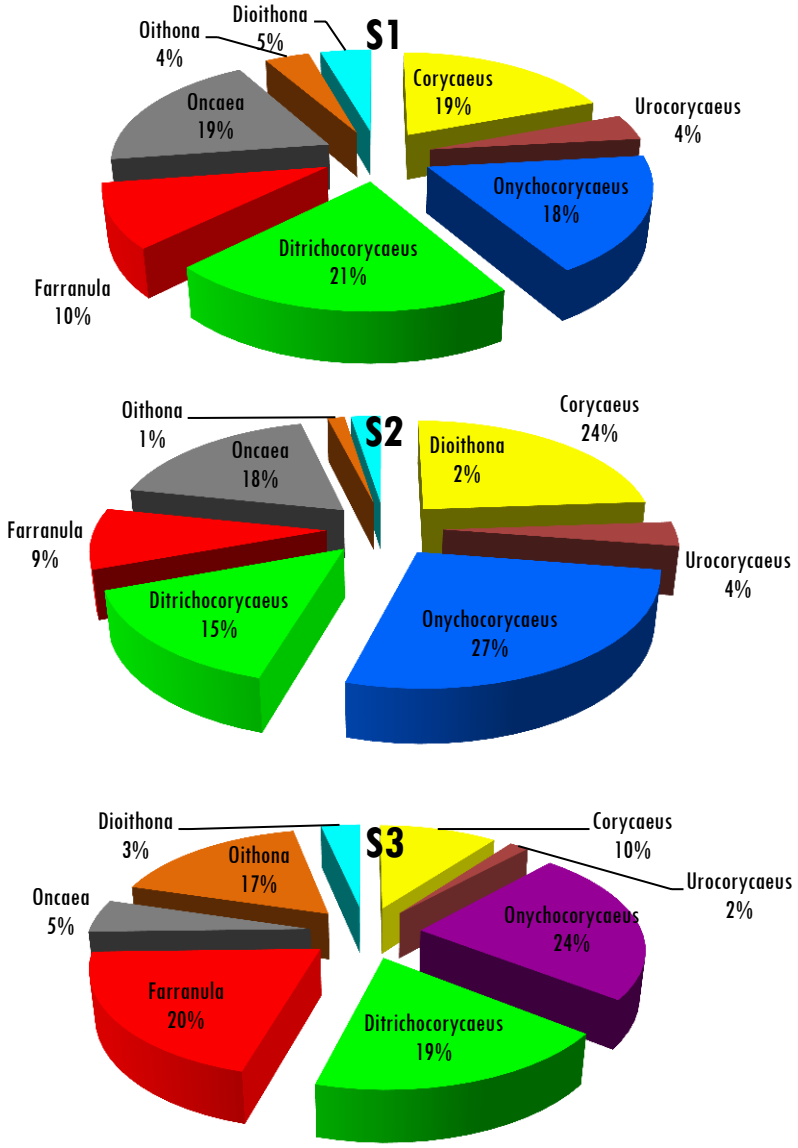


Fig.5.32 Transect wise percentage composition of cyclopoid genus in premonsoon at lagoon stations of Kavaratti during 2014-15.

5.6 Cyclopoid abundance and diversity of open ocean stations

Fifty one cyclopoid species belonging to four families and seven genera were identified (Table.7).Total abundance of cyclopoid copepods varied among stations and ranged between 310 (S5) to 1680 No/100m^3 (S18) (av.700±386 No/100m^3) (Fig.5.33). *Sapphirina* formed the most abundant cyclopoid genus with an average abundance of 97 to 565 No/100m^3 followed by *Copilia* (22 to 190 No/100m^3), *Oncaea* (27 to 155No/100m^3), *Onychocorycaeus* (21 to 120 No/100m^3), *Corycaeus* (22 to 129No/100m^3), *Oithona* (13 to 127 No/100m^3),

Ditrichocorycaeus (29 to 181 No/100m^3), *Farranula* (14 to 123 No/100m^3), *Dioithona* (4 to 73 No/100m^3) and *Urocorycaeus* (1 to 66 No/100m^3)(Fig.5.34).The most diverse family was Corycaedaea (23spp.)followed by Sapphirinidae family that formed the next diverse one with 13 spp. Oncaedae having (8spp.) and Oithonidae being the least (6spp.).Station wise percentage composition of cyclopoid genus during premonsoon at Minicoy open ocean stations is shown in Fig.5.35. Open ocean zones of Minicoy were characterized by the dominance of the genus *Sapphirina* (34%) followed by *Copilia* (13%), *Onychocorycaeus* and *Oncaea* (10%), *Corycaeus* (7%), *Ditrichocorycaeus* (6%), *Farranula* (4%), *Oithona* (4%), *Dioithona* (4%) and *Urocorycaeus* (4%).

The open ocean cyclopoid community of Minicoy was dominated by Sapphirinid species of which the most abundant was *S.auronitens* and least was *S.scarlata*. Among the Corycaeids, *O.pumilus* was the most abundant species and the least being *D.lubbocki.* From the genus *Copilia*, the most abundant species was found to be *C.hendorffi* and the least being *C.quadrata*. Among the genus Oncaea, *O.mediterranea* formed the most abundant and the least being O.*media*. From the Oithonids, *O.plumifera* was the most abundant species and the least being *O.brevicornis.* When total abundance was compared, *C.hendorffi* was the most abundant species and *O.brevicornis*, the least from the Minicoy open ocean during the present study.

Table.7 Cyclopoid copepod species recorded at Minicoy open ocean during 2014-2015

	Cyclopoids	**Premonsoon**
Family Corycaedae		
Genus *Corycaeus*	*Corycaeus crassiusculus*	++
	Corycaeus speciosus	++
	Corycaeus clausi	++
	Corycaeus vitreus	++
Genus *Urocorycaeus*	*Urocorycaeus furcifer*	++
	Urocorycaeus lautus	++
Genus *Onychocorycaeus*	*Onychocorycaeus catus*	++
	Onychocorycaeus agilis	++
	Onychocorycaeus giesbrechti	++
	Onychocorycaeus latus	++
	Onychocorycaeus pumilus	++
	Onychocorycaeus pacificus	++

Genus *Ditrichocorycaeus*	*Ditrichocoryceus andrewsi*	++
	Ditrichocorycaeus affinis	++
	Ditrichocoryceus dahli	++
	Ditrichocoryceus tenius	++
	Ditrichocorycaeus subulatus	++
	Ditrichocorycaeus lubbocki	+
Genus *Farranula*	*Farranula gibbula*	++
	Farranula concinna	++
	Farranula gracilis	++
	Farranula rostrata	++
	Farranula curta	++
Family Oncaedae		
Genus *Oncaea*	*Oncaea clevei*	++
	Oncaea media	++
	Oncaea paraclevie	++
	Oncaea venusta	++
	Oncaea scottodicarloi	++
	Oncaea mediterranea	++
	Oncaea macilenta	++
	Oncaea curta	++
Family Oithonidae		
Genus *Oithona*	*Oithona similis*	++
	Oithona brevicornis	+
	Oithona plumifera	++
	Oithona nana	++
	Oithona simplex	++
Genus *Dioithona*	*Dioithona rigida*	++
	Dioithona oculata.	++
Family Sapphirinidae		
Genus *Sapphirina*	*Sapphirina angusta*	++
	Sapphrina auronitens	+++
	Sapphrirna gastrica	++
	Sapphirina metallina	++
	Sapphirina nigromaculata	+++
	Sapphirina opalina	+++
	Sapphirina scarlata	++
	Sapphirina stellata	++
	Sapphirina siniuicauda	+++
	Sapphrina vorax	++
Genus *Copilia*	*Copilia mirabilis*	+++
	Copilia hendorffi	+++
	Copilia quadrata	+++

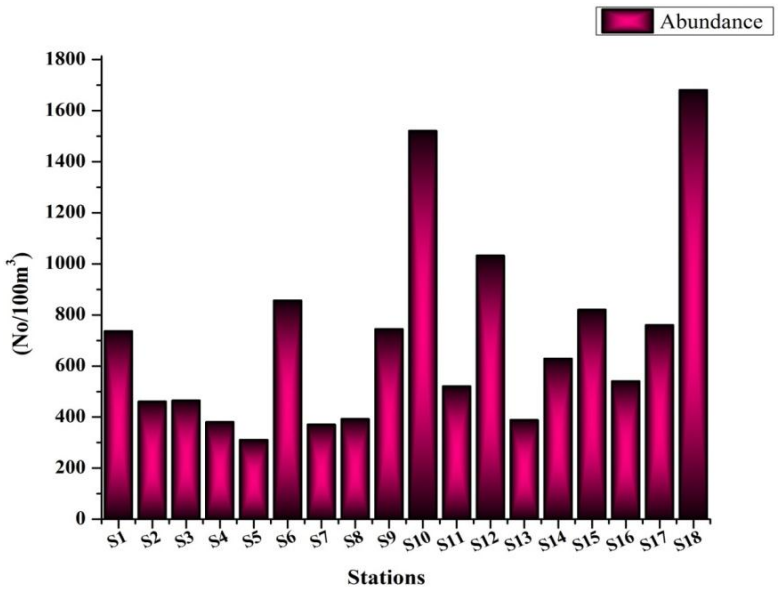


Fig.5.33 Station wise variation in abundance of cyclopoids of open ocean stations in Minicoy during 2015

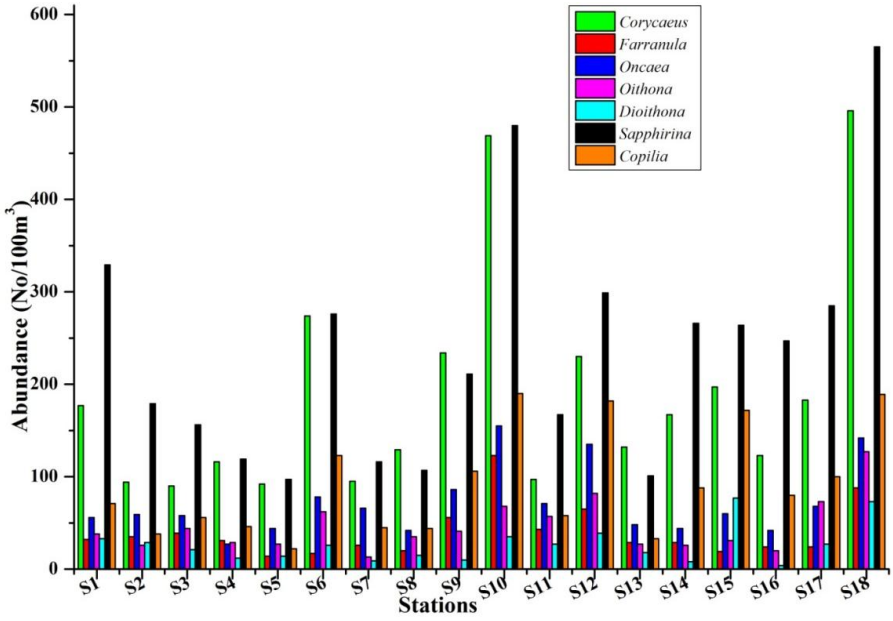


Fig.5.34 Station wise variation in abundance of major cyclopoid genera of open ocean stations in Minicoy during 2015

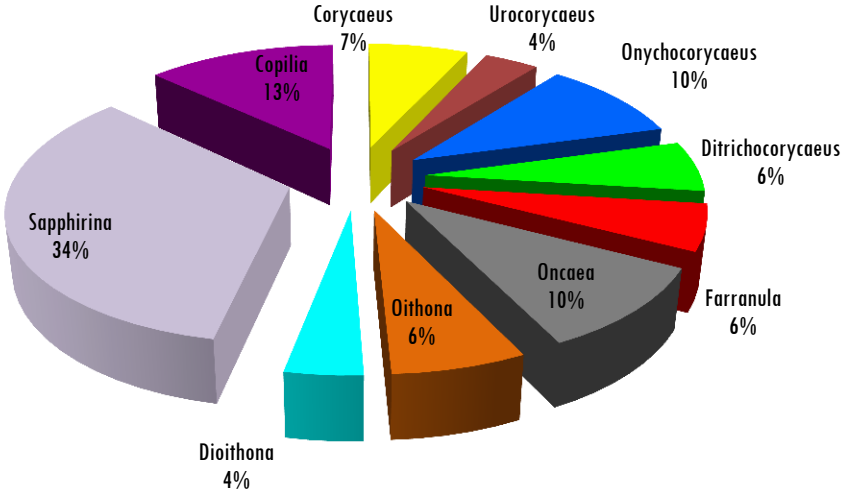


Fig.5.35 Station wise percentage composition of cyclopoid genus in premonsoon at Minicoy open ocean stations during 2015

5.7 Community structure of cyclopoids

5.7.1 Univariate analyses of cyclopoid community structure in lagoon stations

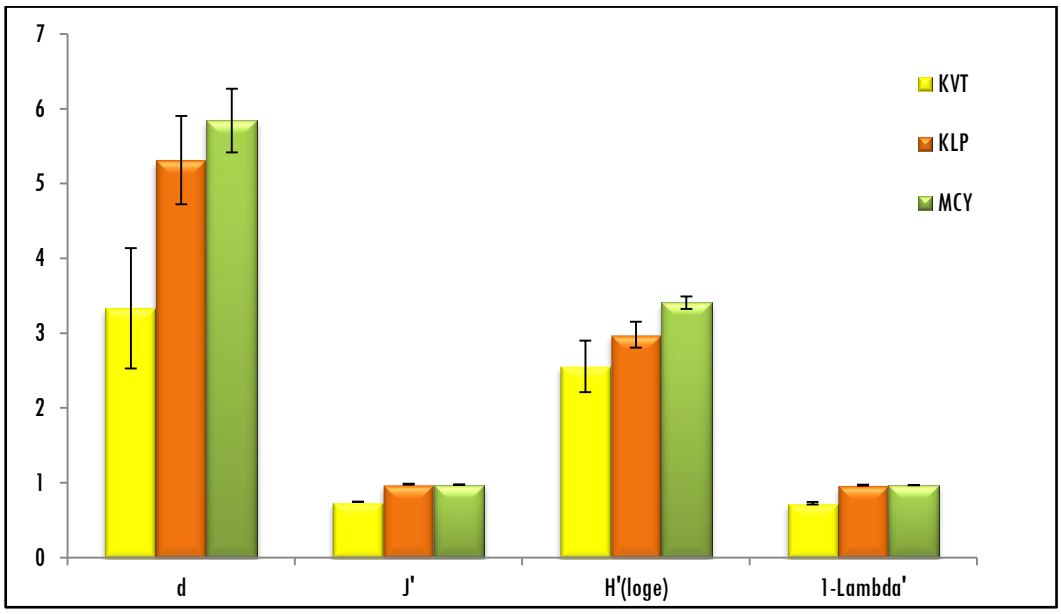


Fig.5.36 Diversity indices of cyclopoid copepods of lagoon stations of Kavaratti, Kalpeni and Minicoy during 2013-14.

In the first year, Minicoy represented the maximum value for Margalef species richness index (5.841), Shanon diversity index (3.408) and Simpson's dominance index (0.969) whereas Kalpeni registered maximum Pielou's evenness index (0.979). But Kavaratti represented the minimum value for Margalef species

richness index (3.246), Shanon index (2.664), Simpson's index (0.797) and Pielou's index(0.827) (Fig.5.36).However during the second year, Bangaram registered maximum value for Margalef index (6.862), Shanon index (3.445), Simpson's index (0.974) and Pielou's index(0.977) while Kavaratti having the minimum values for Margalef index (6.437), Shanon index (3.245), Simpson's index (0.973) and Pielou's index (0.971) (Fig.5.37).

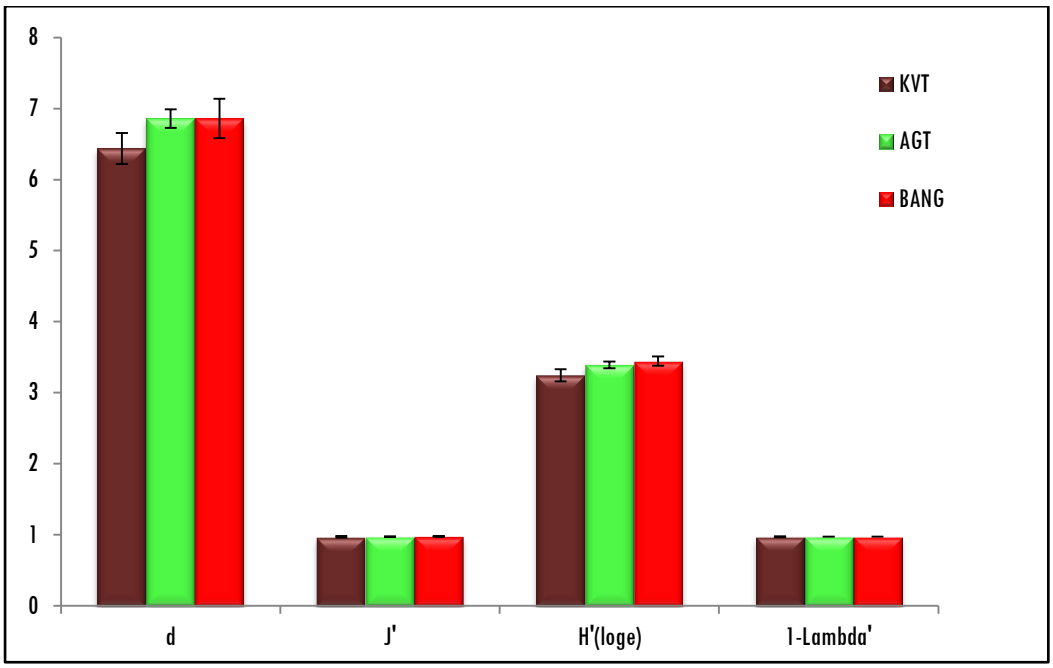


Fig.5.37 Diversity indices of cyclopoid copepods of lagoon stations of Kavaratti, Kalpeni and Minicoy during 2014-15.

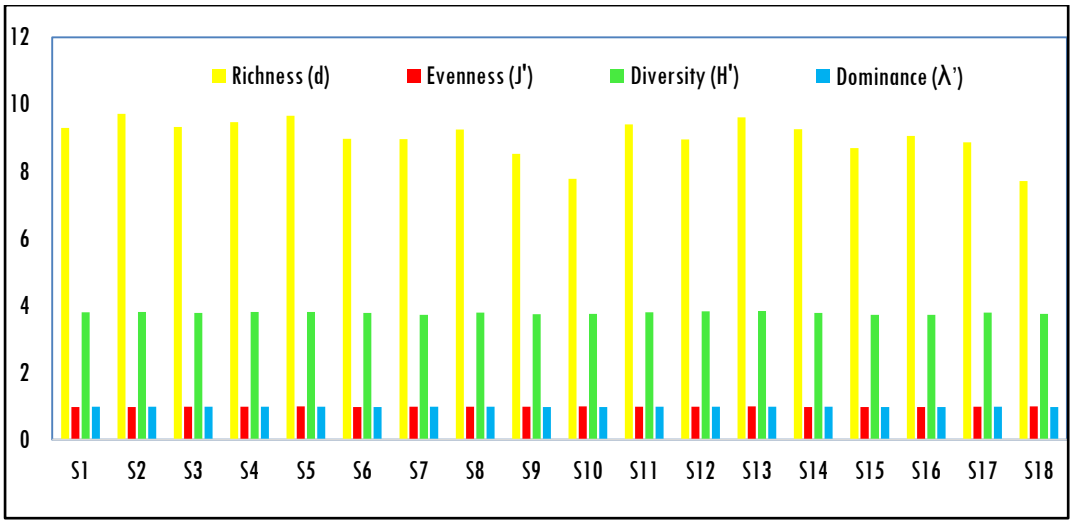


Fig.5.38 Diversity indices of cyclopoid copepods of open ocean zones of Minicoy during 2014-15

5.7.2 Univariate analyses of cyclopoid community structure of Minicoy open ocean stations

The maximum richness was recorded in S2(d=9.72) and the least in S18 (d=7.71).The evenness based on cyclopoid species was high in S5,S8,S10,S13,S18 **(J'=0.99)** and the least in S15 **(J'=0.972)**. Whereas Shannon diversity was higher in S13 (H'=3.83) and the least diversity was shown by S7 (H'=3.724). When dominance of cyclopoid species in Minicoy was compared, almost all stations showed more or less equal dominance of 0.98.The lowest of 0.97 was shown by three stations (S10, S15, S18)(Fig.5.38).

5.7.3 Multivariate analysis of cyclopoid community structure of lagoons

a. Cluster analysis

Bray Curtis analysis was carried out to analyze the similarity between transects and seasons based on numerical abundance of mesozooplankton. In Kavaratti during 2013-14, dendrogram based on numerical abundance of mesozooplankton showed that the seasons were apart with more than 70% similarity. However the transects of monsoon season showed 93% similarity whereas transects of postmonsoon and premonsoon seasons showed more than 95% similarity. Whereas in MonT2 and T3 showed 93% similarity;MonT1 and PreMon T2 stood apart from that with 78% and 69% similarity respectively. PoMonT3 and T2 were clustered under 95% similarity and PreMon T1andT3 under 91% similarities (Fig.5.39).Dendrogram based on numerical abundance of cyclopoid species depicted two significant clusters.MonT1 and PreMonT2 formed part of the first cluster with more than 75% similarity. But the MonT2 and MonT3 stood apart. PoMonT3 and PoMonT1 clustered together with more than 80% similarity while PreMonT3 and PreMonT1 formed another cluster with more than 90% similarity.PoMonT2 stood apart from the second main cluster (Fig.5.40).

In Kalpeni during 2013-14, the Bray Curtis similarity based on numerical abundance of mesozooplankton showed that both seasons were apart with only 42% similarity. However the transects of both the seasons showed more than 90% similarity (Fig.5.41).Dendrogram based on cyclopoid abundance depicted PoMonT2 and T1 clustered together with 70% similarity while MonT1 and T2 stood apart (Fig.5.42).

In Minicoy during 13-14, dendrogram based on mesozooplankton abundance depicted two main clusters set apart with only 62% similarity (Fig.5.43).Dendrogram based on cyclopoid abundance also showed both seasons being set apart (Fig.5.44).

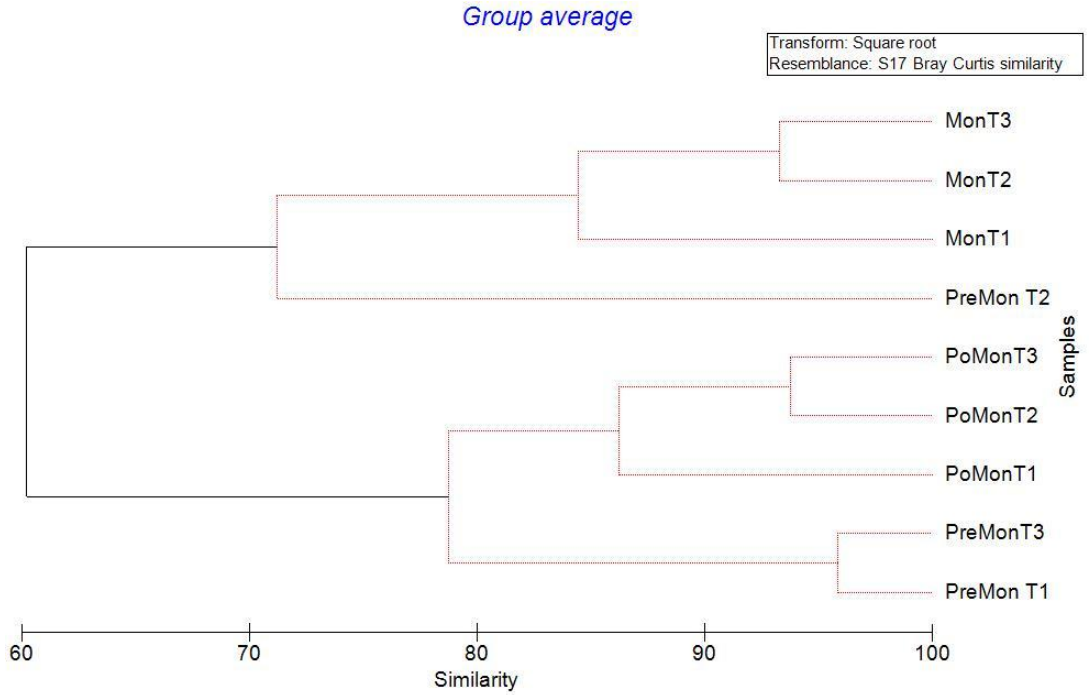


Fig.5.39 Dendrogram of numerical abundance of mesozooplankton showing similarities in Kavaratti lagoon during 2013-14

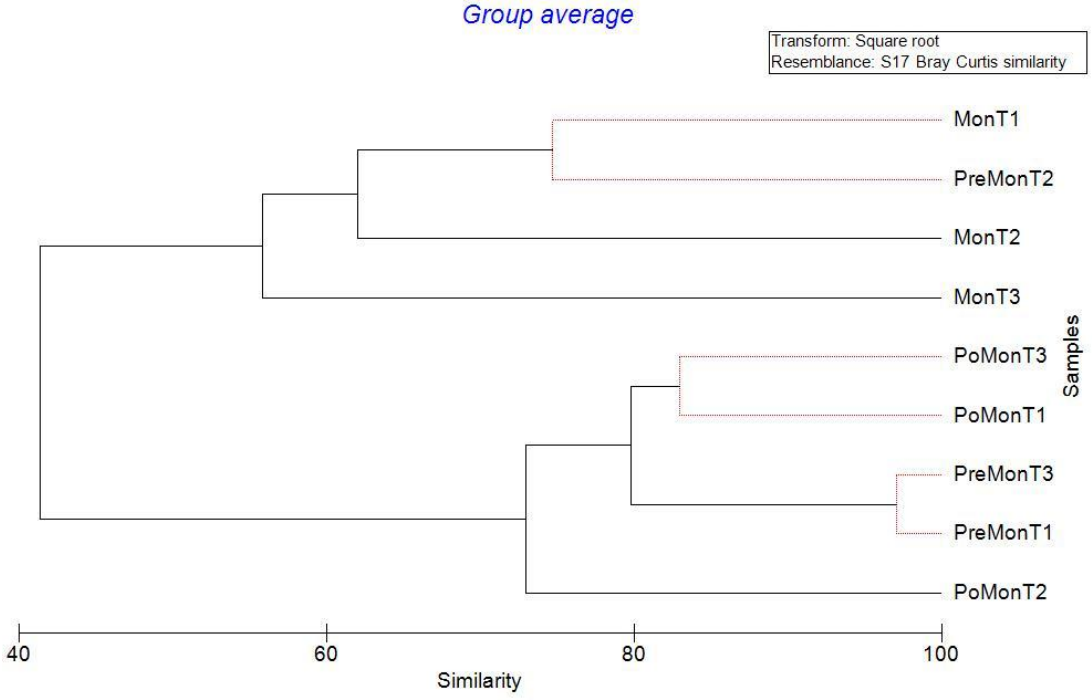


Fig.5.40 Dendrogram showing numerical abundance of cyclopoid species showing similarities in Kavaratti lagoon during 2013-14

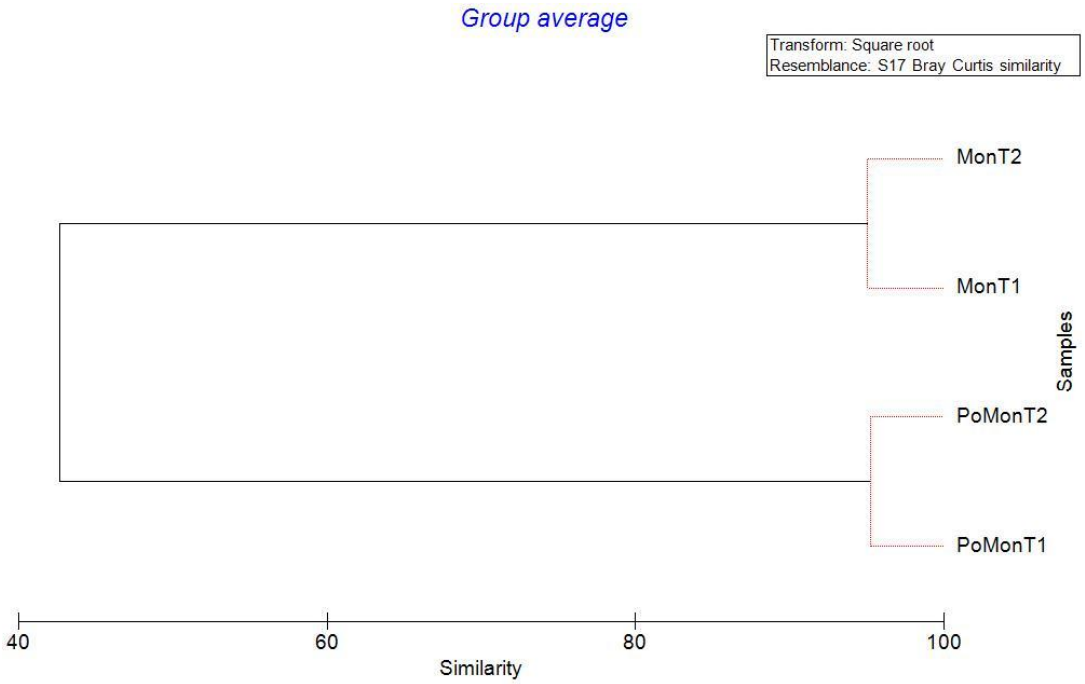


Fig.5.41 Dendrogram of numerical abundance of mesozooplankton showing similarities in Kalpeni lagoon during 2013-14

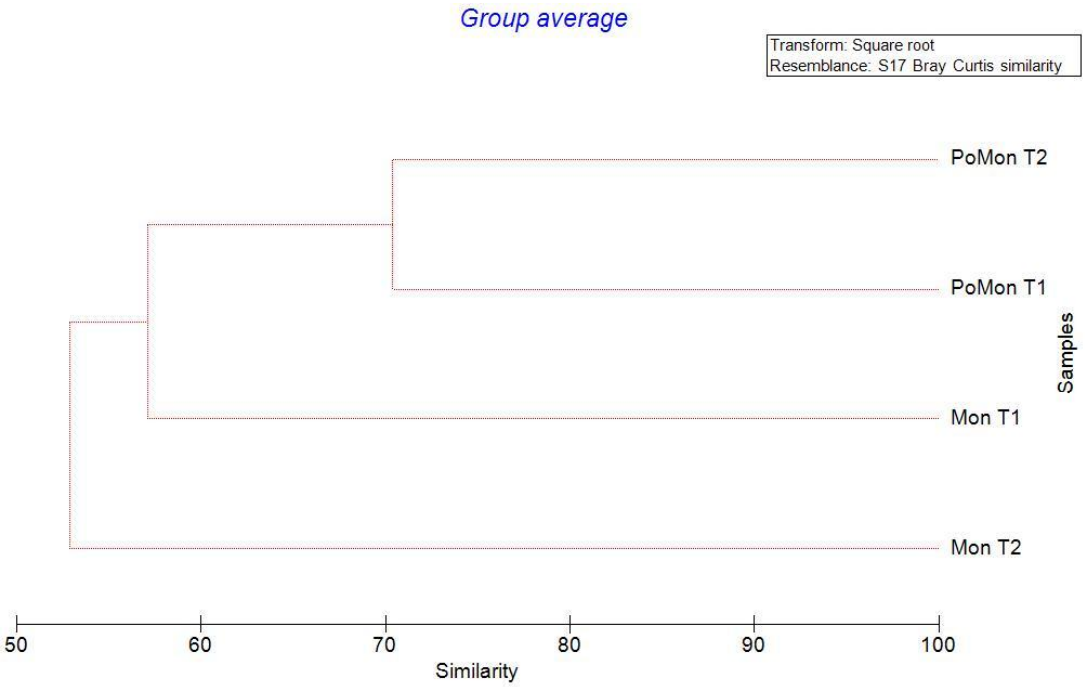


Fig.5.42 Dendrogram showing numerical abundance of cyclopoid species showing similarities in Kalpeni lagoon during 2013-14

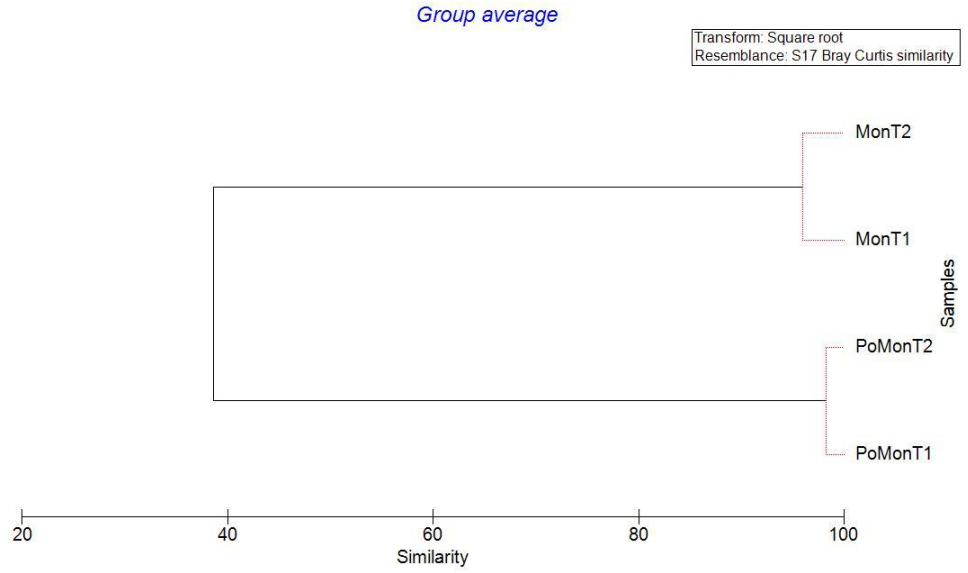


Fig.5.43 Dendrogram of numerical abundance of mesozooplankton showing similarities in Minicoy lagoon during 2013-14

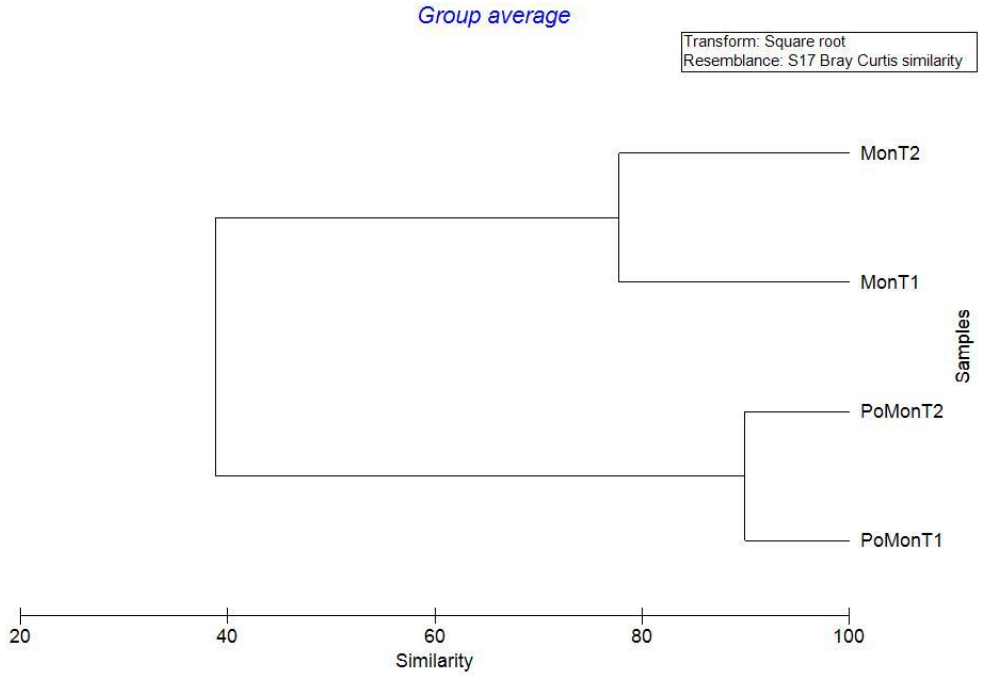


Fig.5.44 Dendrogram showing numerical abundance of cyclopoid species showing similarities in Minicoy lagoon during 2013-14.

In Agatti, Kavaratti and Bangaram during 2014-15, similarity based on numerical abundance of mesozooplankton groups showed three main clusters. BangPreMonT3,T2 (Bangaram premonsoon) were clustered together with 86% similarity forming one main cluster. AgtPreMon (Agatti premonsoon) T1 T2, T3, formed the next cluster with 95% similarity from which KvtPreMon (Kavaratti

premonsoon) T3 stood apart. Bang PreMonT1 also fell apart from these two main clusters. KvtPreMonT2, T1 were clustered next with 88% similarity (Fig.5.45).While dendrogram based on cyclopoid abundance showed two transects (T1 and T2) of Agatti clustering together while AgtT3 and BangT3 stood apart. BangPreMonT2 and T1 formed the next cluster with more than 85% similarity from which KvtT1 and KvtT2 stood apart. KvtT3 clustered individually (Fig.5.46).

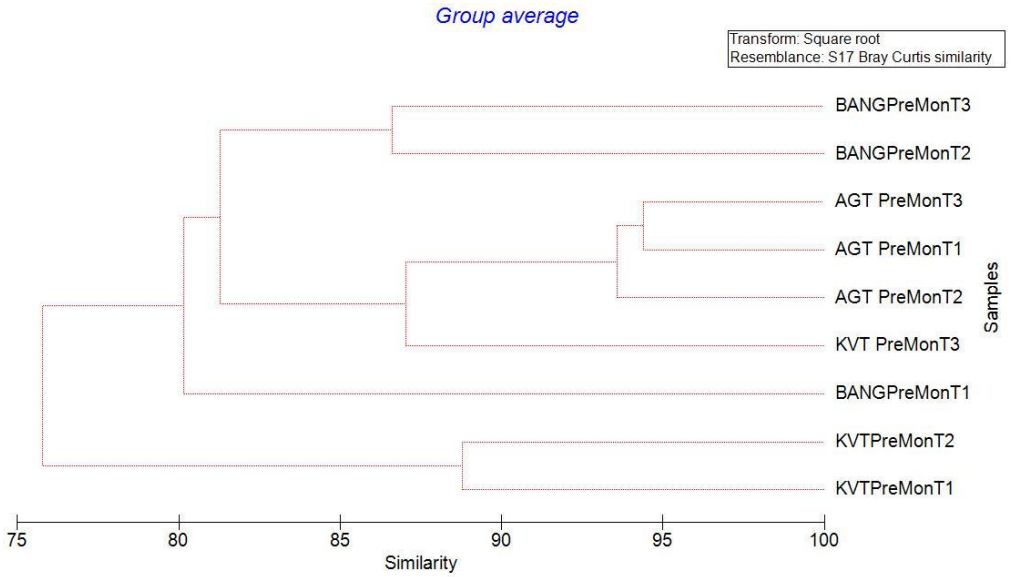


Fig.5.45 Dendrogram of numerical abundance of mesozooplankton showing similarities in Agatti. Kavaratti, Bangaram during 2014-15

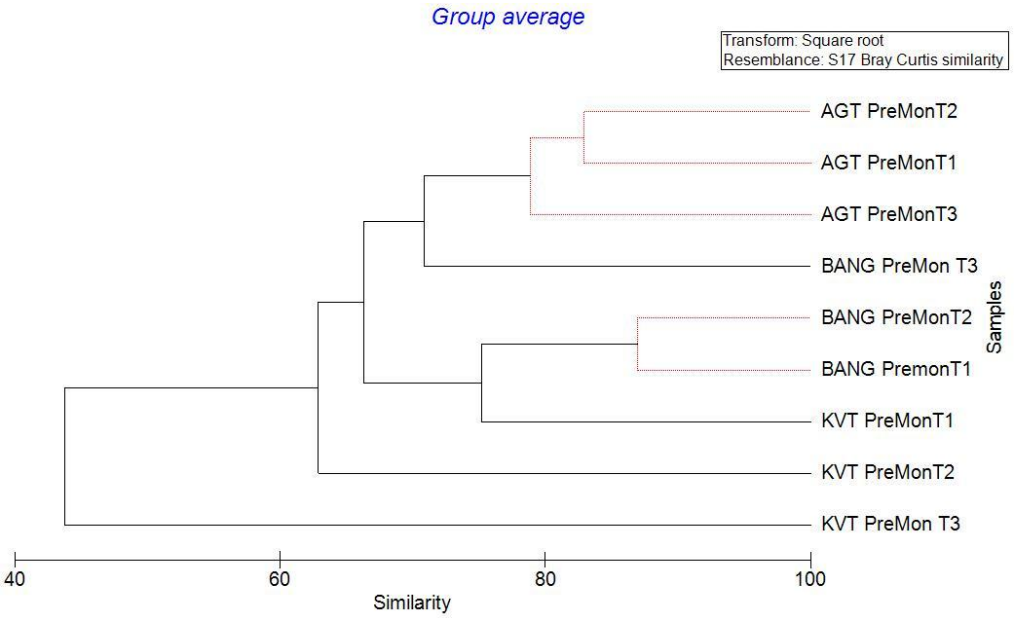


Fig.5.46 Dendrogram showing numerical abundance of cyclopoid species showing similarities in Agatti. Kavaratti, Bangaram during 2014-15

a. MDS plots (Non metric - Multi Dimensional Scaling)

MDS plots of Kavaratti during 2013-14 with respect to numerical abundance of mesozooplankton gave a good ordination having the stress value of 0.01 forming four clusters (Fig.5.47). PoMonT1, T2, T3 were clustered under 80% similarity.PreMonT1, T3 too were clustered under 80% similarity. Mon T1, T2 and T3 formed another cluster with 80% similarity. Finally, PreMonT2 was clustered individually under 80% similarity. MDS plots for numerical abundance of cyclopoid species gave a good ordination with stress value 0.01 forming three main clusters. PoMonT1, T2, T3, PreMonT1, T3 were clustered together at 60% similarity within which PoMonT1 and T3 showed 80% similarity. MonT1, T2 and PreMonT2 were clustered together at 60%. MonT3 formed an individual cluster with an average of 60% similarity (Fig.5.48). The MDS plots of Kalpeni during 2013-14 showed an average of 20% similarity for all the seasons and transects. Both transects of monsoon and postmonsoon season each were clustered together at 80% similarity (Fig.5.49).MDS plots for numerical abundance of cyclopoid species between transects and seasons of Kalpeni island showed that PoMon T1 & T2 were clustered together with 60% similarity. Whereas Mon T1 and Mon T2 formed separate clusters each with 60% similarity (Fig.5.50).In both plots the stress value was zero.

The MDS plots of Minicoy13-14 with respect to numerical abundance of mesozooplankton showed a good ordination with stress value of zero with an average of 20% similarity for all the seasons and transects. Both transects of monsoon season clustered together at 80% similarity. Similarly both the transects of post monsoon also clustered together at 80%(Fig.5.51).MDS plots for numerical abundance of cyclopoid species between transects and seasons of Minicoy island showed that PoMon T1 and T2 were clustered together with 80% similarity. Whereas Mon T1 and Mon T2 formed another cluster with 80% similarity (Fig.5.52).

The MDS plots of Agatti, Bangaram and Kavaratti during 2014-15 with respect to numerical abundance of mesozooplankton showed two main clusters (Fig.5.53).KvtPreMonT2 and T1 were clustered under 80% similarity. Rest of transects of Bangaram, Agatti and Kavaratti were clustered into one with 80% similarity.The MDS plots for numerical abundance of cyclopoid species Agatti, Bangaram and Kavaratti during 2014-15 included two small clusters with 60% similarity with Kvt PreMon T3 in one cluster and rest of the transects in another cluster (Fig.5.54).

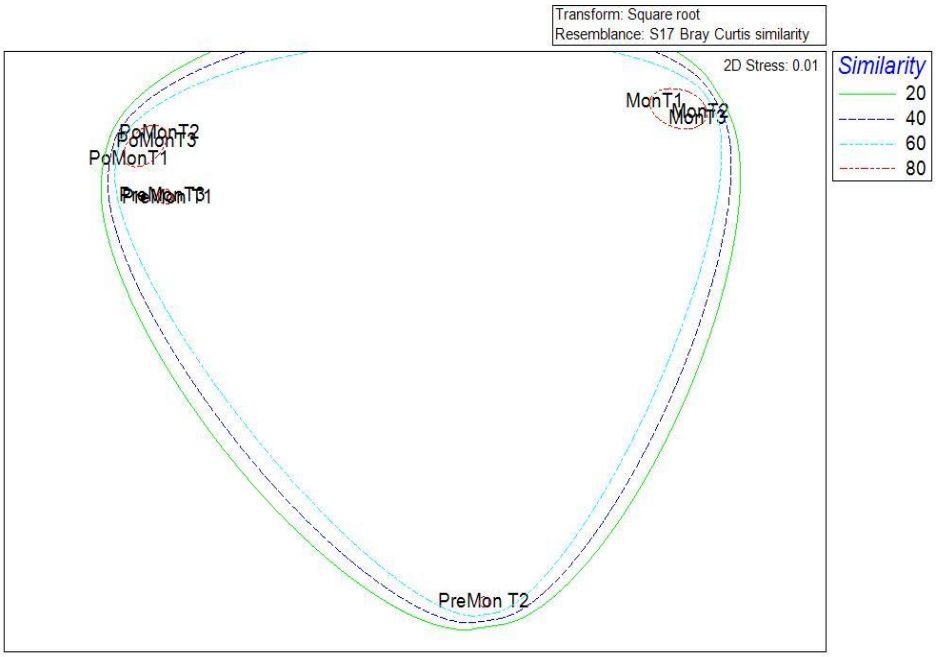


Fig.5.47 MDS ordination plot with respect to the numerical abundance of mesozooplankton groups in Kavaratti during 2013-14.

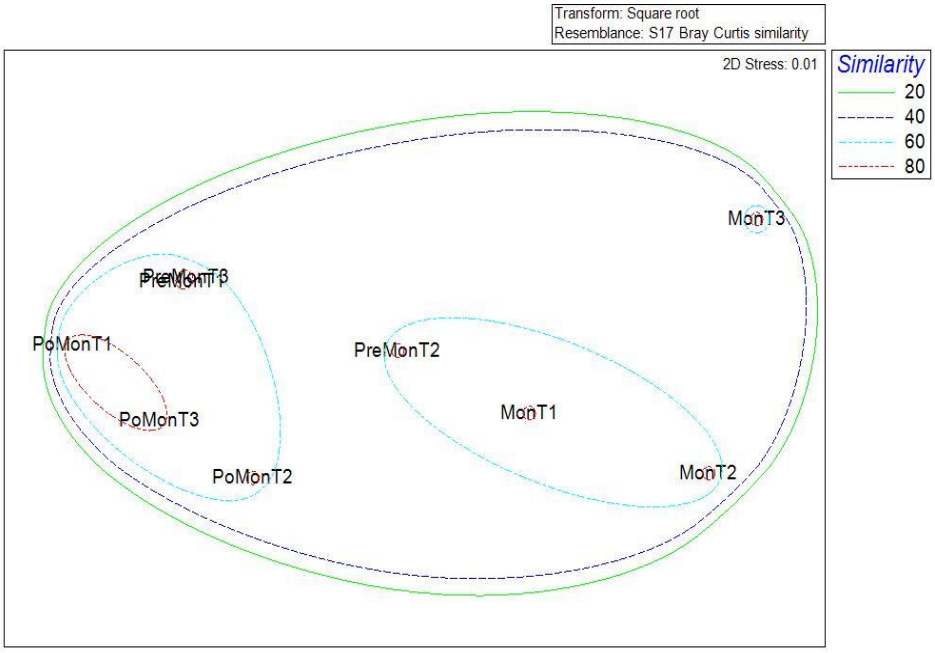


Fig.5.48 MDS ordination plot with respect to the numerical abundance of cyclopoids in Kavaratti during 2013-14.

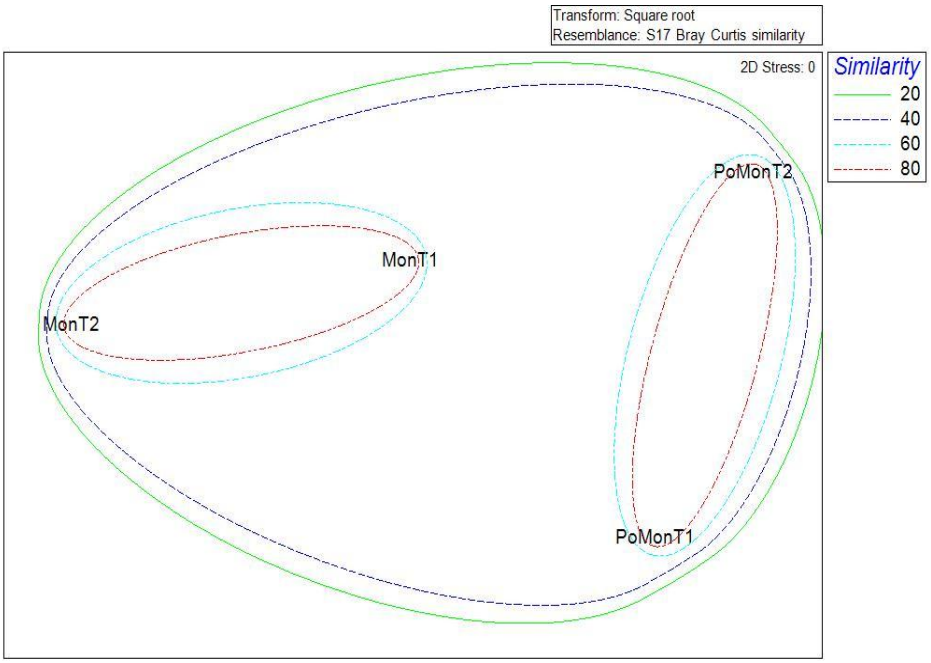


Fig.5.49 MDS ordination plot with respect to the numerical abundance of mesozooplankton groups in Kalpeni during 2013-14

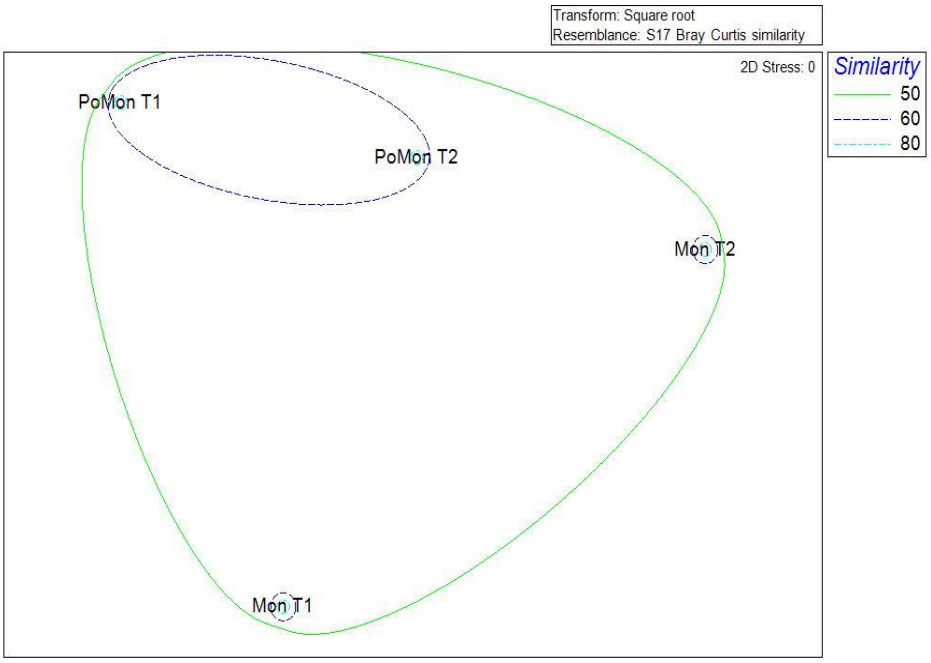
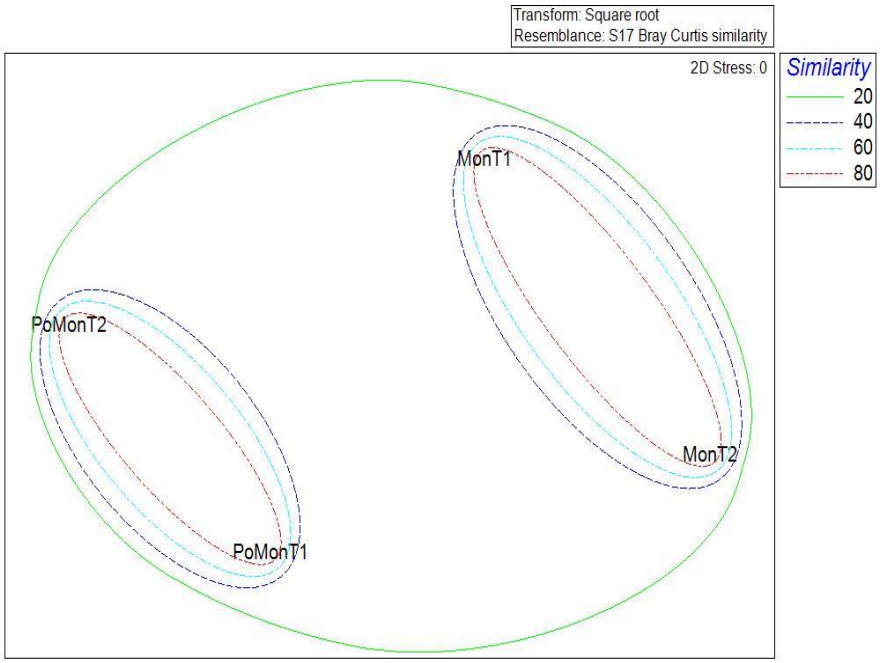


Fig.5.50 MDS ordination plot with respect to the numerical abundance of cyclopoids in Kalpeni during 2013-14.



Fi.5.51 MDS ordination plot with respect to the numerical abundance of mesozooplankton groups in Minicoy during 2013-14.

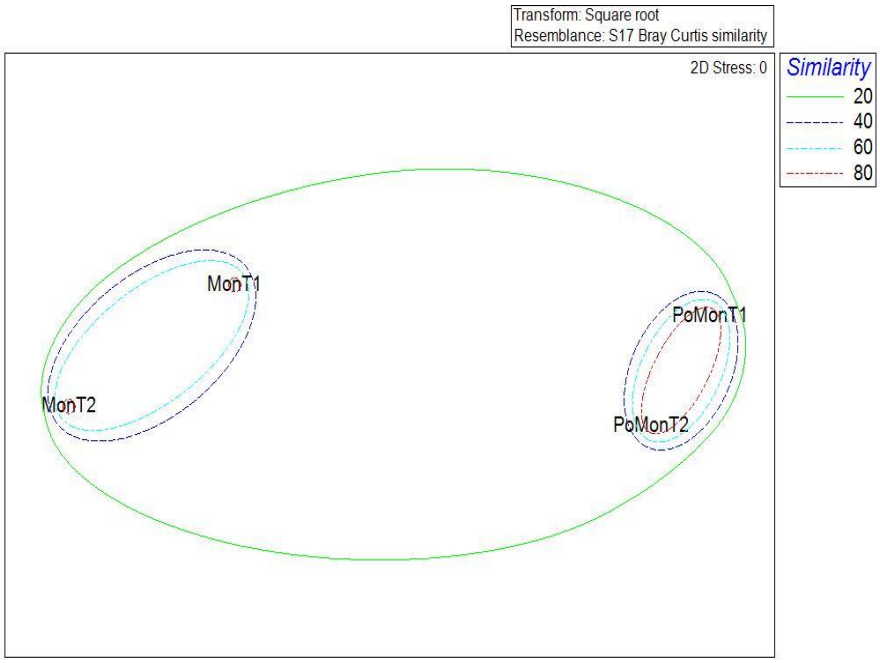


Fig.5.52 MDS ordination plot with respect to the numerical abundance of cyclopoids in Minicoy during 2013-14.

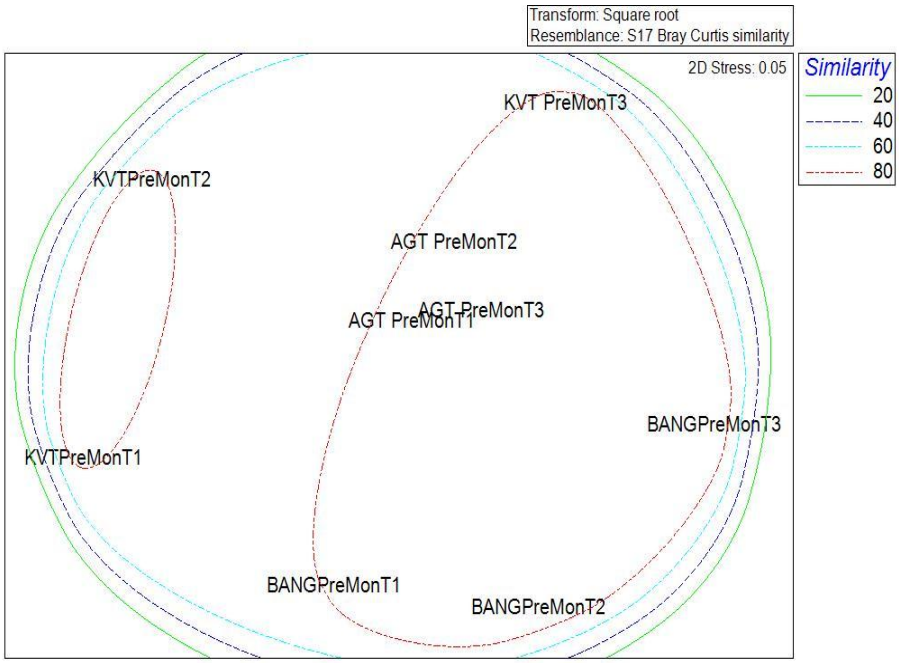


Fig.5.53 MDS ordination plot with respect to the numerical abundance of mesozooplankton groups in Kavaratti, Bangaram, Agatti during 2014-15

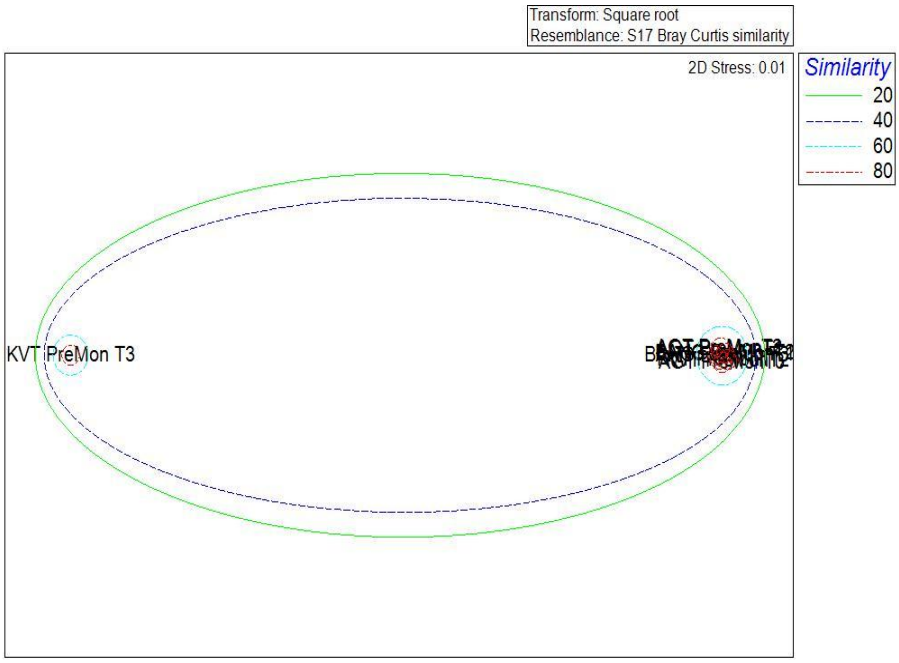


Fig.5.54 MDS ordination plot with respect to the numerical abundance of cyclopoids in Kavaratti, Bangaram, Agatti during 2014-15.

5.7.4 Multivariate analyses of cyclopoid community structure of Minicoy open ocean stations.

In Minicoy open ocean stations, the Bray Curtis analysis based on numerical abundance of mesozooplankton showed S7 (station 7) stood apart with only 70% similarity. However the stations showed more than 80% similarity (Fig.5.55).The MDS plots of Minicoy open ocean during 2014-15 with respect to numerical abundance of mesozooplankton showed three main clusters (Fig.5.57). S6 (Station6) and S2 (Station2) formed first cluster from which S17 and S18 stood apart. S5 (Station5), S3 (Station3), S15 (Station15), S12 (Station12) and S14 (Station14) formed next cluster with 80% similarity from which S9 and S4 stood apart. S15 (Station11), S8 (Station8), S13 (Station13) formed another cluster. S16 (Station16) and S1 (Station1)formed next cluster with more than 85% similarity from which S10 and S4 stood apart.S7 clustered individually. When MDS plots of cyclopoid abundance was compared, S7(Station7), S11(Station11) and S15(Station15) were clustered as single units and rest of the stations were clustered as six groups each with 80% similarity(Fig.5.58).

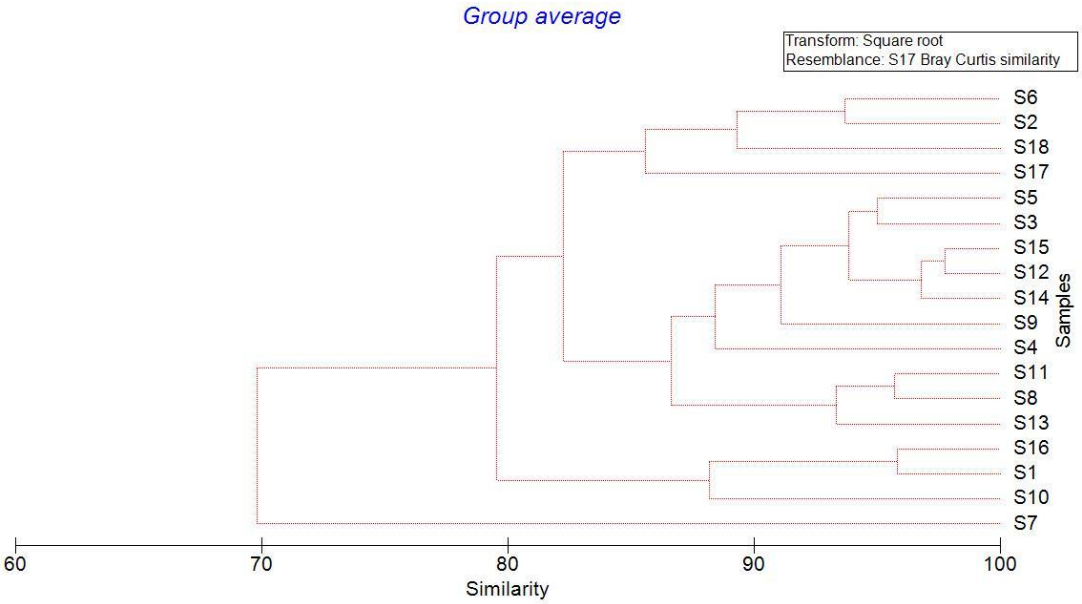


Fig.5.55 Dendrogram of numerical abundance of mesozooplankton showing similarities in open ocean of Minicoy during 2015

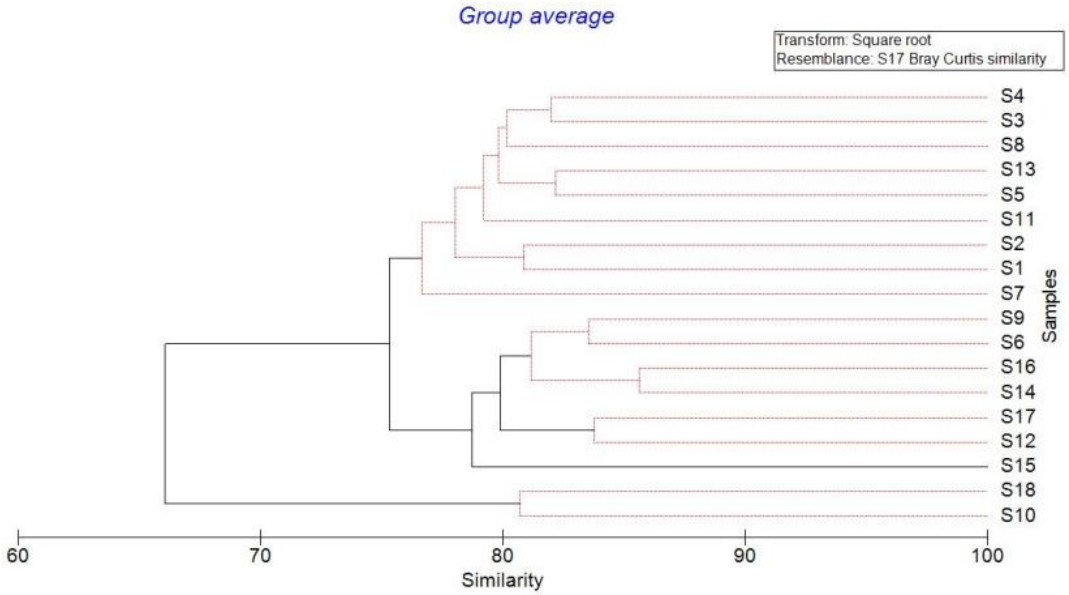


Fig.5.56 Dendrogram showing numerical abundance of cyclopoid species showing similarities in open ocean of Minicoy during 2015

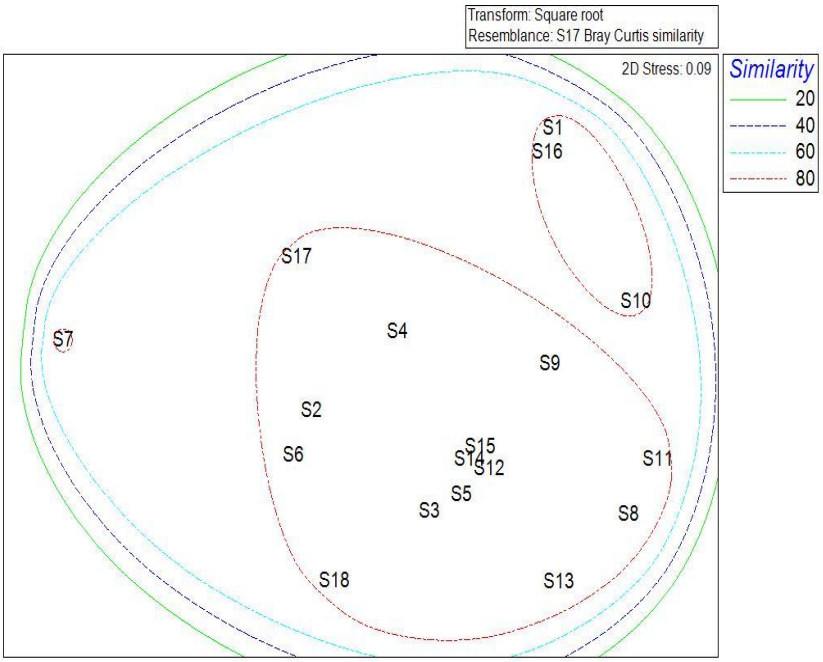


Fig.5.57 MDS ordination plot with respect to the numerical abundance of mesozooplankton groups open ocean zones of Minicoy during 2015

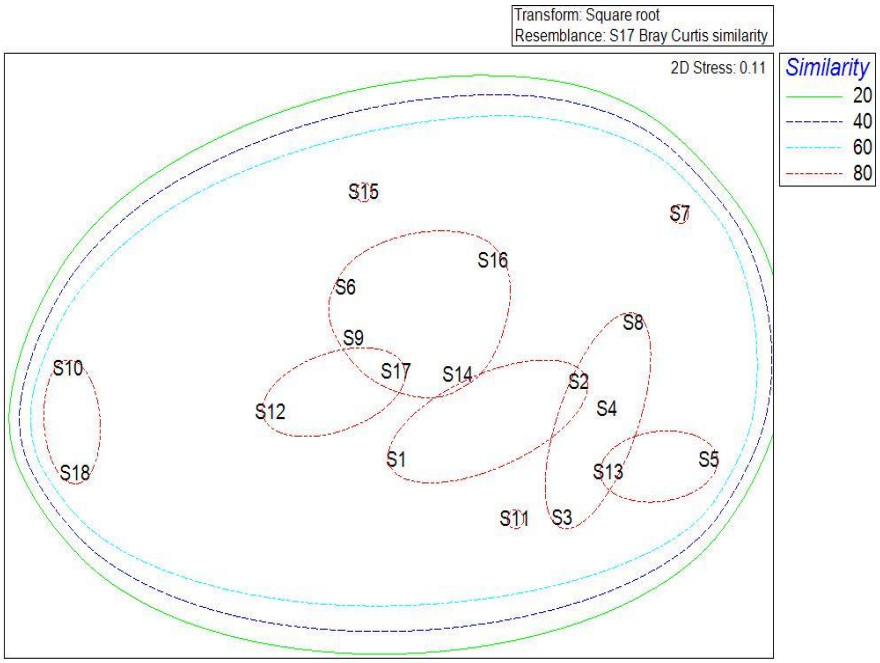


Fig.5.58 MDS ordination plot with respect to the numerical abundance of cyclopoids in open ocean zones of Minicoy during 2015

5.7.5 Best analysis

Best analysis of lagoon stations

The BEST analysis in PRIMER also showed that the best environmental variables predicting the distribution of cyclopoid species were different for different islands. In Kavaratti, pH and ammonia were the best matching variables (σ=0.622). In Kalpeni, SST, SSS, pH, nitrate, nitrite, phosphate, silicate (σ=0.600).Where as in Agatti, nitrate was found to be the best matching variable (σ=0.1). Bangaram, Minicoy all were found to be matching variables (σ=1.000). But none of the values were statistically significant (Tables. 8 to 12), Figs.5.59 to 5.64).

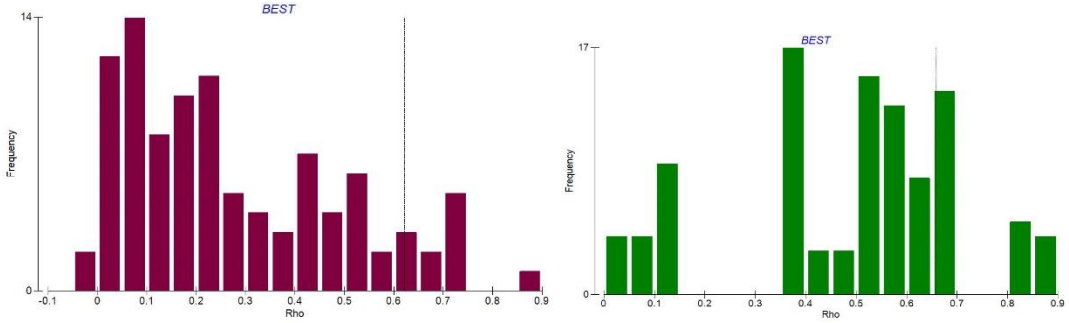


Fig.5.59 Histogram showing the BEST results for cyclopoid abundance (Rho 0.622) in Kavaratti during 2013-14. **Fig.5.60.**Histogram showing the BEST results for cyclopoid abundance (Rho 0.600) in Kalpeni during 2013-14

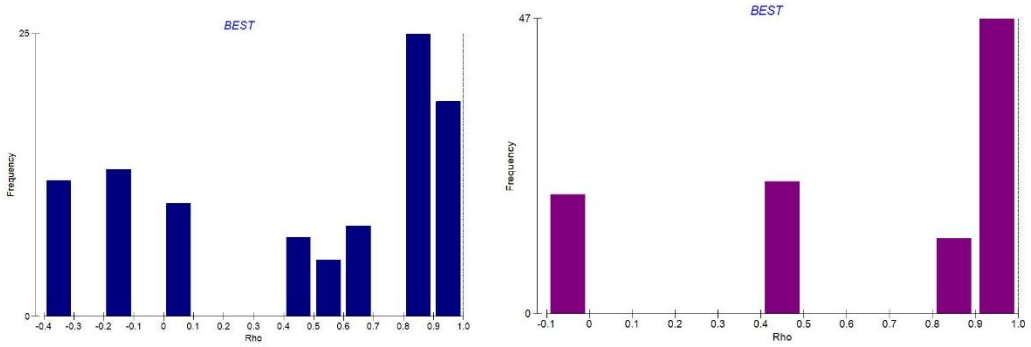


Fig.5.61 Histogram showing the BEST results for cyclopoid abundance (Rho 1.000) in Minicoy during 2013-14. **Fig.5.62.**Histogram showing the BEST results for cyclopoid abundance (Rho 1.000) in Agatti during 2014-15

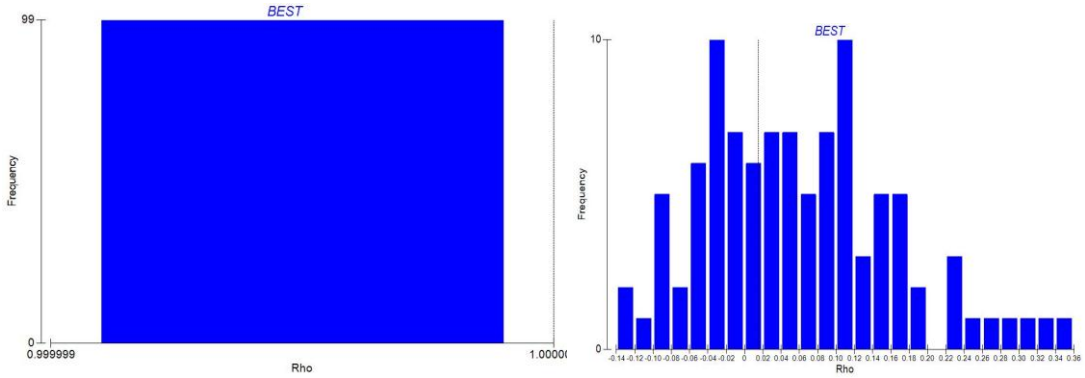


Fig.5.63 Histogram showing the BEST results for cyclopoid abundance (Rho1.000) in Bangaram during 2014-15.**Fig.4.64.**Histogram showing the BEST results for cyclopoid abundance (Rho0.015) in Minicoy Open Ocean during 2015

Table.8 BEST results for cyclopoid abundance in Kavaratti 2013-14 during premonsoon, monsoon and postmonsoon

Variables	Variables selected	BEST correlation values (Rho)
1 SST	3,9	0.622
2 SSS	1,3,9	0.614
3 pH	1-3,9,10	0.607
4 DO	3,7,9	0.602
5 Nitrate	2,3,7,9,10	0.583
6 Nitrite	2,3,10	0.580
7 Phosphate	2,3,9,10	0.574
8 Silicate	3,7,9	0.569
9 Ammonia	1,2,9,10	0.564
10.Chlorophyll a	3,7	0.564

Table.9 BEST results for cyclopoid abundance in Kalpeni 2013-14 during monsoon and postmonsoon

Variables	Variables selected	BEST correlation values (Rho)
1 SST	5	0.657
2 SSS	5,8	0.600
3 pH	5-8	0.600
4 DO	1,5-8	0.600
5 Nitrate	2.5-8	0.600
6 Nitrite	3,5-8	0.600
7 Phosphate	5-9	0.543
8 Silicate	4,6	0.543
9 Ammonia	6,8	0.543
10 Chlorophyll a	1,4,6	0.543

Table.10 BEST results for cyclopoid abundance in Minicoy 2013-14 during monsoon and postmonsoon.

Variables	Variables selected	BEST correlation values (Rho)
1 SST	5	1.000
2 SSS	9	1.000
3 pH	1,5	1.000
4 DO	1,9	1.000
5 Nitrate	2,5	1.000
6 Nitrite	2,9	1.000
7 Phosphate	3,5	1.000
8 Silicate	3,9	1.000
9 Ammonia	5,6	1.000
10 Chlorophyll a	5,7	1.000

Table.11 BEST results for cyclopoid abundance in Agatti 2014-15 during premonsoon

Variables	Variables selected	BEST correlation values (Rho)
1 SST	5	1.000
2 SSS	3,5	1.000
3 pH	4,5	1.000
4 DO	5,6	1.000
5 Nitrate	5,7	1.000
6 Nitrite	5,8	1.000
7 Phosphate	5,9	1.000
8 Silicate	3-5	1.000
9 Ammonia	3,5,6	1.000
10 Chlorophyll a	3,5,7	1.000

Table.12 BEST results for cyclopoid abundance in Bangaram 2014-15 during premonsoon

Variables	Variables selected	BEST correlation values (Rho)
1 SST	6	1.000
2 SSS	1,2	1.000
3 pH	2,8	1.000
4 DO	6,8	1.000
5 Nitrate	1,2,6	1.000
6 Nitrite	1,2,8	1.000
7 Phosphate	2,3,8	1.000
8 Silicate	2,6,8	1.000
9 Ammonia	2,7,8	1.000
	2,8,9	1.000

Best analysis of Minicoy open ocean

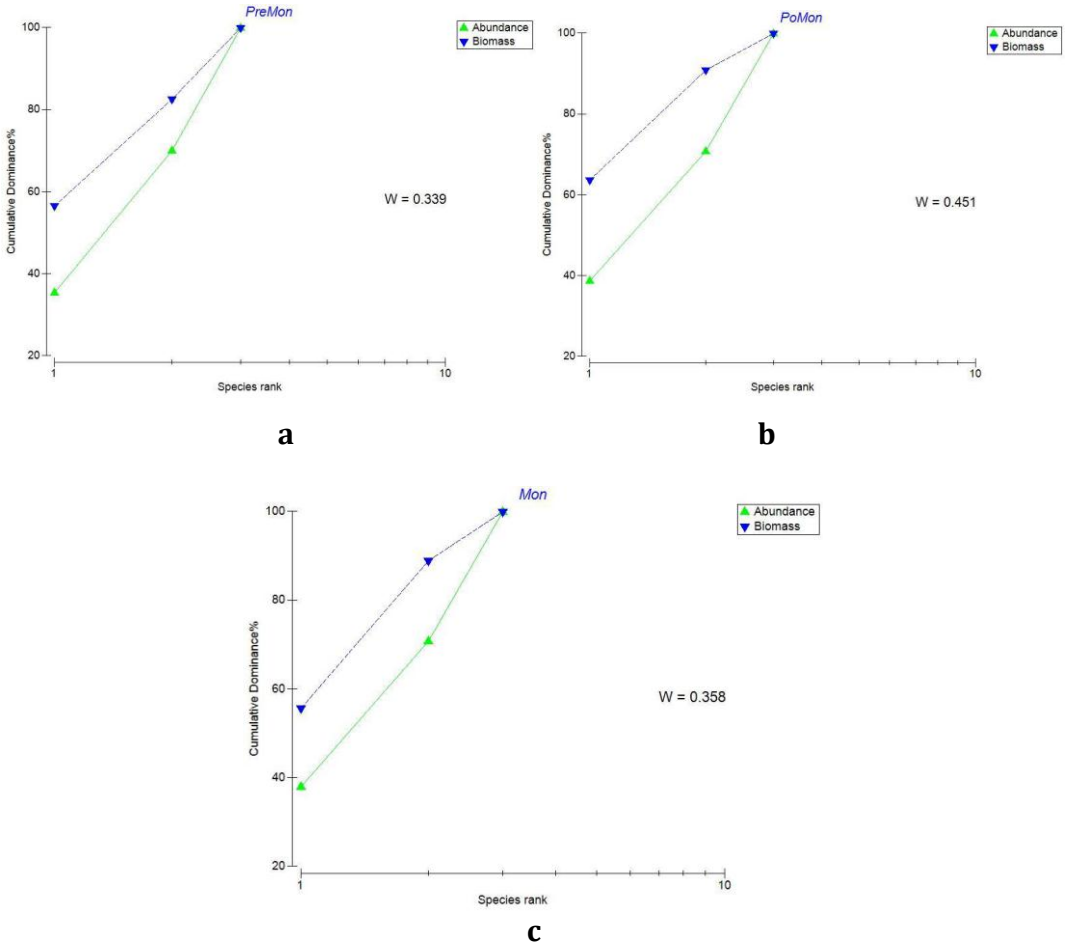
In Minicoy open Ocean, DO was the best matching variable (σ=0.015) (Fig.5.64 and Table .13)

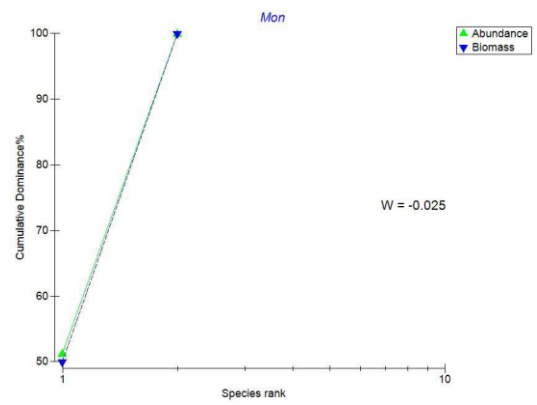
Table.13 BEST results for cyclopoid abundance in Minicoy open ocean 2015 during premonsoon

Variables	Variables selected	BEST correlation values (Rho)
1. DO	1	0.015
2. SSS	1,2	-0.097
	2	-0.113

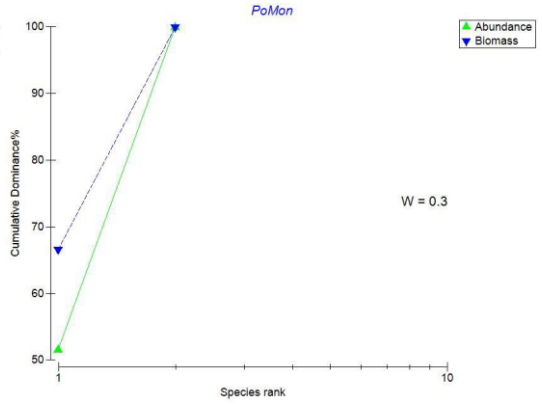
5.7.6 Abundance Biomass Curve (ABC) plots

ABC plots were used to investigate the mesozooplankton community stress in Lakshadweep islands (Fig.5.65).During the first year, ABC plots indicated Kalpeni (Mon) (5.65d) and Minicoy (PoMon) (5.65g) to be moderately disturbed community as the abundance and biomass curve intersected and showed a low W value. Whereas in Kavaratti (PreMon), Kavaratti (Mon), Kavaratti (PoMon) (5.65a,b,c),Kalpeni (PoMon)(5.65e)and Minicoy (Mon) (5.65f),biomass curve was above the abundance curve with a comparatively high W value, indicating an undisturbed community. However in the second year, Kavaratti (PreMon), Agatti (PreMon) and Bangaram (PreMon) were established to be undisturbed communities since biomass curve was above the abundance curve (5.65h,i,j). In Minicoy open ocean zones (PreMon) biomass curve was above the abundance curve with a comparatively higher W value, indicating an undisturbed community. (5.65k).

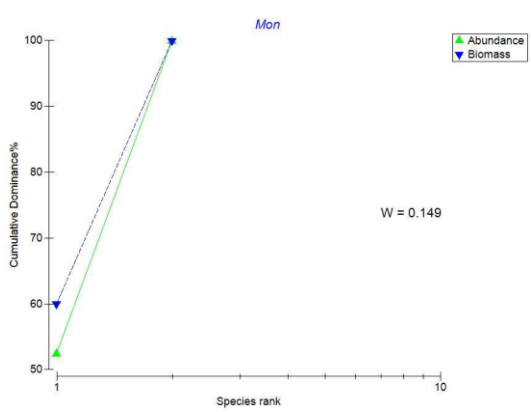



Mon
Abundance
Biomass
Cumulative Dominance%
Species rank
W = -0.025

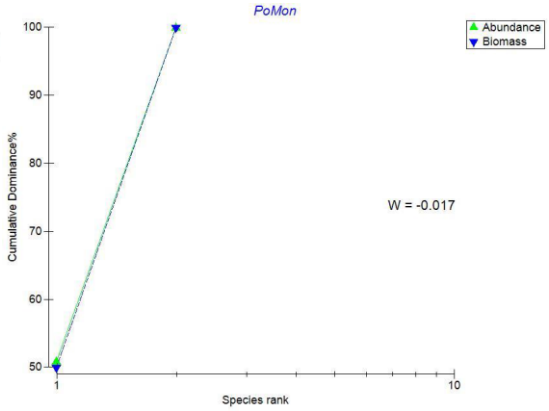
d


PoMon
Abundance
Biomass
Cumulative Dominance%
Species rank
W = 0.3

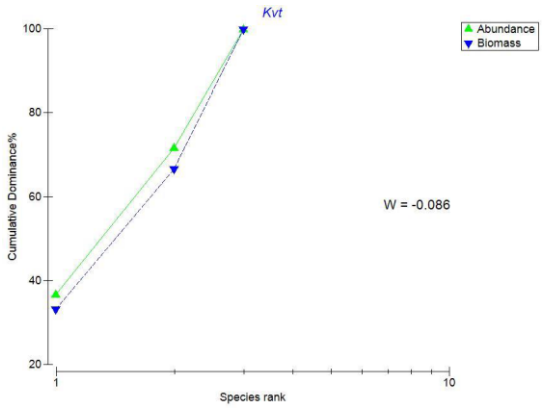
e


Mon
Abundance
Biomass
Cumulative Dominance%
Species rank
W = 0.149

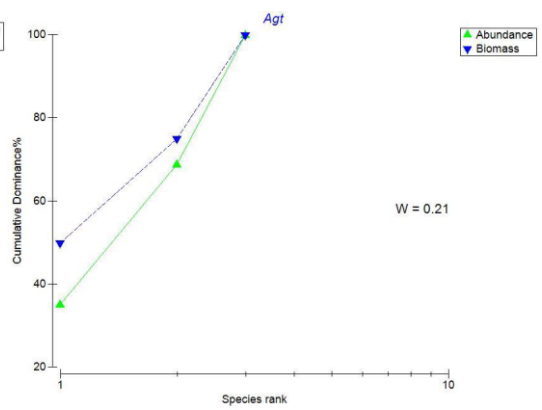
f


PoMon
Abundance
Biomass
Cumulative Dominance%
Species rank
W = -0.017

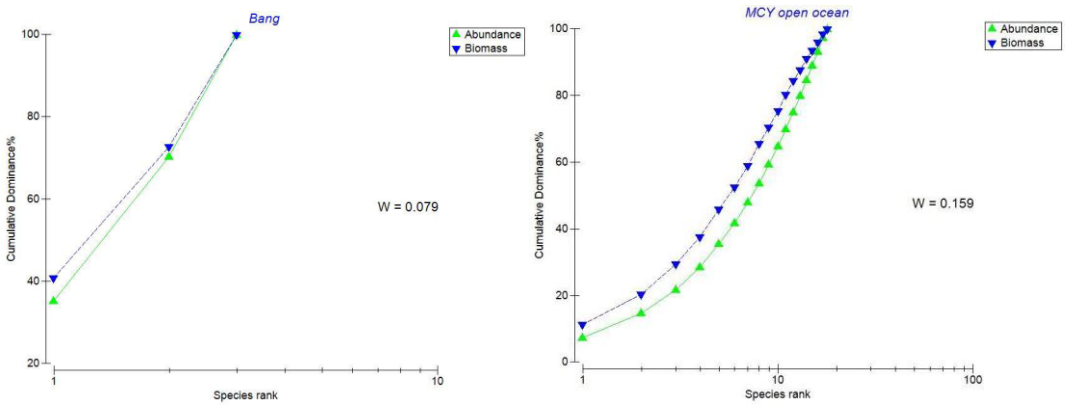
g


Kvt
Abundance
Biomass
Cumulative Dominance%
Species rank
W = -0.086

h


Agt
Abundance
Biomass
Cumulative Dominance%
Species rank
W = 0.21

i



j **k**

Fig.5.65 ABC plots of mesozooplankton groups in lagoons of Kavaratti (a,b,c,h), Kalpeni (d,e), Minicoy(f,g) , Agatti(i), Bangaram (j) and open ocean of Minicoy (k)during 2013-15

5.7.7 SIMPER Analysis

SIMPER analysis grouped stations based on species responsible for the clustering pattern of cyclopoids. To reveal differences between sampling stations and to identify the discriminating species (species contributed to the similarities and dissimilarities) SIMPER (Similarity percentage) analysis was performed. In Kavaratti during 2013-14, average similarity of T1 (55.39%), T2 (55.29%), T3 (43.47%) was mainly contributed by 21 species of which *Corycaeus crassiusculus* became the most discriminating species (Table.14).In Kalpeni stations during 2013-14, average similarity of T1 (55.26%) was mainly contributed by 17 species of which, *Dioithona rigida* was the major contributor. While average similarity of T2(62.66%) was mainly contributed by 13 species of which *Ditrichocorycaeus dahli* was the major contributor (Table.30). In Minicoy stations 2013-14, the average similarity of T1(39.96%) was mainly contributed by 23 species of which *Farranula gibbula* was the major contributor. While average similarity of T2 (38.98%) was mainly contributed by 26 species of which *Oithona plumifera* was the major contributor (Table.15).

In Kavaratti stations during 2014-15, the average dissimilarity of 29.25% between T1 and T2 was mainly contributed by *Ditrichocorycaeus dahli*, while *Oncaea scottidicarloi* contributed mainly to average dissimilarity of 69.31% between T1 and T3 and *Onychocorycaeus agilis* contributed mainly to average dissimilarity of 50.39% between T2 and T3 (Table.16).

In Agatti during 2014-15 during the second year, the average dissimilarity between T1 and T2(17.05%), between T1 and T3 (18.89%) was mainly contributed by *Onychocorycaeus giesbrechti* and that between T2 and T3 (23.36%) was contributed by *Corycaeus crassiusculus* (Table.17).

In Bangaram stations during 2014-15, the average dissimilarity of 13.5% observed between T1 and T2 was mainly contributed by *Oithona similis*, while *Corycaeus vitreus* contributed mainly to average dissimilarity of 39.55% between T1 and T3 and *Corycaeus crassiusculus* contributed mainly to average dissimilarity of 35.54% between T2 and T3(Table.18).

In open ocean stations of Minicoy, the average dissimilarity between stations were mainly contributed by *Sapphirina scarlata*(S1&S2,S2&S4,S2 &S5,S2&S10), *Sapphirina nigromaculata* (S1&S3,S1&S4, S1&S5,S1&S7,S5&S7, S6&S7,S7&S8,S7&S9,S3&S10,S4&S10,S7&S10,S1&S13), *Oncaea scottodicarloi* (S2&S3, S3&S4, S3&S5,S5&S8,S4&S11,S5&S11,S1&S12,S3&S16), *Oncaea media* (S4&S5,S1&S6), *Farranula curta* (S2&S6,S6&S9), *Ditrichocoryceus andrewsi* (S3&S6, S4&S6,S14&S18,S3&S17), *Copilia mirabilis* (S5&S6) *Sapphirina stellata* (S2&S7,S1&S8, S2&S8, S3&S8,S4&S8,S1&S10,S12&S18), *Sapphrina vorax* (S3&S7,S4&S7,S7&S12), *Copilia hendorffi* (S6&S8), *Dioithona oculata* (S1&S9,S6&S10,S9&S10,S&S14), *Farranula gracilis* (S2&S9,S5&S9), *Farranula curta* (S6&S9,S7&S11,S8&S11,S2&S17),*Corycaeus vitreus* (S3&S9), *Sapphrina auronitens* (S4&S9), *Onceaea macilenta* (S8&S9), *Urocorycaeus lautus* (S1&S11, S6&S11, S10&S11), *Oithona simplex* (S2&S11), *Copilia mirabilis* (S5&S12), *Ditrichocoryceus dahli* (S17&S18), *Sapphirina metallina* (S13&S18), *Sapphirina siniuicauda* (S9&S18), *Copilia quadrata* (S2&S12,S3&S12,S6&S12,S1&S15) *Oithona nana* (S4&S12), *Ditrichocorycaeus lubbocki*(S10&S12), *Ditrichocorycaeus affinis* (S3&S13), *Sapphirina angusta* (S5&S14,S14&S16), *Oithona plumifera* (S6&S16), *Corycaeus crassiusculus* (S2&S18).

Table.14 SIMPER test results showing the characteristic cyclopoid species in Kavaratti during 2013-14
Av.similarity T1 (55.39%), T2 (55.29%), T3 (43.47%)

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Corycaeus crassiusculus	37.86	3.66	6.61	6.61	6.61
Corycaeus speciosus	34.41	3.29	6.41	5.94	12.55
Onychocorycaeus agilis	38.36	3.06	2.01	5.53	18.08
Ditrichocoryceus andrewsi	35.09	2.88	6.08	5.19	23.28
Farranula concinna	36.61	2.77	2.68	5.00	28.28
Farranula gracilis	32.15	2.73	2.83	4.93	33.20
Ditrichocorycaeus lubbocki	26.75	2.72	7.75	4.90	38.11
Corycaeus vitreus	32.01	2.64	3.22	4.77	42.87
Farranula gibbula	37.46	2.53	1.48	4.57	47.44
Oncaea media	28.59	2.50	4.22	4.51	51.95
Oncaea clevei	29.02	2.17	2.01	3.91	55.86
Oithona plumifera	26.43	2.17	2.01	3.91	59.77
Corycaeus clausi	28.53	2.12	2.12	3.82	63.59
Onychocorycaeus catus	25.94	2.12	2.12	3.82	67.42
Farranula rostrata	28.53	2.12	2.12	3.82	71.24
Farranula curta	28.92	2.12	2.12	3.82	75.07
Ditrichocorycaeus affinis	24.42	2.07	2.27	3.73	78.80
Ditrichocorycaeus subulatus	24.93	2.07	2.27	3.73	82.53
Oithona brevicornis	24.39	2.01	2.45	3.64	86.17
Onychocorycaeus pacificus	25.67	1.96	2.68	3.54	89.70
Ditrichocoryceus tenius	22.76	1.96	2.68	3.54	93.24

Table.15 SIMPER test results showing the characteristic cyclopoid species in Kalpeni (monsoon and post monsoon) during 2013-14
T1 (Average similarity: 55.26)

Species	Av.Abund	Av.Sim	Contrib%	Cum.%
Dioithona rigida	*4.18*	*5.75*	*10.41*	*10.41*
Onychocorycaeus agilis	*3.76*	*4.70*	*8.50*	*18.90*
Corycaeus clausi	*2.58*	*3.32*	*6.01*	*24.91*
Corycaeus vitreus	*2.12*	*3.32*	*6.01*	*30.92*
Ditrichocorycaeus lubbocki	*2.12*	*3.32*	*6.01*	*36.92*
Oithona plumifera	*4.16*	*3.32*	*6.01*	*42.93*
Onychocorycaeus pacificus	*2.28*	*2.88*	*5.20*	*48.13*
Ditrichocoryceus dahli	*3.78*	*2.88*	*5.20*	*53.34*
Ditrichocorycaeus subulatus	*2.87*	*2.88*	*5.20*	*58.54*
Oncaea curta	*1.87*	*2.88*	*5.20*	*63.74*
Farranula gibbula	*1.57*	*2.35*	*4.25*	*67.99*
Oncaea paraclevie	*2.94*	*2.35*	*4.25*	*72.24*
Oncaea venusta	*2.58*	*2.35*	*4.25*	*76.49*
Oncaea mediterranea	*2.29*	*2.35*	*4.25*	*80.73*
Oithona brevicornis	*1.93*	*2.35*	*4.25*	*84.98*
Oncaea clevei	*1.37*	*1.66*	*3.00*	*87.99*
Oncaea scottodicarloi	*1.82*	*1.66*	*3.00*	*90.99*

T2 (Average similarity: 62.66)

Species	Av.Abund	Av.Sim	Contrib%	Cum.%
Ditrichocoryceus dahli	*4.18*	*6.81*	*10.86*	*10.86*
Ditrichocorycaeus subulatus	*2.32*	*5.56*	*8.87*	*19.74*
Corycaeus clausi	*1.87*	*4.81*	*7.68*	*27.42*
Oncaea paraclevie	*2.45*	*4.81*	*7.68*	*35.10*
Oncaea curta	*1.73*	*4.81*	*7.68*	*42.78*
Ditrichocorycaeus lubbocki	*2.12*	*3.93*	*6.27*	*49.06*
Oncaea media	*1.41*	*3.93*	*6.27*	*55.33*
Oncaea venusta	*1.71*	*3.93*	*6.27*	*61.60*
Oncaea mediterranea	*1.83*	*3.93*	*6.27*	*67.87*
Oncaea macilenta	*1.71*	*3.93*	*6.27*	*74.15*
Oithona similis	*1.93*	*3.93*	*6.27*	*80.42*
Oithona plumifera	*2.37*	*3.93*	*6.27*	*86.69*
Oithona brevicornis	1.72	2.78	4.44	91.13

Table.16 SIMPER test results showing the characteristic cyclopoid species in Minicoy (monsoon and post monsoon) during 2013-14

T1 (Average similarity: 39.96)

Species	Av.Abund	Av.Sim	Contrib%	Cum.%
Farranula gibbula	*13.25*	*2.22*	*5.57*	*5.57*
Corycaeus crassiusculus	*14.56*	*2.18*	*5.46*	*11.03*
Corycaeus speciosus	*14.84*	*2.05*	*5.14*	*16.16*
Onychocorycaeus agilis	*14.07*	*2.05*	*5.14*	*21.30*
Ditrichocoryceus andrewsi	*13.29*	*2.01*	*5.02*	*26.33*
Dioithona rigida	*14.23*	*1.98*	*4.97*	*31.29*
Oithona plumifera	*13.75*	*1.87*	*4.67*	*35.96*
Oithona similis	*15.94*	*1.82*	*4.54*	*40.51*
Dioithona oculata.	*13.56*	*1.82*	*4.54*	*45.05*
Corycaeus vitreus	*11.69*	*1.74*	*4.35*	*49.40*
Oncaea clevei	*11.98*	*1.63*	*4.08*	*53.48*
Corycaeus clausi	*12.58*	*1.60*	*4.01*	*57.49*
Onychocorycaeus catus	*9.90*	*1.57*	*3.94*	*61.42*
Oncaea venusta	*13.57*	*1.51*	*3.79*	*65.21*
Onychocorycaeus giesbrechti	*11.82*	*1.45*	*3.63*	*68.84*
Ditrichocorycaeus affinis	*8.83*	*1.42*	*3.55*	*72.40*
Oncaea mediterranea	*4.92*	*1.21*	*3.03*	*75.42*
Farranula curta	*4.32*	*1.13*	*2.83*	*78.26*
Onychocorycaeus pumilus	*8.21*	*1.05*	*2.62*	*80.88*
Ditrichocoryceus dahli	*4.78*	*1.00*	*2.51*	*83.39*
Farranula gracilis	*5.32*	*0.96*	*2.40*	*85.79*
Oncaea paraclevie	*10.70*	*0.86*	*2.14*	*87.93*
Oithona brevicornis	*9.06*	*0.86*	*2.14*	*90.07*

T2 (Average similarity: 38.98)

Species	Av.Abund	Av.Sim	Contrib%	Cum.%
Oithona plumifera	13.18	2.00	5.12	5.12
Onychocorycaeus pacificus	11.32	1.95	5.00	10.12
Ditrichocoryceus andrewsi	11.22	1.82	4.67	14.79
Corycaeus crassiusculus	12.58	1.76	4.53	19.31
Onychocorycaeus agilis	12.70	1.76	4.53	23.84
Dioithona rigida	13.89	1.76	4.53	28.36
Corycaeus speciosus	11.74	1.62	4.16	32.52
Oncaea clevei	11.84	1.59	4.08	36.60
Onychocorycaeus giesbrechti	10.62	1.53	3.92	40.52
Farranula gibbula	12.03	1.53	3.92	44.44
Ditrichocorycaeus affinis	8.60	1.50	3.84	48.28
Dioithona oculata.	11.95	1.50	3.84	52.12
Oncaea mediterranea	5.70	1.46	3.75	55.87
Oithona similis	15.84	1.46	3.75	59.62
Onychocorycaeus catus	10.24	1.39	3.58	63.20
Corycaeus vitreus	12.55	1.21	3.10	66.30
Oncaea media	11.42	1.17	2.99	69.29
Onychocorycaeus pumilus	11.39	1.12	2.88	72.18
Farranula rostrata	9.63	1.12	2.88	75.06
Corycaeus clausi	12.21	1.03	2.65	77.72
Urocorycaeus lautus	6.66	1.03	2.65	80.37
Onychocorycaeus latus	4.23	0.99	2.53	82.90
Urocorycaeus furcifer	4.95	0.88	2.26	85.16
Ditrichocoryceus dahli	5.16	0.88	2.26	87.43
Oithona nana	3.77	0.83	2.12	89.54
Oithona brevicornis	7.95	0.76	1.96	91.50

Table.17 SIMPER test results showing the characteristic cyclopoid species in Kavaratti (premonsoon) during 2014-15

Groups T1 and T2 (Average dissimilarity = 29.25)

	Group T1 Av.Abund	Group T2 Av.Abund	Av.Diss	Contrib%	Cum.%
Ditrichocoryceus dahli	*6.00*	*1.00*	*2.48*	*8.47*	*8.47*
Oncaea clevei	*4.36*	*0.00*	*2.16*	*7.38*	*15.85*
Ditrichocorycaeus lubbocki	*4.00*	*0.00*	*1.98*	*6.78*	*22.63*
Corycaeus vitreus	*5.29*	*2.24*	*1.51*	*5.18*	*27.81*
Ditrichocorycaeus subulatus	*3.87*	*1.00*	*1.42*	*4.87*	*32.67*
Oithona simplex	*3.87*	*1.00*	*1.42*	*4.87*	*37.54*
Dioithona oculata.	*4.36*	*1.73*	*1.30*	*4.45*	*41.99*
Ditrichocoryceus andrewsi	*3.61*	*1.00*	*1.29*	*4.41*	*46.40*
Farranula concinna	*3.87*	*1.41*	*1.22*	*4.17*	*50.57*
Oncaea scottodicarloi	*5.92*	*3.46*	*1.21*	*4.15*	*54.72*
Corycaeus clausi	*0.00*	*2.45*	*1.21*	*4.15*	*58.87*
Onychocorycaeus giesbrechti	*6.16*	*3.87*	*1.14*	*3.88*	*62.76*
Onychocorycaeus pacificus	*2.24*	*0.00*	*1.11*	*3.79*	*66.54*
Farranula rostrata	*5.74*	*3.74*	*0.99*	*3.39*	*69.94*
Urocorycaeus furcifer	*4.80*	*2.83*	*0.97*	*3.33*	*73.27*
Oncaea venusta	*4.90*	*3.00*	*0.94*	*3.22*	*76.49*
Onychocorycaeus pumilus	*5.83*	*4.36*	*0.73*	*2.49*	*78.98*
Urocorycaeus lautus	*0.00*	*1.41*	*0.70*	*2.40*	*81.38*
Oithona brevicornis	*1.41*	*0.00*	*0.70*	*2.40*	*83.77*
Ditrichocorycaeus affinis	*2.83*	*4.24*	*0.70*	*2.40*	*86.17*
Onychocorycaeus catus	*1.00*	*2.24*	*0.61*	*2.09*	*88.26*
Corycaeus crassiusculus	*5.92*	*4.69*	*0.61*	*2.08*	*90.34*

Groups T1 and T3 (Average dissimilarity = 61.31)

Species	Group T1 Av.Abund Cum.%	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Oncaea scottodicarloi	*5.92*	*0.00*	*3.75*	*6.11*	*6.11*
Corycaeus vitreus	*5.29*	*0.00*	*3.35*	*5.47*	*11.58*
Onychocorycaeus giesbrechti	*6.16*	*1.00*	*3.27*	*5.34*	*16.92*
Ditrichocoryceus dahli	*6.00*	*1.00*	*3.17*	*5.17*	*22.09*
Corycaeus speciosus	*6.71*	*1.73*	*3.15*	*5.14*	*27.23*
Corycaeus crassiusculus	*5.92*	*1.00*	*3.11*	*5.08*	*32.31*
Oncaea venusta	*4.90*	*0.00*	*3.10*	*5.06*	*37.37*
Urocorycaeus furcifer	*4.80*	*0.00*	*3.04*	*4.96*	*42.33*
Farranula rostrata	*5.74*	*1.00*	*3.01*	*4.90*	*47.23*
Oncaea mediterranea	*4.00*	*0.00*	*2.53*	*4.13*	*51.36*
Ditrichocoryceus tenius	*5.66*	*1.73*	*2.49*	*4.06*	*55.42*
Ditrichocorycaeus subulatus	*3.87*	*0.00*	*2.45*	*4.00*	*59.42*
Farranula concinna	*3.87*	*0.00*	*2.45*	*4.00*	*63.42*
Onychocorycaeus agilis	*4.69*	*1.00*	*2.34*	*3.81*	*67.24*
Onychocorycaeus pumilus	*5.83*	*2.24*	*2.28*	*3.71*	*70.95*
Oncaea clevei	*4.36*	*1.00*	*2.13*	*3.47*	*74.42*
Dioithona oculata.	*4.36*	*1.41*	*1.87*	*3.04*	*77.47*
Ditrichocoryceus andrewsi	*3.61*	*1.00*	*1.65*	*2.69*	*80.16*
Ditrichocorycaeus lubbocki	*4.00*	*1.41*	*1.64*	*2.67*	*82.83*
Oncaea paraclevie	*3.46*	*1.00*	*1.56*	*2.55*	*85.38*
Oithona simplex	*3.87*	*1.41*	*1.56*	*2.54*	*87.92*
Dioithona rigida	*2.45*	*0.00*	*1.55*	*2.53*	*90.45*

Groups T2 and T3 Average dissimilarity = 50.39

Species	Group T2 Av.Abund	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Onychocorycaeus agilis	5.83	1.00	4.14	8.21	8.21
Corycaeus speciosus	5.83	1.73	3.51	6.97	15.18
Oncaea mediterranea	3.87	0.00	3.32	6.58	21.76
Corycaeus crassiusculus	4.69	1.00	3.16	6.27	28.03
Oncaea scottodicarloi	3.46	0.00	2.97	5.89	33.92
Oncaea venusta	3.00	0.00	2.57	5.10	39.02
Onychocorycaeus giesbrechti	3.87	1.00	2.46	4.88	43.90
Ditrichocoryceus tenius	4.58	1.73	2.44	4.84	48.75
Urocorycaeus furcifer	2.83	0.00	2.42	4.81	53.55
Farranula rostrata	3.74	1.00	2.35	4.66	58.21
Oncaea paraclevie	3.46	1.00	2.11	4.19	62.40
Ditrichocorycaeus affinis	4.24	2.00	1.92	3.81	66.21
Corycaeus vitreus	2.24	0.00	1.92	3.80	70.01
Onychocorycaeus pumilus	4.36	2.24	1.82	3.61	73.62
Oithona plumifera	0.00	2.00	1.71	3.40	77.02
Dioithona rigida	2.00	0.00	1.71	3.40	80.42
Onychocorycaeus pacificus	0.00	1.73	1.48	2.94	83.36
Ditrichocorycaeus lubbocki	0.00	1.41	1.21	2.40	85.77
Farranula concinna	1.41	0.00	1.21	2.40	88.17
Corycaeus clausi	2.45	1.41	0.89	1.76	89.93
Ditrichocorycaeus subulatus	1.00	0.00	0.86	1.70	91.63

Table.18 SIMPER test results showing the characteristic cyclopoid species in Agatti (premonsoon) during 2014-15

Average dissimilarity = 17.05

Species	Group T1 Av.Abund Cum.%	Group T2 Av.Abund	Av.Diss	Contrib%	Cum.%
Onychocorycaeus giesbrechti	*3.00*	*0.00*	*1.59*	*9.31*	*9.31*
Ditrichocorycaeus lubbocki	*4.12*	*1.73*	*1.27*	*7.42*	*16.73*
Urocorycaeus lautus	*0.00*	*2.24*	*1.18*	*6.94*	*23.67*
Onychocorycaeus agilis	*2.65*	*1.00*	*0.87*	*5.11*	*28.78*
Ditrichocoryceus dahli	*4.58*	*3.00*	*0.84*	*4.91*	*33.70*
Corycaeus crassiusculus	*3.74*	*2.24*	*0.80*	*4.67*	*38.37*
Corycaeus clausi	*0.00*	*1.41*	*0.75*	*4.39*	*42.76*
Oithona similis	*2.83*	*4.24*	*0.75*	*4.39*	*47.15*
Oncaea curta	*2.24*	*1.00*	*0.65*	*3.84*	*50.98*
Onychocorycaeus latus	*2.24*	*3.32*	*0.57*	*3.35*	*54.34*
Corycaeus vitreus	*3.46*	*2.45*	*0.54*	*3.15*	*57.49*
Ditrichocorycaeus affinis	*2.45*	*3.46*	*0.54*	*3.15*	*60.64*
Farranula concinna	*3.46*	*2.45*	*0.54*	*3.15*	*63.79*
Ditrichocorycaeus subulatus	*1.00*	*0.00*	*0.53*	*3.10*	*66.89*
Oncaea media	*1.00*	*0.00*	*0.53*	*3.10*	*69.99*
Oncaea macilenta	*1.00*	*0.00*	*0.53*	*3.10*	*73.10*
Oncaea paraclevie	*5.00*	*5.92*	*0.48*	*2.84*	*75.94*
Dioithona rigida	*4.36*	*3.46*	*0.47*	*2.78*	*78.72*
Dioithona oculata.	*2.83*	*2.00*	*0.44*	*2.57*	*81.29*
Oithona simplex	*2.24*	*1.41*	*0.44*	*2.55*	*83.84*
Onychocorycaeus pacificus	*4.12*	*3.32*	*0.43*	*2.50*	*86.35*
Oithona brevicornis	*1.73*	*1.00*	*0.39*	*2.27*	*88.62*
Oncaea clevei	*2.45*	*1.73*	*0.38*	*2.23*	*90.84*

Groups T1 and T3 (Average dissimilarity = 18.89)

Species	Group T1 Av.Abund	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Onychocorycaeus giesbrechti	3.00	0.00	1.49	7.86	7.86
Oithona nana	0.00	3.00	1.49	7.86	15.72
Onychocorycaeus pacificus	4.12	1.41	1.34	7.10	22.82
Onychocorycaeus agilis	2.65	0.00	1.31	6.93	29.76
Corycaeus speciosus	1.73	3.87	1.06	5.61	35.37
Ditrichocoryceus andrewsi	3.32	1.41	0.94	4.99	40.36
Farranula concinna	3.46	1.73	0.86	4.54	44.89
Farranula curta	0.00	1.73	0.86	4.54	49.43
Corycaeus crassiusculus	3.74	5.39	0.81	4.31	53.74
Corycaeus vitreus	3.46	2.24	0.61	3.22	56.96
Ditrichocoryceus tenius	2.83	3.87	0.52	2.74	59.70
Farranula rostrata	3.46	4.47	0.50	2.64	62.34
Corycaeus clausi	0.00	1.00	0.50	2.62	64.96
Farranula gibbula	3.00	2.00	0.50	2.62	67.58
Oncaea media	1.00	0.00	0.50	2.62	70.20
Oncaea paraclevie	5.00	4.00	0.50	2.62	72.82
Oncaea macilenta	1.00	2.00	0.50	2.62	75.44
Oncaea venusta	5.10	4.24	0.42	2.24	77.69
Onychocorycaeus latus	2.24	3.00	0.38	2.00	79.69
Oithona simplex	2.24	3.00	0.38	2.00	81.69
Urocorycaeus furcifer	3.74	3.00	0.37	1.94	83.64
Ditrichocorycaeus affinis	2.45	1.73	0.36	1.88	85.52
Oncaea clevei	2.45	3.16	0.35	1.87	87.38
Oncaea scottodicarloi	2.00	2.65	0.32	1.69	89.08
Oithona similis	2.83	3.46	0.31	1.67	90.74

Groups T2 and T3 (Average dissimilarity = 23.36)

Species	Group T2 Av.Abund	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Corycaeus crassiusculus	*2.24*	*5.39*	*1.67*	*7.17*	*7.17*
Oithona nana	*0.00*	*3.00*	*1.59*	*6.83*	*14.00*
Urocorycaeus lautus	*2.24*	*0.00*	*1.19*	*5.09*	*19.09*
Corycaeus speciosus	*1.73*	*3.87*	*1.14*	*4.87*	*23.96*
Ditrichocorycaeus lubbocki	*1.73*	*3.87*	*1.14*	*4.87*	*28.83*
Oncaea macilenta	*0.00*	*2.00*	*1.06*	*4.55*	*33.39*
Oncaea paraclevie	*5.92*	*4.00*	*1.02*	*4.36*	*37.75*
Onychocorycaeus pacificus	*3.32*	*1.41*	*1.01*	*4.33*	*42.08*
Oncaea curta	*1.00*	*2.83*	*0.97*	*4.16*	*46.24*
Ditrichocorycaeus affinis	*3.46*	*1.73*	*0.92*	*3.94*	*50.18*
Farranula curta	*0.00*	*1.73*	*0.92*	*3.94*	*54.13*
Ditrichocoryceus andrewsi	*3.00*	*1.41*	*0.84*	*3.61*	*57.74*
Oithona simplex	*1.41*	*3.00*	*0.84*	*3.61*	*61.35*
Dioithona oculata.	*2.00*	*3.46*	*0.78*	*3.33*	*64.68*
Oncaea clevei	*1.73*	*3.16*	*0.76*	*3.26*	*67.94*
Ditrichocoryceus tenius	*2.45*	*3.87*	*0.76*	*3.24*	*71.18*
Ditrichocoryceus dahli	*3.00*	*4.36*	*0.72*	*3.09*	*74.27*
Onychocorycaeus agilis	*1.00*	*0.00*	*0.53*	*2.28*	*76.55*
Ditrichocorycaeus subulatus	*0.00*	*1.00*	*0.53*	*2.28*	*78.82*
Farranula gibbula	*3.00*	*2.00*	*0.53*	*2.28*	*81.10*
Oithona brevicornis	*1.00*	*2.00*	*0.53*	*2.28*	*83.38*
Oncaea scottodicarloi	*1.73*	*2.65*	*0.49*	*2.08*	*85.46*
Oithona similis	*4.24*	*3.46*	*0.41*	*1.77*	*87.23*
Oncaea venusta	*5.00*	*4.24*	*0.40*	*1.72*	*88.95*
Farranula concinna	*2.45*	*1.73*	*0.38*	*1.63*	*90.58*

Table.19 SIMPER test results showing the characteristic cyclopoid species in Bangaram (premonsoon) during 2014-15

Groups T1and T2 (Average dissimilarity = 13.05)

Species	Group T1 Av.Abund	Group T2 Av.Abund	Av.Diss	Contrib%	Cum.%
Oithona similis	*4.00*	*0.00*	*1.26*	*9.64*	*9.64*
Onychocorycaeus giesbrechti	*6.32*	*3.32*	*0.95*	*7.25*	*16.88*
Onychocorycaeus pumilus	*7.75*	*5.00*	*0.86*	*6.62*	*23.50*
Oncaea mediterranea	*5.39*	*2.65*	*0.86*	*6.60*	*30.10*
Oncaea paraclevie	*5.29*	*2.65*	*0.83*	*6.37*	*36.48*
Oithona brevicornis	*3.87*	*1.41*	*0.77*	*5.92*	*42.40*
Oncaea macilenta	*0.00*	*2.45*	*0.77*	*5.90*	*48.30*
Dioithona oculata.	*2.00*	*4.24*	*0.71*	*5.40*	*53.70*
Corycaeus speciosus	*6.93*	*5.20*	*0.54*	*4.17*	*57.88*
Corycaeus vitreus	*6.48*	*4.80*	*0.53*	*4.06*	*61.94*
Oncaea venusta	*4.00*	*2.45*	*0.49*	*3.74*	*65.67*
Farranula gracilis	*7.87*	*6.56*	*0.41*	*3.17*	*68.84*
Onychocorycaeus latus	*6.24*	*5.10*	*0.36*	*2.76*	*71.61*
Onychocorycaeus pacificus	*6.32*	*5.29*	*0.32*	*2.49*	*74.09*
Oithona simplex	*3.46*	*2.45*	*0.32*	*2.44*	*76.54*
Ditrichocoryceus tenius	*4.24*	*5.10*	*0.27*	*2.06*	*78.60*
Farranula concinna	*4.24*	*5.10*	*0.27*	*2.06*	*80.67*
Oncaea scottodicarloi	*1.41*	*2.24*	*0.26*	*1.98*	*82.65*
Urocorycaeus furcifer	*6.16*	*5.39*	*0.24*	*1.88*	*84.52*
Onychocorycaeus agilis	*4.69*	*4.00*	*0.22*	*1.66*	*86.19*
Oncaea clevei	*4.00*	*4.69*	*0.22*	*1.66*	*87.85*
Ditrichocorycaeus lubbocki	*4.24*	*4.80*	*0.17*	*1.33*	*89.18*
Ditrichocorycaeus subulatus	*4.90*	*4.36*	*0.17*	*1.30*	*90.48*

Groups T1 and T3 (Average dissimilarity = 39.55)

Species	Group T1 Av.Abund	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Corycaeus vitreus	6.48	0.00	2.64	6.66	6.66
Ditrichocoryceus dahli	6.24	0.00	2.54	6.42	13.08
Oncaea mediterranea	5.39	0.00	2.19	5.54	18.62
Onychocorycaeus latus	6.24	2.00	1.73	4.36	22.98
Farranula gracilis	7.87	3.87	1.63	4.11	27.10
Onychocorycaeus giesbrechti	6.32	2.45	1.58	3.98	31.08
Onychocorycaeus pumilus	7.75	3.87	1.57	3.98	35.06
Dioithona rigida	6.63	3.00	1.48	3.74	38.80
Corycaeus speciosus	6.93	3.32	1.47	3.71	42.51
Oncaea curta	5.00	1.41	1.46	3.69	46.20
Ditrichocorycaeus affinis	5.74	2.24	1.43	3.61	49.81
Onychocorycaeus pacificus	6.32	2.83	1.42	3.59	53.40
Ditrichocorycaeus subulatus	4.90	1.41	1.42	3.58	56.98
Oithona simplex	3.46	0.00	1.41	3.56	60.55
Corycaeus crassiusculus	6.24	3.00	1.32	3.34	63.88
Urocorycaeus furcifer	6.16	3.16	1.22	3.09	66.97
Oithona brevicornis	3.87	1.00	1.17	2.95	69.92
Ditrichocorycaeus lubbocki	4.24	1.41	1.15	2.91	72.83
Oithona plumifera	7.00	4.24	1.12	2.83	75.67
Oithona similis	4.00	1.41	1.05	2.66	78.32
Onychocorycaeus agilis	4.69	2.24	1.00	2.52	80.85
Onychocorycaeus catus	5.29	3.00	0.93	2.36	83.20
Oncaea venusta	4.00	1.73	0.92	2.33	85.54
Farranula concinna	4.24	2.00	0.91	2.31	87.84
Ditrichocoryceus tenius	4.24	2.45	0.73	1.84	89.68
Farranula gibbula	5.48	3.74	0.71	1.78	91.47

Groups T2 and T3 (Average dissimilarity = 35.54)

Species	Group T2 Av.Abund	Group T3 Av.Abund	Av.Diss	Contrib%	Cum.%
Ditrichocoryceus dahli	5.74	0.00	2.57	7.23	7.23
Corycaeus vitreus	4.80	0.00	2.14	6.03	13.26
Corycaeus crassiusculus	6.71	3.00	1.66	4.67	17.93
Oncaea curta	5.00	1.41	1.60	4.51	22.44
Ditrichocorycaeus lubbocki	4.80	1.41	1.51	4.25	26.69
Dioithona rigida	6.24	3.00	1.45	4.08	30.78
Dioithona oculata.	4.24	1.00	1.45	4.08	34.86
Ditrichocorycaeus affinis	5.39	2.24	1.41	3.96	38.82
Onychocorycaeus latus	5.10	2.00	1.39	3.90	42.72
Farranula concinna	5.10	2.00	1.39	3.90	46.62
Ditrichocorycaeus subulatus	4.36	1.41	1.32	3.71	50.32
Farranula gracilis	6.56	3.87	1.20	3.38	53.70
Ditrichocoryceus tenius	5.10	2.45	1.18	3.33	57.03
Oncaea mediterranea	2.65	0.00	1.18	3.33	60.36
Onychocorycaeus pacificus	5.29	2.83	1.10	3.10	63.46
Oithona simplex	2.45	0.00	1.10	3.08	66.54
Oithona plumifera	6.48	4.24	1.00	2.82	69.36
Urocorycaeus furcifer	5.39	3.16	0.99	2.80	72.16
Corycaeus speciosus	5.20	3.32	0.84	2.36	74.52
Oncaea paraclevie	2.65	4.47	0.82	2.30	76.82
Farranula gibbula	5.57	3.74	0.82	2.30	79.12
Onychocorycaeus catus	4.80	3.00	0.80	2.26	81.38
Onychocorycaeus agilis	4.00	2.24	0.79	2.22	83.60
Ditrichocoryceus andrewsi	4.36	2.65	0.77	2.16	85.75
Oncaea clevei	4.69	3.16	0.68	1.92	87.68
Oncaea macilenta	2.45	1.00	0.65	1.82	89.50
Oithona similis	0.00	1.41	0.63	1.78	91.28

5.7.8 Taxonomic Distinctness of cyclopoid copepods

Average taxonomic distinctness (Delta+) and variation in taxonomic distinctness (Lambda+) of Kavaratti Island ranged between 30 to 39 and 49 to 140 respectively. These values were superimposed on the funnel to find out the deviation from the normal distribution (within 95% confidence limit). In the first year, the 95% confidence funnel drawn for average taxonomic distinctness values of Kavaratti showed that all the points fell outside the confidence level showing deviation from normal distribution (Fig.5.66). The delta (Δ+) values of cyclopoids in MonT3 was lying lower to 95% probability limit of the funnel than other transects denoted significant differences in diversity of cyclopoids. The funnel plot of variation in taxonomic distinctness (lambda values) showed that all points clustered together within 95% confidence level showing no significant deviation from normal distribution except for MonT3 which fell outside the confidence limit and denoted significant difference in diversity of cyclopoids. Whereas PoMonT3 was on the borderline (Fig.5.67). In the first year, the 95% confidence funnel drawn for average taxonomic distinctness values of Kalpeni (42-43) showed that all points fell within the confidence level showing no deviation from normal deviation (Fig.5.68) While, the 95% confidence funnel drawn for variation in taxonomic distinctness values of Kalpeni (149-180) showed that MonT2 and PoMonT2 were on the borderline of the funnel but rest of the points (MonT1 and PoMon T1) also clustered almost at the same point representing no significant variation in diversity of cyclopoids (Fig.5.69).

In Minicoy, in the first year, the 95% confidence funnel drawn for average taxonomic distinctness (Delta+) (Fig.5.70) and variation in taxonomic distinctness (Lambda+) (Fig.5.71) showed that all points fell within the confidence level showing no deviation from normal distribution. Average taxonomic distinctness (Delta+) and variation in taxonomic distinctness (Lambda+) values of Minicoy island ranged between 40 to 42 and 140 to 150 respectively.

However in the second year, confidence funnel drawn for average taxonomic distinctness values (Delta+) (Fig.5.72) and variation in taxonomic distinctness (Lambda+) (Fig.5.73) values of Kavaratti, Agatti and Bangaram showed that all points clustered together within 95% confidence level showing no deviation from normal distribution. Average taxonomic distinctness (Delta+) and

variation in taxonomic distinctness (Lambda+) of Kavaratti, Agatti and Bangaram ranged between 40 to 43 and 140 to 150 respectively. Average taxonomic distinctness (Delta+) (Fig.5.74) and variation in taxonomic distinctness (Lambda+) (Fig.4.85) of the open ocean zones in Minicoy Island ranged between 40 to 45 and 100 to 150 respectively. These values were superimposed on the funnel to find out the deviation from the normal distribution (within 95% confidence limit). The 95% confidence funnel drawn for average taxonomic distinctness values of open ocean zones of Minicoy Island revealed that all the points clustered within 95% confidence level showing no deviation from normal distribution.

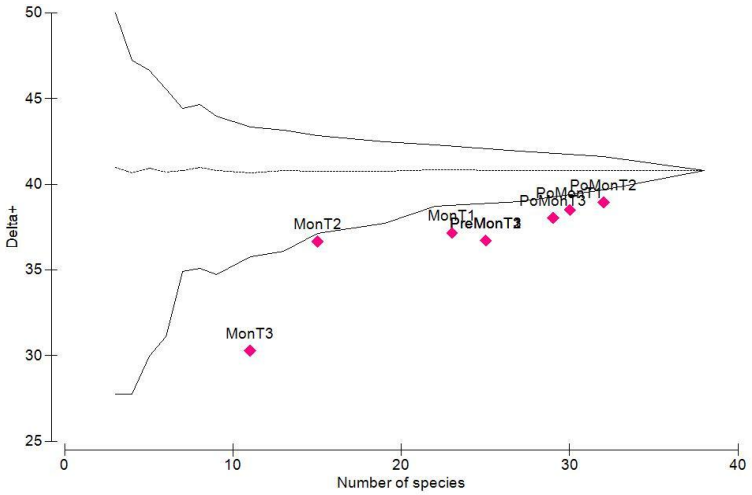


Fig.5.66 The 95% confidence funnel for the average taxonomic distinctness (Delta+) values of cyclopoid diversity in Kavaratti Island during 2013-14

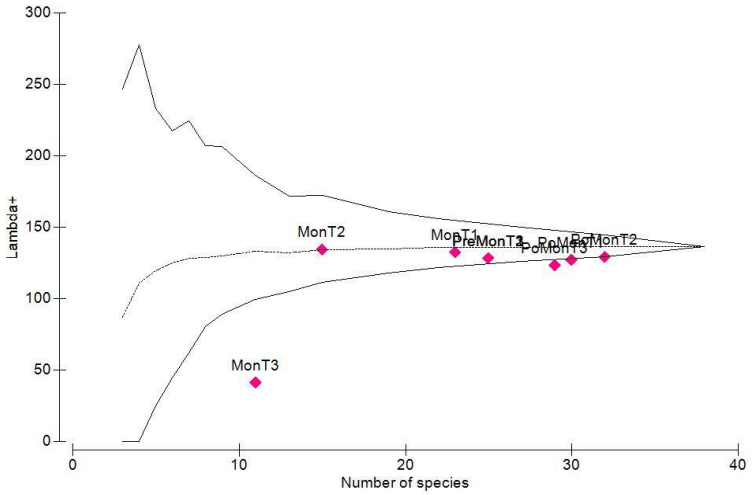


Fig.5.67 The 95% confidence funnel for variation in taxonomic distinctness (Lambda+) values of cyclopoid diversity in Kavaratti Island during 2013-14

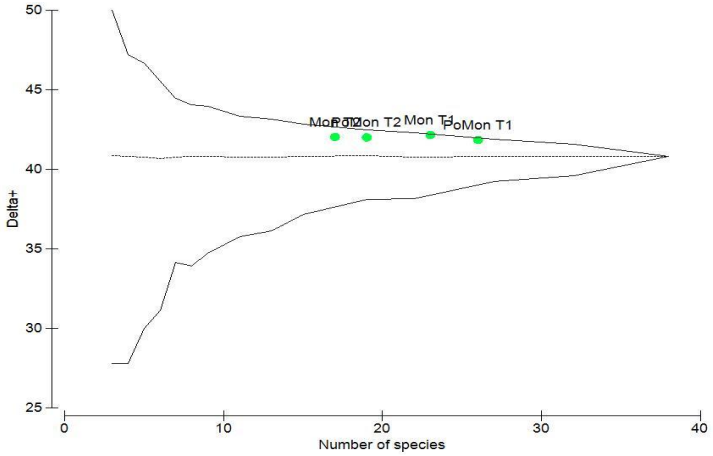


Fig.5.68 The 95% confidence funnel for the average taxonomic distinctness (Delta+) values of cyclopoid diversity in Kalpeni Island during 2013-14

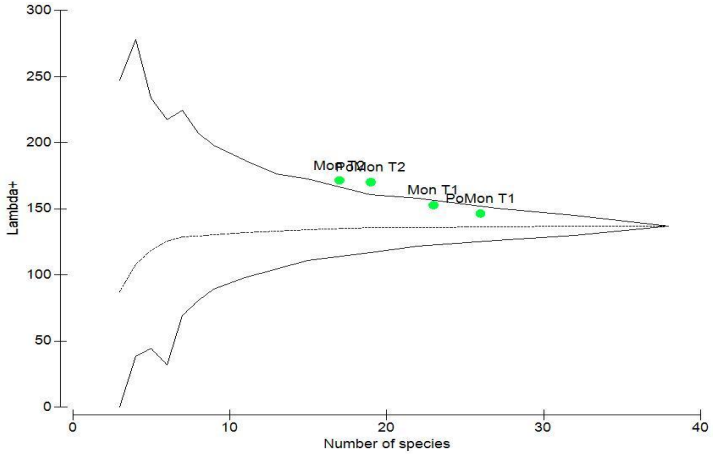


Fig.5.69 The 95% confidence funnel for variation in taxonomic distinctness (Lambda+) values of cyclopoid diversity in Kalpeni Island during 2013-14

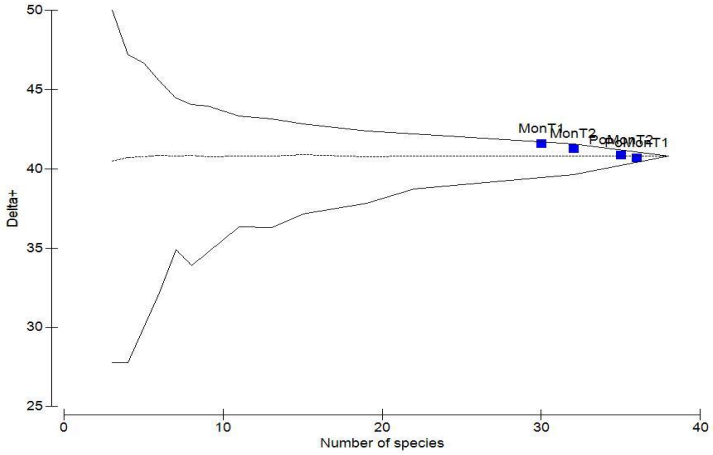


Fig.5.70 The 95% confidence funnel for the average taxonomic distinctness (Delta+) values of cyclopoid diversity in Minicoy Island during 2013-14

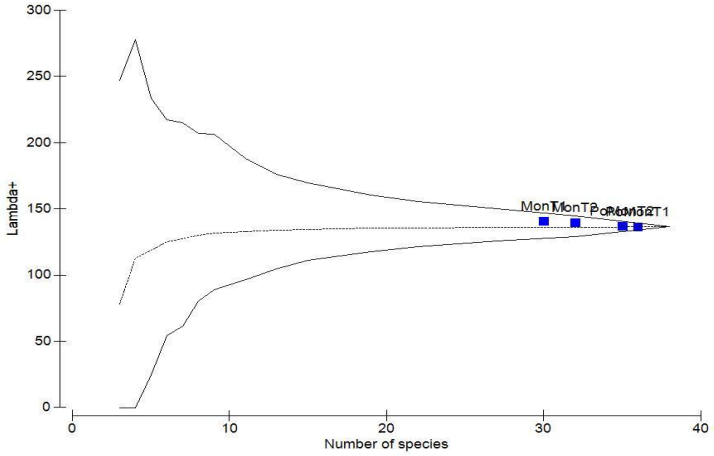


Fig.5.71 The 95% confidence funnel for variation in taxonomic distinctness (Lambda+) values of cyclopoid diversity in Minicoy Island during 2013-14

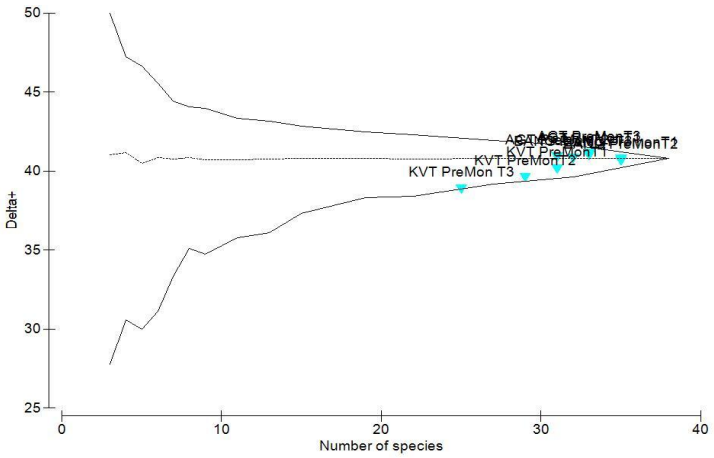


Fig.5.72 The 95% confidence funnel for the average taxonomic distinctness (Delta+) values of cyclopoid diversity in Kvt-Agt-Bang Island during 2014-15

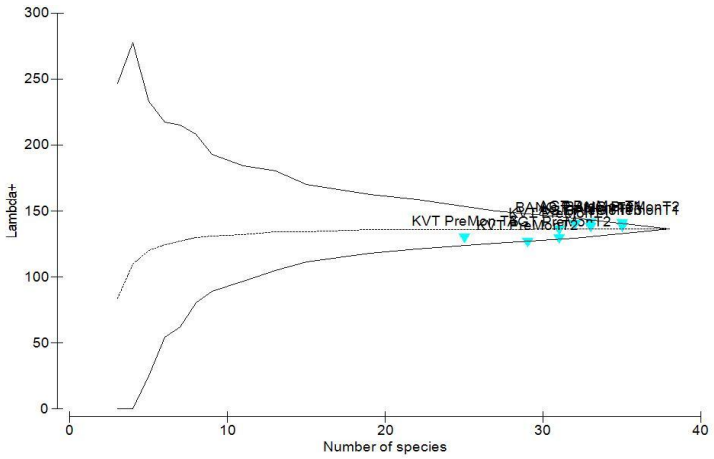


Fig.5.73 The 95% confidence funnel for variation in taxonomic distinctness (Lambda+) values of cyclopoid diversity in Kvt-Agt-Bang Island during 2014-15

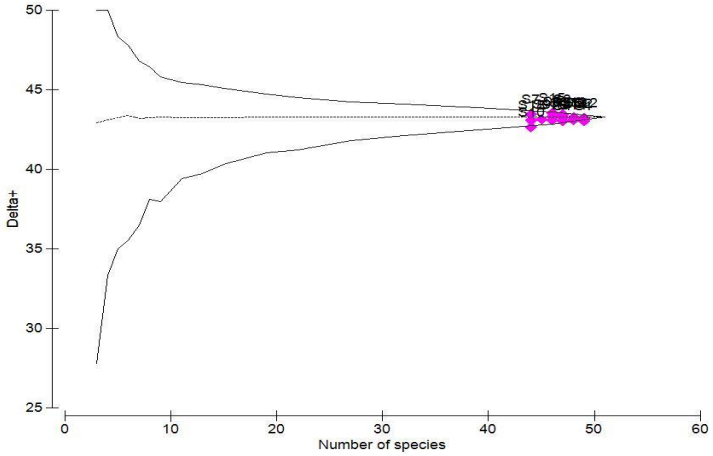


Fig.5.74 The 95% confidence funnel for the average taxonomic distinctness (Delta+) values of cyclopoid diversity in open ocean zones of Minicoy Island during 2015

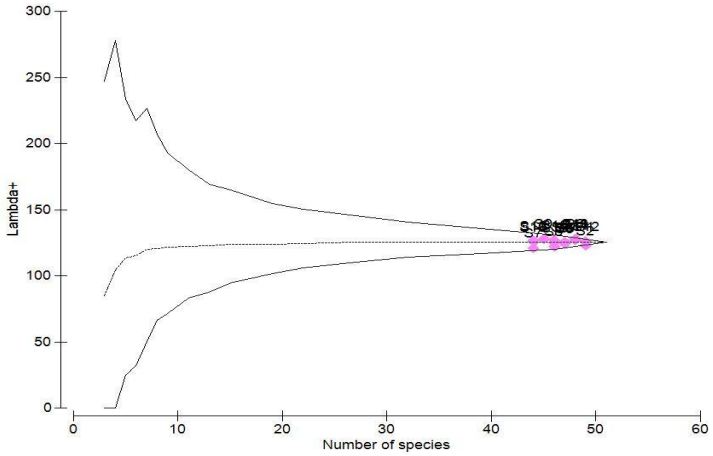


Fig.5.75 The 95% confidence funnel for variation in taxonomic distinctness (Lambda+) values of cyclopoid diversity in open ocean zones of Minicoy Island during 2015

5.7.9 Species accumulation plot

Species accumulation plot shows the cumulative species count against sample number and a number of estimators. The curve denotes whether the data representing the population has given the real patterns in biodiversity. During the first year sampling in Kavaratti, the species observed (Sobs) was 34 and the maximum number of species estimated by species estimators like Chao1, Chao2, Jacknife1, Jacknife 2, Bootstrap, MM and UGE were 34,34,36,40,32,29 and 24 respectively, thus signifying the sampling intensity (Fig.5.76).In Kalpeni, Sobs (species observed) was 31 and the maximum number of species estimated by

Chao1, Chao2, Jacknife1, Jacknife 2, Bootstrap, MM and UGE were 30,35,36,37,33,27and 27 respectively (Fig.5.77). Whereas in Minicoy, Sobs (species observed) was 38 and the maximum species predicted by estimators were Chao1(37spp), Chao2 (38spp), Jacknife1(39spp), Jacknife2 (40spp), Bootstrap (37spp), MM (37spp) and UGE (37spp) (Fig.5.78).During the second year sampling, Sobs was 38 and the maximum species was predicted by Jacknife2 (40spp),followed by Jacknife1 (39spp), Chao2 (38spp), Bootstrap(37spp), MM(37spp) and UGE(37spp) (Fig.5.79). An interisland comparison of the species accumulation plots predicted maximum species by Chao2 (44spp) (Fig.5.80).While in the Minicoy open ocean zones, the species observed (Sobs) was 51 and the maximum species was predicted by Jacknife2 (53spp) thus signifying the sampling intensity (Fig.5.81).

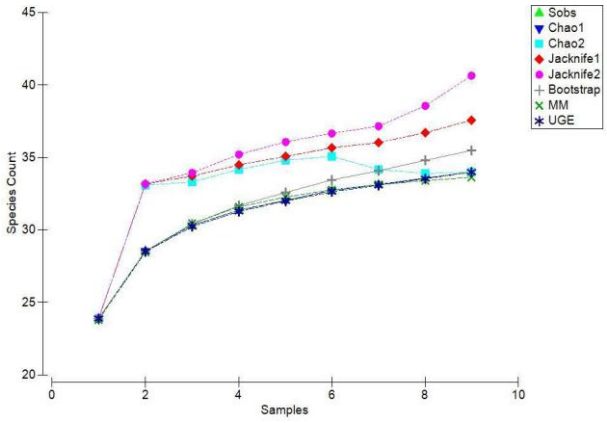


Fig.5.76 Species estimators for cyclopoid species in Kavaratti lagoon during 2013-14

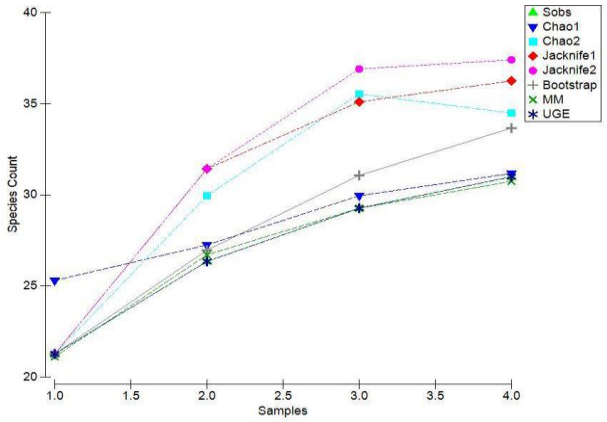


Fig.5.77 Species estimators for cyclopoid species in Kalpeni lagoon during 2013-14

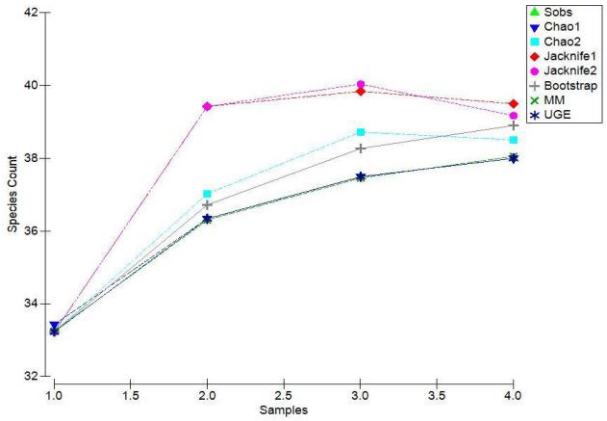


Fig.5.78 Species estimators for cyclopoid species in Minicoy lagoon during 2013-14

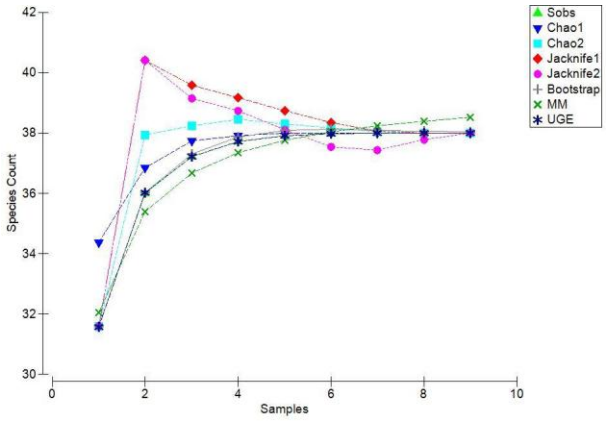


Fig.5.79 Species estimators for cyclopoid species in Kavaratti, Agatti and Bangaram lagoon during 2014-15

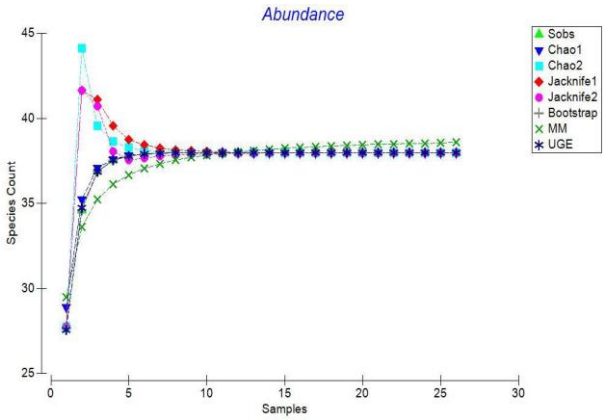


Fig.5.80 An inter-island comparison of species estimators for cyclopoid species during 2013-15

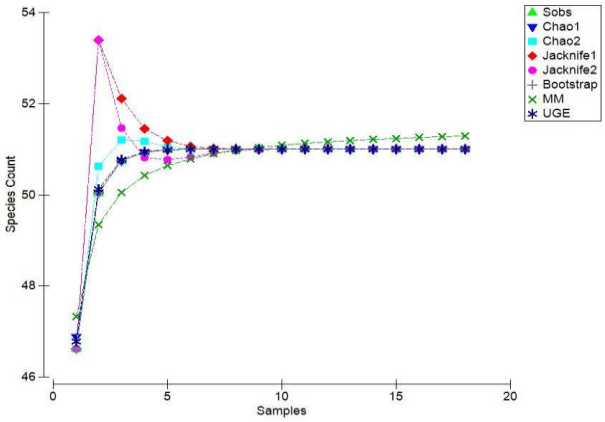


Fig.5.81 Species estimators for cyclopoid species in open ocean zones of during 2014-15

5.8 Discussion

In a marine pelagic food web, the significant role played by the zooplankton in transferring organic carbon from the phytoplankton and bacteria to higher trophic levels have been well depicted in various research papers. Due to their short generation times, zooplankton serves as a measure of biological productivity and responds to any subtle changes in physical chemical and biological parameters in their surroundings (Jagadeesan *et al*., 2013; Anger, 2003; Beaugrand, 2004; Bonnet and Frid, 2004; Queiroga and Blanton, 2004).The zooplankton community, which plays an important role in sustaining the productivity of world's major oceans, has been assessed in numerous research works. Even after the IIOE studies, a dearth of information on quantitative and qualitative distribution of mesozooplankton and copepods from Indian Ocean (Lakshadweep waters) still exists, with very few studies that has been reported (Tranter and George, 1969; Qasim *et al*.,1972; Goswami, 1973; Madhupratap *et al*.,1977;Madhupratap and Haridas 1990; Madhuprathap and Haridas ,1986; Madhupratap *et al*.,1990; Rosamma, 2001;Jean *et al*., 2010; Robin *et al*., 2012).

BoB (Bay of Bengal),the eastern counterpart of Indian Ocean, is generally considered to sustain low biological production (Qasim, 1977; Madhu *et al*.,2002) which in turn is due to cloud cover, large sediment load, narrow shelf, stable stratification and weak winter cooling (Qasim 1977; Senguptha *et al*.,1977; Radhakrishna *et al.,* 1978; Gomes *et al*.,2000; Madhupratap *et al*., 2003; Jyothibabu *et al*.,2004, Sabu *et al*.,2015),now seems to be much more biologically productive

through its cyclones and cyclonic eddies (Madhu *et al*., 2002; Vinayachandran and Mathew,2003;Maneesha *et al*.,2011;Jyothibabu *et al.,*2015).Several studies have documented such an enhancement of biological productivity of BoB during different seasons in response to above said oceanic features (Ramasastry and Balaramamurty 1957; Rao and Sastry 1981; Legeckis 1987; Babu *et al*.,1991, 2003; Murty *et al*.,1993, 2000; Shetye *et al.,*1993; Sanilkumar *et al*.,1997; Madhusoodhanan and James 2003; Prasanna Kumar *et al.*,2002, 2007; Muraleedharan *et al.,* 2007;Kurien *et al.,*2010; Nuncio and Prasanna Kumar,2012, Jyothibabu *et al*.,2015; Sabu *et al*., 2015).However documentation of such oceanic features is limited to western part of Indian Ocean (Arabian Sea)where biological productivity is comparatively higher. As opined by eminent researchers (Madhupratap *et al.,* 1996; Bhattathiri *et al.,* 1996; Nair *et al.,* 1999), coastal and open ocean upwelling during premonsoon and surface cooling of Northern Arabian Sea during monsoon are the main aspects of Arabian sea productivity. Data on distribution of zooplankton in the Atlantic Ocean (Deevey and Brooks 1977; Madin *et al*.,2001; Gaudy *et al*.,2003; Alcaraz *et al*.,2007) and the Pacific Ocean (Roman *et al*.,1995; White *et al*.,1995;Saltzman and Wishner 1997; Kang *et al*., 2004) are also considerable (Fernandes and Ramiah,2009).

Panicker (1968) reported a zooplankton biomass of 0.25ml/m^3 (23mg dry weight/m^3) from Somalia coast and 0.30ml/m^3 (27mg) from Arabian coast. Madhuprathap *et al* (1990) reported a biomass of 108 to 315mg (1.5-3.5 ml/m^3) from central west coast of India. All these reports were comparatively higher than those reported from Lakshadweep lagoons and open ocean waters during the present study. Due to the occurrence of crustacean nauplii, various larval forms along with copepods accounted to higher count and abundance whereas their biomass remained lesser (0.01to 0.13ml/m^3).

Muraleedharan *et al* (2007) recorded mesozooplankton biomass of 0.67ml/m^3 during the summer season in the northern BoB whereas Fernandes and Ramaiah (2009) reported a higher biomass of 1200 mg Cm^{-2} during the summer season from northern BoB. However Jyothibabu *et al* (2008) reported a mesozooplankton biomass of 776 mgCm^{-2} during winter season from Northern BoB. Zooplankton biomass values ranging from 0.01 to 0.3ml/m^3 reported from

GoM (Gulf of Mannar) by Jagadeesan (2015) agreed with the present study but indicated high zooplankton standing stock when compared to adjacent areas. This may be due to the fact that enhancement in phytoplankton biomass during northeast monsoon season (post monsoon) along Indian coast eventually translates to high zooplankton stock (Madhu *et al.,* 2006; Rakhesh *etal*.,2006; Jagadeeshan *et al*.,2013). On the contrary, Jyothibabu *et al* (2008) has reported a low productive season with low zooplankton stock along south east coast of Indian Ocean during premonsoon. Sabu *et al* (2015) reported mesozooplankton biovolume of 0.35ml/m^3 from BoB (Bay of Bengal) and corresponding higher numerical abundance (277ind/m^3) during early winter monsoon season. Besides this, copepods dominated the major mesozooplankton taxa with an average of 225ind m^{-3} (81%). Indeed, Lakshadweep open ocean biomass values during the present study, had an average biomass of 0.03 ml/m^3 with comparatively higher numerical abundance (av.8989 No/m^3) were in accordance to that of above mentioned study. The projected reasons behind the enhancement of mesozooplankton of Northern BoB and North western Arabian sea is due to the deepening of MLD(Mixed Layer Depth)(47m and 55m) respectively as well as long duration of eddies (6 months) in BoB. Similar studies on the increased mesozooplankton standing stock from the eddy region of BoB have been well documented (Muraleedharan *et al*., 2007; Jyothibabu *et al*.,2008).

During the succession of zooplankton, some groups tend to dominate during various seasons in different lagoons and open ocean. The percentage of dominance varied in each season in each lagoon as well as open ocean area. During the present study, all lagoons showed varied nature of zooplankton dominance, during different seasons. In Kavaratti, while cyclopoid copepods showed the highest numerical abundance in premonsoon, other groups and calanoids predominated during monsoon and post monsoon respectively. However in Kalpeni the "other groups" predominated the lagoon but cyclopoids dominated the Minicoy lagoon during postmonsoon. In Agatti and Bangaram lagoons also "other groups'' and copepods predominated. Sea surface temperature and salinity as important predictors of copepod composition has been previously reported from world's major oceans too (Berasategui *et al*., 2005).Qasim and Sankaranarayanan (1970)

have also pointed out previously that lagoons sustain high zooplankton biomass due to higher production of organic matter in the reefs .The dominance of other groups of zooplankton rather than copepods in Minicoy open ocean zones might be due to their salinity tolerance. Persistence of certain copepod groups in the surface layers of ocean may be due to their herbivorous nature which aids them to flourish together without competition (Stephen, 1991). Wide distribution of certain cyclopoid species is partly due to the fact that they have euryhaline (Torres-Sorando *et al*., 2003; Hansen *et al*., 2004) and having eurythermal characteristics (Turner, 2004).

The zooplankton at Kavaratti, Agatti and Suhelipar was studied by Madhuprathap *et al* (1977) while that of Kalpeni and Agatti atolls were dealt by Achuthankutty *et al* (1989). Zooplankters of Kadmat, Kiltan, Chetlat, Agatti, Kalpitti, Bangaram, Bitra, Kavaratti, Suhelipar, Androth, Minicoy and Kalpeni were studied by Girijavallabhan *et al* (1989).An account on diel variation in zooplankton of Minicoy lagoon and Kavaratti atoll was given by Goswami and Goswami (1990). While Suresh and Mathew (1997) studied the zooplankton in Kavaratti atoll; Minicoy lagoon zooplankton was worked out by Nasser *et al* (1998).Prabhakaran (2008) gave an account on the ecological studies on the seagrass ecosystem of Minicoy lagoon. An account on *Sagitta* from Agatti lagoon was given by Casanova and Nair (1999) whereas Bhalla *et al* (2007) reviewed on the foraminiferal studies in Laccadive Islands. A hierarchical analysis of zooplankton assemblages over semidiel pattern in the lagoon of Kavaratti atoll was made by Jose *et al* (2010) and Robin *et al* (2012) studied planktonic communities and their trophic interactions in Kavaratti waters. Recently, Varghese *et al* (2015) gave an account on the zooplankton abundance in Amini and Kadamat islands.

An interisland comparison on the basis of mesozooplankton abundance established that Kavaratti was the most abundant island and Kalpeni, the least during the first year. Whereas during the second year, Bangaram contributed to the peak abundance of fauna and the least for Kavaratti Island. Since, open ocean samples of only Minicoy Island could be taken; a comparison of it with its respective lagoon (Minicoy lagoon) revealed that the lagoon is more abundant in zooplankton than the ocean. This might be due to relatively stable environmental

conditions, which prevailed inside the lagoon. On the contrary, deprivation of abundance in Kavaratti lagoon compared with Agatti and Suhelipar lagoons was formerly reported by Madhuprathap *et al* (1991).However, the present study revealed Minicoy open ocean to be more abundant than Kalpeni, Agatti and Bangaram lagoons .This might be because the open oceans are larger and deeper and have more carrying capacity as stated by Madhuprathap *et al* (1991) who reported the zooplankton abundance in Kavaratti being higher in sea compared to lagoons.

In Kalpeni, both the seasons witnessed comparatively lower abundance of copepods and other zooplankton in T1 (coral area). A lower zooplankton abundance was observed in the coral reef area and according to Gerber and Marshall (1974) and Sale *et al* (1976) it is typical of such coral reef environments. Avoidance behavior to this shallow area as well as predation by the coral reef community may be the reason for this (Glynn, 1973).Whereas, the greater abundance of zooplankton in the lagoon area might be of the reason wherein that particular environment is more apt to promote growth and reproduction of holoplanktonic species. Another possible explanations might be better food conditions, lack of intensive predation, lack of shelter such as sea grass foliage which provides more shelter to the zooplankton groups (Goswami,1973) and comparatively deeper water column. Present study witnessed the abundance of not being confined to a specific area but showing variation among lagoons.

The inter-annual variation of zooplankton is also greatly influenced by rainfall pattern and salinity zonation as these parameters would vary according to seasons. The temperature is also a major factor driving the year-to-year variability in zooplankton abundance. Studies pertaining to the implications of eddies to the mesozooplankton community structure are very few. Documentation on sustaining high mesozooplankton biomass, abundance and diversity by cyclonic eddies in the BoB has been reported by Muraleedharan *et al* (2007).

Earlier studies that have portrayed a substantial impact of ocean circulation on the physico- chemical aspects of island waters has been well discussed in chapter 4. Therefore, this subsequently will have an effect on its zooplankton distribution.

Oceanographic literatures has sustained a vigorous discussion on the biophysical forcing that drives spatial and temporal variability in marine productivity. Physicochemical characteristics like temperature, salinity, pH, inorganic nutrients and dissolved oxygen influences the abundance and distribution of zooplankton which substantiates the fact where seasonality in mesozooplakton abundance may be associated with variation in the physicochemical parameters (Chicaro and Chicaro,2000). Factors like low light intensity, high current velocity and high turbidity adversely affects mesozooplankton abundance (Nasser *et al.*, 1998).Shankar and Shetye (1997) have very well explained the dynamics of the Lakshadweep highs and lows in the south eastern Arabian Sea with an analytic model and with numerical simulations using a dynamical reduced-gravity model. Huntley *et al* (2000) have also suggested the importance of the life span or persistence of eddies in the favourable distribution of mesozooplankton. Studies by several researchers have proved the importance of mesoscale features in controlling the structure and productivity of marine planktonic communities (Owen 1981; Angel and Fasham 1983; Mann and Lazier 1991; Olson 1991).

In the present study, chlorophyll a have showed a significant ($p \leq 0.01$) negative correlation with mesozooplankton and cyclopoid abundance. Maximum concentration of chlorophyll a that coincided with peak value of phytoplankton standing crop (11350-13250 cell/L) and high primary productivity (1.32-2.58 g C m^3d^{-1}) but low zooplankton density (538-648 no/m^3) was documented by Robin *et al* (2013) from Kavaratti waters who also found a positive correlation between chlorophyll a with phytoplankton standing crop. This was supported by similar studies by Devassy and Goes (1991) from Mauritius island. Therefore, lower zooplankton abundance recorded in Kalpeni during monsoon season can be attributed to comparatively higher chlorophyll a values during the present study and vice versa during postmonsoon season. Relatively higher chlorophyll a values were noted than the present study (0.91mg/m^3-1.72 mg/m^3) articled by Honey *et al* (2014) from Port Blair Bay and Mahatma Gandhi Marine National Park of Andaman islands is attributed primarily to the rich mangrove and coral reef resources as opined by Gopinathan and Rajagopalan (1983) and Pillai (1983) since these ecosystems performs a vibrant role in primary production which in turn

provides food and shelter for zooplankters and thereby accelerating the secondary production. Peak chlorophyll a values (8mg/m^3-22.7mg/m^3) reported from south eastern Arabian Sea in summer monsoon by Lathika *et al* (2013) can be related to the coastal upwelling particularly during this season leading to intense biological productivity (phytoplankton production) and thus lowering the secondary production. Similar results was documented by Karnan *et al* (2017) from south eastern Arabian Sea during premonsoon and south west monsoon seasons. Role of cyclonic eddies on upholding moderate amount of chlorophyll biomass and productivity have been reported by Prasannakumar *et al* (2010) along BoB waters.

Since 1972, many of the eminent scientists have been surveying zooplankton assemblages with special reference to copepods with emphasis on calanoid copepods and little on cyclopoid copepods. Copepod research in Kavaratti island of Lakshadweep archipelago started with Goswami (1973, 1979,1983,1990) from National Institute of Oceanography, who reported fifty two species from Kavaratti lagoon and sea among which only sixteen species belonged to cyclopoid group, the rest being calanoids. Subsequent studies in the same region by Madhuprathap *et al* (1977) included thirty species out of which only seven came under cyclopoids and the rest being majority of calanoids. Madhuprathap *et al* (1991) yielded only one cyclopoid and fourteen species of calanoids from Kavaratti, Kadamat and Minicoy islands. Suresh and Mathew (1997) from CMFRI, Cochin also reported copepods from Kavaratti. Only six species of cyclopoids were reported by Usha Goswami and Goswami (1990) from Kavaratti and Minicoy islands, the rest being thirty three species of calanoids and three species of harpacticoids. Studies by Robin *et al* (2012) reported only three cyclopoid species, ten species of calanoids and one harpacticoid.

Subsequent to the International Indian Ocean Expedition (IIOE, 1962-65), knowledge on the distribution of planktonic copepods has enhanced our knowledge about the Indian Ocean. Inspite of the extensive studies from IIOE, information on planktonic crustaceans especially copepods, from South West Arabian Sea (mainly coral habitats), a biodiversity hot spot, was least accounted. Taxonomic and diversity studies on copepods in Lakshadweep islands have usually been concentrated on calanoid group and little is known about the marine

cyclopoid groups. However, the present study has briefly outlined fifty one species of cyclopoid copepods identified from four important families, ten genera from five islands ie Kavaratti (Kvt), Kalpeni (Klp), Minicoy (Mcy), Agatti (Agt) and Bangaram (Bang).

Cyclopoid species diversity showed a wide range of variation in which the species reported from the present study included eighteen species under the genus *Corycaeus*; five species from genus *Farranula*; eight species from genus *Oncaea*; five species from genus *Oithona*; two species from genus *Dioithona;* ten species from genus *Sapphirina* and three species from genus *Copilia.* Among this *Sapphirina* and *Copilia* species were found only from Minicoy open ocean stations and not from lagoons. On the contrary, Goswami (1973, 1979 and 1983) reported *Copilia mirabilis* from Kavaratti lagoon as well as from sea. But *Oncaea conifera, Corycaeus pellucidus*, *C.longistylis, Oithona tropica, Oithona robusta* and *Sapphirina ovalolanceolata* reported by Goswami, was absent during the present study.

Madhuprathap (1977) reported seven cyclopoid species from Kavaratti and Agatti (sea and lagoon) of which *O.brevicornis* was found only from Agatti (sea and lagoon); *O.plumifera* was only observed from Kavaratti and Agatti Sea and not from the other lagoons; *Corycaeus* spp. from both open sea and lagoons of Kavaratti and Agatti; *Sapphirina* spp*.* and *Copilia* spp. only from Kavaratti and Agatti Sea, not from lagoons. This might be due to the difference in sampling intensity and seasons. The present study were consistent with some of the salient findings of Madhuprathap *et al*.,1991 in which *Sapphirina* and *Copilia* species could be identified only from Minicoy open ocean stations and not from the lagoon stations which may be due to the reason that they prefer warmer and low saline waters than that of lagoons. *O.plumifera* was identified from Kavaratti, Kalpeni, Minicoy, Agatti and Bangaram islands. *Dioithona oculata* was the only cyclopoid species reported by Madhuprathap *et al.,*1991 from Minicoy and the present study also reported the same species from almost all the islands during the second year. The present study presents the pioneering work on cyclopoid diversity from Bangaram waters which reported thirty six species. Robin *et al*., 2012 reported *Oithona nana, Dioithona rigida* and *Oithona similis* from Kavaratti waters which corroborated with the present study.

The total number of species reported in the present study was comparatively higher than other reports from the same area (Madhupratap *et al*., 1977; 1991; Jose *et al*., 2010; Robin *et al*.,2012). Goswami (1973) from National Institute of Oceanography reported six cyclopoids from Kavaratti lagoon and sea. Subsequent studies in the same region (Madhuprathap *et al*., 1977) recorded only two cyclopoids. Goswami and Usha (1977) reported six species of cyclopoids from Kavaratti and Minicoy islands. The present study was represented by four families ie. Corycaeidae, Oncaedae, Oithonidae and Sapphirinidae.

Even though cyclopoids were recorded by Goswami (1979), it was represented by three families as recorded in the present study, but with fewer numbers. The family Oithonidae and Corycaedae contributed greatly to cyclopoid composition in Kavaratti lagoon (Madhuprathap *et al*.,1977), seemed to be consistent with the present study . The cyclopoids reported by Goswami (1990) represented the three families recorded in the present study too. Studies by Robin *et al* (2012) included only two families ie Corycaedae and Oithonidae .

In 2013-14,a seasonal comparison of cyclopoid abundance showed that, post monsoon season witnessed more abundance of cyclopoid species and Minicoy came out with the highest number of cyclopoid species (38spp) followed by Kavaratti (34spp) and Kalpeni being the least (27spp). Monsoon season witnessed comparatively lower number of species in Kavaratti, Kalpeni and Minicoy. However, during 2014-15, Agatti came out with highest diversity (37spp) followed by Bangaram (36spp) and Kavaratti (35spp).However the open ocean stations contributed the most diverse array of cyclopoid species in which *Sapphirina* and *Copilia* species were totally absent in lagoon stations.

In Barnett's (1967) study of the vertical distribution of the copepods at Enewetak lagoon, Marshall islands of Pacific Ocean, he reported sixty seven species. Gerber(1981) has recorded about seventy eight species of planktonic copepods during winter from the same lagoon of which only fourteen were cyclopoids. A comparison of the above reported studies with that of the present study reveals a comparatively higher abundance in the Lakshadweep lagoons. A study from coastal areas of Andaman islands also documented copepods as the most abundant mesozooplankton (Honey *et al*., 2014) that was similar to that of

earlier reports (Marichamy, 1983; Madhupratap *et al*.,1981).Andaman islands witnessed an abundance of cyclopoids and poicilostomatoids during north east monsoon season. Similar reports of cyclopoid dominance from Indian Ocean waters have been previously published by various authors (Madhupratap and Haridas, 1986).Cylopoid species like *Oncaea venusta* and *Corycaeus sp*. were observed in plenty in those studies.

Kasthurirangan (1963) has reported many species of genus *Corycaeus*, *Oithona*, *Sapphirina* and *Copilia*. Stephen (1973) reported the presence of Oncaeidae, Corycaeidae, Sapphirinidae and Oithonidae families from Arabian Sea and Bay of Bengal with 6.2% to 15.5%. Sastry and Rao (1981) reported the prevalence of copepod abundance with a conspicuously high density of 90100/100m^3 from BoB than 30000/100m^3 in Arabian Sea which may be due to low scale upwelling that existed during south west monsoon. It is well stated that the preponderance of cyclopoids along west coast of Indian Ocean is very well supported by the succession of copepods along continental shelf of USA during upwelling (Paffeenhoffer *et al* .,1988). It is also stated that the species under the family Oncaeidae and Oithonidae persists for longer duration in early upwelled waters.

Among the cyclopoids, the families Corycaedae, Oithonidaea, Oncaeadae, Sapphirinidaea dominated in the present study. Goswami (1973) also reported the same families from Kavaratti sea and lagoons. He reported *C.mirabilis* from Kavaratti lagoon but the present study could find *C.mirabilis* only from Minicoy Sea. While Madhupratap (1977) reported *Oithona brevicornis*, *O.plumifera*, *Oithona* spp from Kavaratti lagoons. Many species that were reported to be abundant in previous studies were not found to be occurring in the study conducted by Robin *et al* (2012) in Kavaratti waters as he recorded only *Oithona nana*, *O.rigida* and *O.similis*.

During the succession of cyclopoid copepods, some groups tend to dominate during various seasons in different lagoons and open ocean. Many cyclopoid species appeared in an order and a few one among them dominated leading to the succession of cyclopoid copepods in Lakshadweep Sea. In Kavaratti during premonsoon season, certain species like *Onychocorycaeus agilis, Farranula gibbula, F.concinna, F.gracilis,* and *Corycaeus crassiusculus* predominated the lagoon. While during monsoon season, *C.crassiusculus, C.speciosus* showed predominated. In

postmonsoon season, *F.gibbula, F.concinna, D.andrewsi* and *C.crassiusculus* was found to be the most dominating species.While in Kalpeni during monsoon, *O .latus*, *O.agilis* and *D.dahli* predominated. However, during post monsoon, a clear succession of *Oithona plumifera* occurred over the other existing species even if some of it (*D.dahli*) showed its prevalence. The monsoon season of Minicoy witnessed the succession of *Dioithona rigida, Oithona plumifera* over the existing species under the family Corycaedae (*C.crassiusculus, O.agilis, D.andrewsi*) whereas the postmonsoon season of Minicoy lagoon beheld the preponderance of *Oncaea venusta* and *Oithona similis.* During premonsoon season, when Agatti showed the predominance of *Oncaea* species (*O.venusta* and *O. paraclevei*), Bangaram and Kavaratti showed the predominance of *F.gracilis* and *C.speciosus* respectively. However most of the species occurrence in lagoon stations of various islands showed more a less a homogenous pattern of distribution. Anyhow, in Minicoy open ocean zones during premonsoon season, a clear succession *Sapphirina* and *Copilia* species encountered with *S.auronitens, S.opalina, C.mirabilis* and *C.hendorffi* predominating the cyclopoid copepod community. All these spatiotemporal disparity in the type of species could be possible since different species could fill the different niches owing to their salinity temperature tolerance and preference (Madhupratap, 1977)

Several studies related to the predominance of copepoda group in the mesozooplankton community have been documented previously in various parts of Indian Ocean. Predominance of copepods during the present study was in agreement with earlier records from GoM (Gulf of Mannar) and Palk Bay (Prasad, 1954; Kartha 1959), coastal waters of Arabian Sea (Madhuprathap *et al*.,1990, 1992) and BoB (Rakesh *et al.*,2006, 2008; Fernandes, 2008). Studies of Muraleedharan *et al* (2007) and Fernandes (2008) which focused on the copepod assemblages and zooplankton standing stock documented the positive response of mesozooplankton to Chl-*a* in the cyclonic eddy region of Northern BoB.

Further Jyothibabu *et al* (2012) documented mesozooplankton along with copepod dominance along the south eastern part of the Indian Ocean. McKinnon *et al* (2012) compared the pelagic copepod communities from Australia's Indian Ocean territory atoll lagoon, adjacent to eastern Indian Ocean where the zooplankton community was dominated by copepods and recorded over two

hundred and twenty copepod species belonging to five orders. In that they reported family Oncaeidae to be the most speciose one with fifty two taxa. The studies on zooplankton assemblage along the south west Indian Ocean coast by Asha *et al* (2016) has revealed the prominence of copepods in terms of species richness and numerical abundance that also included cyclopoids.

Copepods being the predominant zooplankton in the study carried out by Jagadeesan (2015) typically contributed from 6.1 to 7.7% of the total abundance with average abundance value of 27873 No/100m^3 (premonsoon), 53059 (monsoon) and 84220No/100 m^3 (postmonsoon).This was comparatively higher to that of the present study in Lakshadweep lagoon as well as open ocean stations. Similar kind of seasonal mismatch of zooplankton biomass and abundance wherein zooplankton density tends to be higher while zooplankton biomass is moderate (0.01 to 0.3ml/m^3) during premonsoon in south west and vice versa in north east monsoon periods has already been reported from the eastern Arabian Sea (Padmavati and Goswami,1996).

The cyclopoid copepod communities in our study were distinguished broadly in accordance with abundance as criterion for different seasons at five different islands. The assemblages identified by cluster analysis were for the most part determined by species composition and abundance. Documentation on influence of salinity and temperature differences in overall composition and community structure of zooplankton on coastal waters have been documented by eminent researchers (Ashadevi *et al*., 2010; Jyothibabu *et al*., 2008; Gaudy *et al*., 2000; Balncobercial *et al*., 2006; Berasategui *et al*., 2005).While most of the families seemed to show varying degrees of preferences of high salinities, Sapphirinidaea family preferred low salinity and warmer open ocean areas in the present study.

In recent years, in order to understand the role of ocean currents in structuring the mesozooplankton community, there has been an upturn of scientific interest. Although the ocean currents in and around the Indian Ocean had been well documented over the last several decades, their role in configuring the zooplankton community is still unknown (Jyothibabu *et al*., 2008). Jagadeesan *et al* (2015) has pointed out the active role of ocean currents in structuring copepod community along northern Bay of Bengal. Greater abundance of low saline species is interrelated

with ocean currents that bring low saline BoB waters to west coast of India during the north east monsoon period (post monsoon). Occurrence of high saline species like *Farranula gibbula*, *Sapphirina* species and *Copilia* species in Minicoy open ocean zone is attributed to low influence of intruded BoB waters on the hydrography of Lakshadweep during spring inter monsoon (premonsoon) as well as the biogeography of GoM(Gulf of Mannar) which is permanently open to neighboring Arabian Sea.This facilitates the frequent occurrence of high saline species in Lakshadweep waters. Consequently, the impact of salinity and temperature on copepod assemblage along north eastern Arabian Sea during northeast monsoon, spring inter monsoon and fall inter monsoon is in turn governed by the ocean currents. While all the fifty one cyclopoid species were present in open ocean zones of Lakshadweep waters (Minicoy island), only twenty five cyclopoid species existed in lagoon waters during spring inter monsoon (premonsoon) period which may be due to weakened monsoon currents which reverse its direction. This stable environmental conditions during spring intermonsoon preferred the diversification of copepods in open ocean zones with the dominance of *Sapphirina* and *Copilia* species. In summary, a conspicuous difference in copepod composition in open ocean zones and lagoon transects during spring intermonsoon period can be primarily linked with relatively weak ocean currents. On the other hand continuous circulation and increased mixing of waters during the north east monsoon and fall intermonsoon periods resulted in almost a homogenous cyclopoid copepod community in the study area.

5.8.1 Community structure

Diversity is a concise way on how individuals of a community are distributed in subsets of groups. When one or a few groups dominate in a community or when individuals of a more common group replace individuals of a rare group or when one or few groups rapidly reproduce, diversity decreases. Diversity indices are tools that have been developed to analyze mathematically and compare changes in aquatic communities due to environmental influence. In the present study, mesozooplankton diversity was inversely linked to abundance wherein Kavaratti showed low diversity in the first year. This low diversity might be caused by the high abundance of cyclopoid species. Similar trends was reported previously in various parts of Indian Ocean (Varadharajan and Soundarapandian,

2013; Nair *et al*.,1981). In the present study, higher values of J' and H' observed in Kavaratti than those reported by Robin *et al* (2012) in the same lagoon are concomitant with stable environmental conditions prevailing in the lagoon which permitted plankton community to diversify (Goswami *et al*.,1992).

The MDS (Multi-dimensional Scaling) plots are used to construct a "map" of the sampling sites where in, the more similar samples in terms of species abundance are more nearer to each other (Clarke and Green, 1983).MDS plots uses interpretation points in which the points which are close together represents samples with very similar species composition and points that are far apart corresponding to different communities/abundance. The extent of this relationship is expressed as stress coefficient statistics, with low values indicating success (eg. <0.1).

Using multivariate analysis(MDS plots), it was possible to divide the transects into three groups in Kavaratti and Kalpeni based on cyclopoid abundance during the first year ,two groups in Kavaratti, Bangaram and Agatti during premonsoon season of second year and eight groups in Minicoy open ocean. Dendrogram and MDS plots based on mesozooplankton analysis of Minicoy open ocean stations revealed that S7 (Station7) stood apart forming three clusters. From the whole MDS analysis, it was confirmed that seasonal samplings are best for the interpretation of the faunal composition of Lakshadweep islands.

In the present study, the interpretation of similarity ranking of various islands of Lakshadweep using both the mesozooplankton and cyclopoid abundance revealed good ordination with the samples collected. It was indicated by a low stress value of 0.01 for mesozooplankton and cyclopoid abundance in Kavaratti 2013-14;a stress value of zero in Minicoy and Kalpeni 2013-14;a stress value of 0.05(mesozooplankton) and 0.01(cyclopoids) in Kavaratti, Bangaram and Agatti. In Minicoy open ocean, a stress value of 0.09 (mesozooplankton) and 0.11 (cyclopoids) was witnessed.

Bray Curtis similarity analyses based on mesozooplankton and cyclopoid abundance at five lagoons revealed 35-95% and 20-80% similarity in Kavaratti; 42-90% and 23-80% similarity in Kalpeni; 62-93% similarity in Minicoy; 86-88% similarity in Agatti, Bangaram and Kavaratti 2014-15.However, in Kavaratti 13-14, PreMonT2 (inner lagoon) stood apart from other clusters due to reduced copepod

abundance in this transect with the absence of thirteen cyclopoid species whereas MonT1, PoMonT1 stood apart due to higher abundance than the other two transects with fifteen cyclopoid species absent in MonT1 and four spp. absent in PoMonT1. During 2014-15 premonsoon, AgtT2, KvtT3 and BangT1 stood apart from other clusters. It might be due to the lower abundance in inner lagoon area (T2) than other two transects in Agatti; lower abundance of cyclopoids in boat channel (T3) in Kavaratti and higher abundance of cyclopoids in coral area (T1) in Bangaram. Similarity analyses in Minicoy open ocean stations during 2014-15 witnessed S7 (station7) being clustered apart due to least abundance compared to other stations. Further the absence of six cyclopoid species viz *D.dahli*, *D.lubbocki*, *F.curta*, *O.nana*, *S.nigromaculata* and *S.vorax* separated S7 (station 7) this from other stations. S10 (station 10)which stood apart was also characterized by second most abundant station as well as the absence of *D.affinis*, *O.media*, *O.brevicornis*, *O.nana, D.rigida*, *S.stellata* whereas absence of *D.rigida* is unique to this station. Similarly in S17(station17),the least abundance of calanoid copepods were observed compared to all other stations along with the absence of *D.dahli*, *F.curta*, *O.media* and *O.brevicornis*. That might be the reason why it stood apart. At the same time S18 (station18) also clustered apart due to high cyclopoid copepod abundance despite the absence of seven cyclopoid species when compared to all other stations.

However ABC plots established that during first year, Kalpeni (Mon) and Minicoy (PoMon) to be moderately disturbed community (abundance and biomass curve intersect) whereas Kavaratti (PreMon), Kavaratti (Mon), Kavaratti (PoMon), Kalpeni(PoMon) as undisturbed community (biomass curve above abundance curve). However in second year, Kavaratti (PreMon), Agatti (PreMon) and Bangaram (PreMon) were established to be undisturbed community. Similarly, TAXDTEST in Kavaratti depicted a less diverse condition with low delta values in both years.Wheras in Kalpeni and Minicoy, TAXDTEST depicted a diverse condition where intermediate (moderate) disturbance existed. In Bangaram also, TAXDTEST depicted a diverse condition where all points clustered together within 95% confidence level.Taxonomic distinctness (Δ+) and variation in taxonomic distinctness (Λ+) analyses are unique ways to evaluate biological assemblages. Species accumulation plots observed and predicted 40 cyclopoid spp.(Kvt), 37spp. (Klp), 39spp. (Mcy) and 38 spp. (Agt and Bang) thus signifying the accuracy of

sampling intensity. Similarly SIMPER (Similarity percentage) analysis was performed to reveal the differences between the sampling stations and to identify the discriminating species (species contributing to the similarities and dissimilarities).

The interaction between organisms and environmental variables in a marine ecosystem are a must for the healthy survival of the organisms. The statistical analysis justified the interaction of organisms with environmental variables that existed in the study area. The results showed that the BEST correlation coefficient (Rho) for total cyclopoids from Minicoy open ocean was 0.015 for DO. In Kavaratti, pH and ammonia were the best correlating variables (σ=0.622) while in Kalpeni, SST, SSS, pH, nitrate, nitrite, phosphate, silicate (σ=0.600) formed the correlating parameters. But in Agatti, Bangaram and Minicoy all were found to be matching variables (σ=1.000). All these correlation was instructive about the response and behavior of organism with fluctuations of these environmental parameters.

Lack of data on cyclopoid community structure in many of the Islands of Lakshadweep leads to an inappropriate basis for comparison. However Jose *et al* (2010) have provided the hierarchical analysis of data concerning the zooplankton assemblages over a semidiel pattern in Kavaratti lagoon which described the dominance of gastropod larvae and its interrelationship to other zooplankton groups. He also established a single separate cluster formation for copepods and its presence as an opportunistic invader to the lagoon ecosystem.

Chapter 6

General Systematics and morphotaxonomy of Cyclopoid copepods

Contents

6.1 Introduction

The subclass Copepoda is represented in the marine plankton by free forms belonging to eight out of the nine orders of Phylum Crustacea (Boxshall and Halsey, 2004): Platycopipoida, Calanoida, Mormonilloida, Misophrioida, Hapacticoida, Cyclopoida, Siphonostomatoida, Monstrilloida. Order Poecilostomatoida can no longer be considered as a group phylogenetically separated from order Cyclopoida. Further, the controversial Thaumatopsylloida was rejected by Boxshall and Halsey (2004) while the order Gelyelloida has been defined from species inhabiting subterranean systems. Compared with that of the parasitic and benthic forms, the number of free planktonic marine species of copepoda is relatively unpretentious (Razouls *et al*., 2017).

Despite the vastness of the volumes of seas and oceans in this world, the echelon of work done on marine cyclopoids are surprisingly fewer. The importance of copepods (cyclopoids) is not only embodied in the role they play in the transfer of energy from primary production to higher trophic levels (Mauchline, 1998) but also, some species may be used as water mass indicators (Longhurst, 1967; Dawson and Knatz, 1980; Cross and Small, 1967), or as bio-indicators for chemical contamination and eutrophication (Dawson and Knatz, 1980). They are important in aquatic food webs either as primary and secondary consumers or as prey items (Williamson, 1991).Besides the above, the popularity of copepods in ecotoxicological studies has also been increasing (Kulkarni *et al.*,2013), and used as bioindicators of ecosystem health (Hanazato *et al.*, 1989; Hanazato and Yasuno, 1989; Ferdous and Muktadir, 2009). South West Asian cyclopoids have been dealt by numerous workers. About 199

species of marine cyclopoids out of 977 copepods are at hand in the Indian Ocean (Razouls *et al*., 2017). Classical taxonomy, the science of naming and classifying organisms accurately when coupled with its ecological and evolutionary elucidation plays an important role in biodiversity conservation, integrated pest control programs (Godfray *et al*.,2004; Samper, 2004).

6.2 Materials and Methods

The materials and methods followed for the study has been described in Chapter 3 (section .3.3)

6.3 Results

Morphotaxonomic descriptions of the cyclopoid copepod species identified during the study are given in this chapter. Fifty one species from four important families, ten genera have been identified and systematically reviewed based on both taxonomic and molecular methods. In order to compare, the known cyclopoid copepod species and to document the phylogenetic affiliations among congeneric species, molecular analysis based on mtCOI gene sequences of some of the identified species were carried out. The morphotaxonomic ambiguity of some cyclopoid species documented during this study has also been resolved successfully by the DNA barcoding methods. Thus, DNA barcodes of nineteen cyclopoid species belonging to four families were developed out of which fourteen were primary barcodes. The details of relevant cyclopoid species which are molecularly characterized are portrayed family wise in the subsequent chapters (Chapter-7, Chapter-8 and Chapter-9)

6.3.1 Taxonomic listing of cyclopoid species

Kingdom: Animalia (Linnaeus, 1758)
Phylum: Arthropoda (Latreille, 1829)
Superclass: Crustacea (Pennant, 1777)
Class: Maxillopoda (Dahl, 1956)
Superorder: Podoplea (Sars, 1903)
Order : Cyclopoida (Burmeister,1835)

Family: Corycaeidae

Genus: *Corycaeus* (*Corycaeus*) Dana, 1845

1. *Corycaeus crassiusculus* Dana,1849

2. *Corycaeus speciosus* Dana,1849
3. *Corycaeus clausi* Dahl F,1894
4. *Corycaeus vitreus* Dana, 1849

Genus *Corycaeus(Urocorycaeus)* (Dahl 1912)

5. *Urocorycaeus furcifer* Claus, 1863
6. *Urocorycaeus lautus* Dana, 1849

Genus *Corycaeus(Onychocorycaeus)* (Dahl 1912)

7. *Onychocorycaeus catus* Dahl F,1894
8. *Onychocorycaeus agilis* Dana, 1849
9. *Onychocorycaeus giesbrechti* Dahl ,1894
10. *Onychocorycaeus latus* Dana,1849
11. *Onychocorycaeus pumilus* Dahl.M,1912
12. *Onychocorycaeus pacificus* Dahl,F 1894

Genus *Corycaeus(Ditrichocorycaeus)* (Dahl 1912)

13. *Ditrichocoryceus andrewsi* Farran,1911
14. *Ditrichocoryceus affinis* McMurich,1916
15. *Ditrichocoryceus dahli* Tanaka,1957
16. *Ditrichocoryceus tenius* Giesbrecht, 1891
17. *Ditrichocorycaeus subulatus* Herrick,1887
18. *Ditrichocorycaeus lubbocki* Giesbrecht, 1891

Genus *Farranula* Wilson,1932

19. *Farranula gibbula* Giesbrecht, 1891
20. *Farranula concinna* Dana, 1853
21. *Farranula gracilis* Dana, 1849
22. *Farranula rostrata* Claus, 1863
23. *Farranula curta* Farran,1911

Family: Oncaedae

Genus *Oncaea* Philippi, 1843

24. *Oncaea clevei* Früchtl, 1923
25. *Oncaea media* Giesbrecht, 1891
26. *Oncaea paraclevie* Bottger-Schnack,2001
27. *Onceaea venusta* Philippi,1843

28. Oncaea scottodicarloi Heron –Bradford,1995

29. Oncaea mediterranea Claus 1863

30. Oncaea macilenta Heron,1977

31. Oncaea curta Sars,1916

Family: Oithonidae

Genus *Oithona* Baird, 1843

32. Oithona similis Giesbrecht,1892

33. *Oithona brevicornis* Giesbrecht,1891

34. Oithona plumifera Baird,1843

35. Oithona nana Farran,1913

36. Oithona simplex Giesbrecht,1892

Genus *Dioithona* Kiefer ,1935

37. Dioithona rigida Giesbrecht,1896

38. Dioithona oculata. Farran,1913

Family: Sapphirinidae

Genus *Sapphirina* Thompson, 1829

39. Sapphirina angusta

40. Sapphirina scarlata Giesbrecht,1891

41. Sapphirina stellate Giesbrecht,1891

42. Sapphrina auronitens Claus,1863

43. Sapphirina opalina Dana,1849

44. Sapphirina metallina Claus,1863

45. Sapphrina vorax Giesbrecht,1891

46. Sapphrirna gastrica Giesbrecht,1891

47. Sapphirina nigromaculata Claus,1863

48. Sapphirina siniuicauda Brady,1883

Genus *Copilia* Dana ,1849

49. Copilia mirabilis Dana,1849

50. Copilia hendorffi Dahl,1892

51. Copilia quadrata Dana,1849

6.3.2 Systematic Account on the cyclopoid copepods of Lakshadweep islands

***Corycaeus crassiusculus* Dana,1849**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy and Bangaram (Refer Table 3.1 and 3.2)

Female (**Fig.1, Plate1):** Total length 0.78-0.8mm.Prosome four segmented, frontal margin arc shaped, with two large separate cuticular lenses. Prosome about twice longer than urosome including caudal rami (2.6:1.3); about 1.8 times as long as wide (2.6:1.4). Genital segment is shorter than anal somite and caudal rami combined. Urosome two segmented with very divergent caudal rami. Genital somite overlaps anal somite at dorsal margin. Anal somite is rectangular shaped with its distal margin ornamented with spinules ventrolaterally; 0.98 times as long as wide at base; slightly shorter than genital somite.

Remarks : Females of *C.crassiusculus* are largely identified by the overlapping of genital segment on anal segment at the dorsal margin; the specimen described here is characterized by body length of 0.78mm; two segmented urosome with very divergent caudal rami; ventro lateral ornamentation of the anal somite; six segmented antennule; ornamentation of the first endopodal segment of the antenna. Descriptions of *C.crassiusculus* by Dana's (1848,1952-55) were based exclusively on male specimens. Yet, the female of *C.venustus* described in the same papers was later identified by Dahl (1912) as the female of *C.crassiusculus.* Therefore the name C.*venustus* was dropped. The present specimen from the waters of the Lakshadweep Islands on comparison with all the known species of the genus show closest similarity with *C.crassiusculus* in shape, size, features of the appendages, arrangements of spines and setae and other characteristics.

Distribution: Atlantic, Mediterranean, Indo-Pacific, Japan Sea, North Pacific (http:// copepods. obs-banyuls.fr/en)

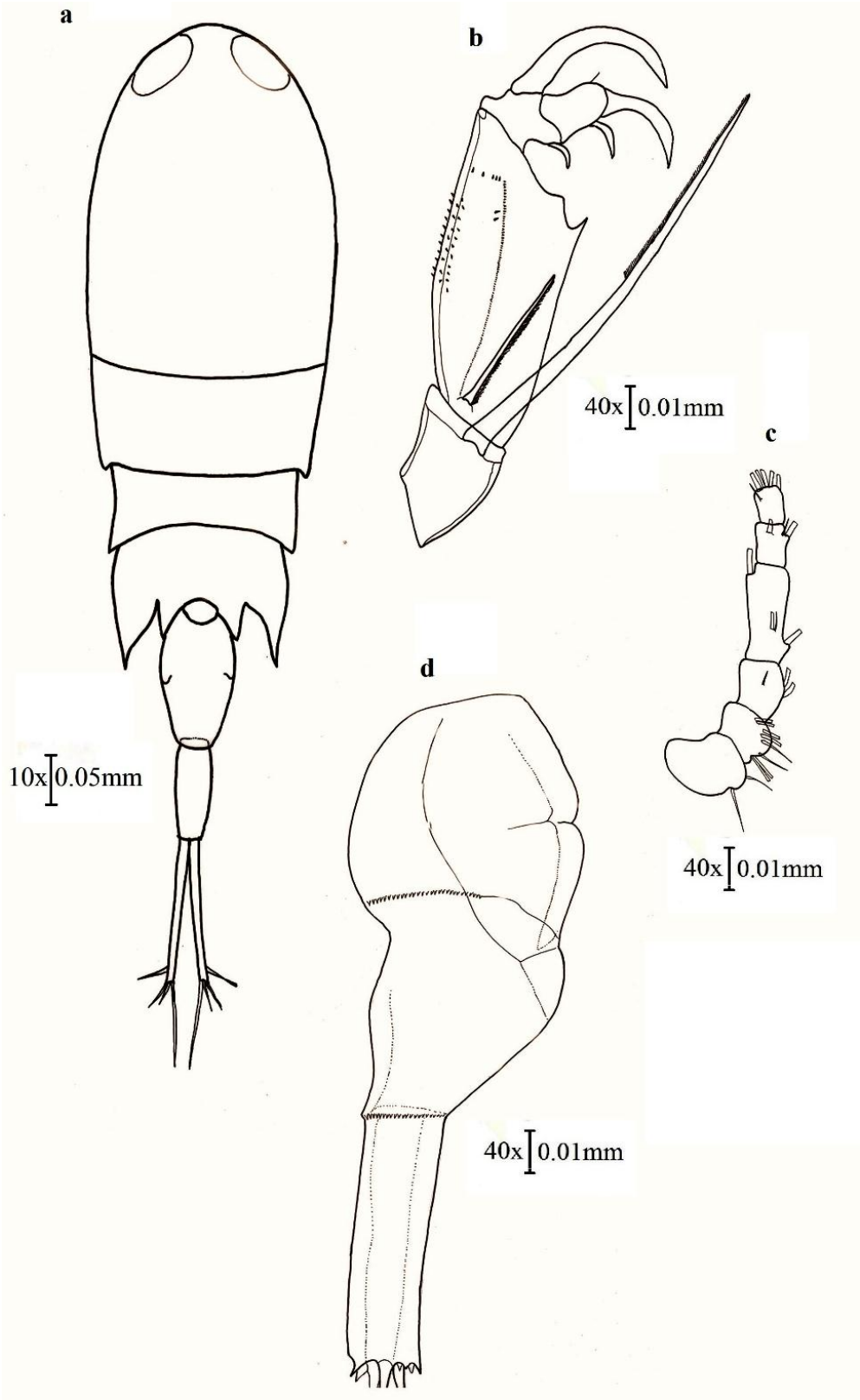


Fig.1. *Corycaeus crassiusculus* female. a, Habitus (dorsal); b, Antenna; c, Antennule; d, Urosome (lateral view).

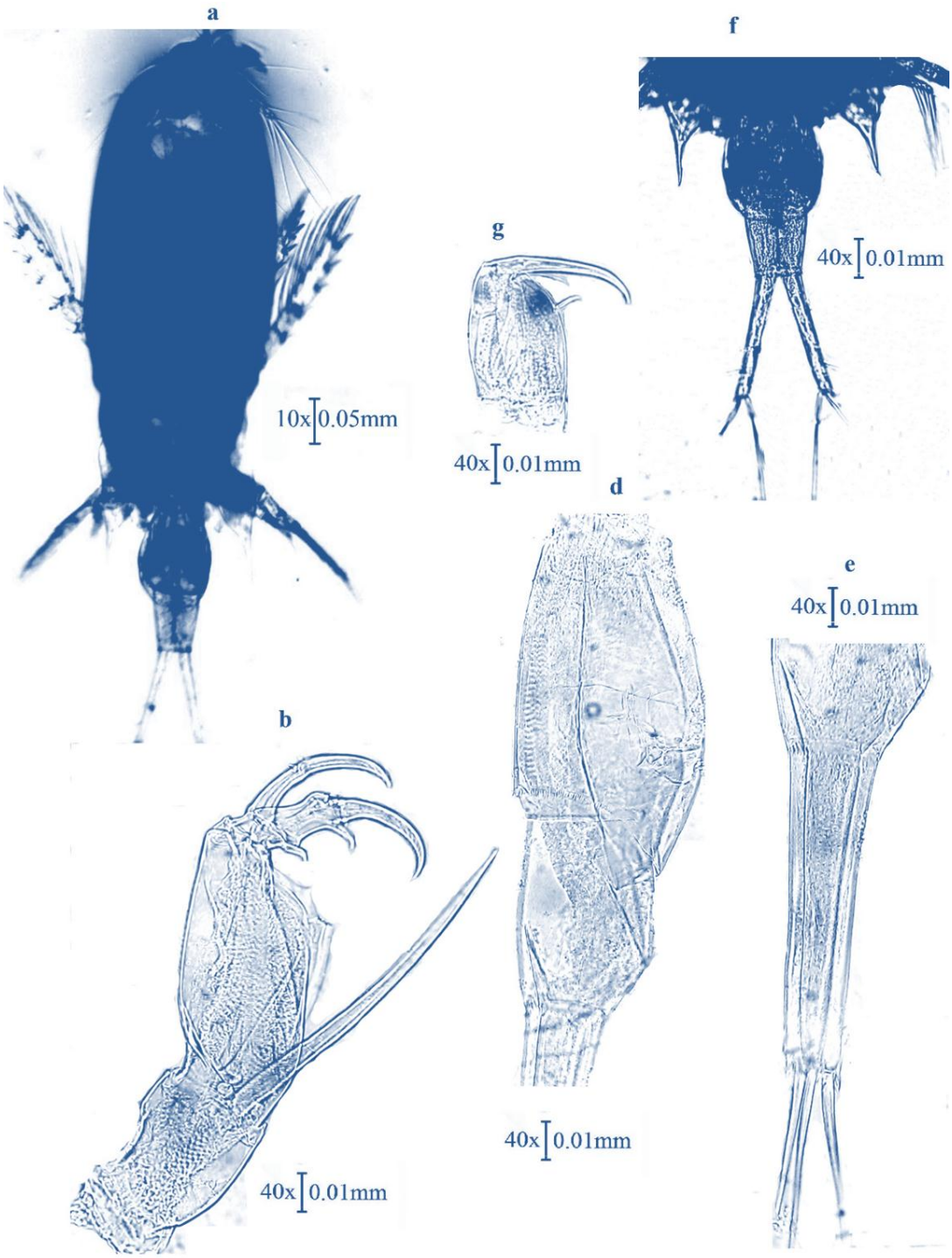


Plate.1. *Corycaeus crassiusculus* female a. Habitus; b,A2;d,Genital segment(GS) (lateral); e, AS and CR; f,urosome;g,maxilliped.

Corycaeus speciosus Dana,1849

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy and Bangaram (Refer Table 3.1 and 3.2)

Female (**Fig.2, Plate2):** Total length 1.80-2.33mm.Prosome 2.05 times longer than wide and 1.4 times as long as urosome. Dorsally visible cuticular lenses present (Fig.2a).Urosome two segmented 3.7 times longer than wide. Almost rhomboid shaped genital double somite 1.95 times longer than wide.AS 1.3 times as long as wide.CR divergent at its base, 1.48 times as long as wide. Ratio of length of urosomal somites and CR 10:4.7:1.7(Fig.2b).A2 four segmented. Coxobasis with a coxobasal setae which is 2.75 times longer than endopodal setae.1st endopodal segment bears a short endopodal setae. 2nd endopodal segment bears 3 elements-one larger and two small. Lateral margin bears numerous spines.3rd endopodal segment bears two elements (Fig.2c)

Male **(Fig.3, Plate3):** Total length 1.03-1.15mm.Prosome 2.05 times longer than wide and 1.6 times as long as urosome. Urosome 2 segmented 2.8 times longer than wide. Genital double somite 1.41times longer than wide.AS 1.81 times as long as wide.CR parallel, 3.66 times as long as wide. Length ratio of urosomal somites and CR 2.4:1:1.1 (Fig.3a). A2 four segmented. Coxobasis with a coxobasal setae which is 1.38 times longer than endopodal setae.1st endopodal segment bears a short endopodal setae. 2nd endopodal segment bears two elements.Lateral margin bears numerous spines.3rd endopodal segment bears two elements of which one is adrawn out as a claw (Fig.2b).

Remarks: In Arabian Sea, this species was first reported by Sewell in 1947. *C.speciosus* is distinguished by its divergent CR, rounded forehead in female and broad one in male. Presence of minute spines on the mid lateral region of the first endopodal segment of the A2 in both females and males is also a distinguishing character. Females are comparatively larger than males. *C.speciosus* is an epipelagic or sometimes bathypelagic species. According to Motoda (1963), this species forms the most common *Corycaeus* in Hawaiian waters and Oahu Island. Kang *et al.,*1990 and Motoda(1963)noted that the length of the coxobasal setae of A2 was 2.8 times that of endopodal setae. Length of coxobasal to endopodal setae was 2.75 for ♀ and

1.38 for ♂ of Lakshadweep specimen. Dana (1849) opined on the length width ratio of CR being 12 times for males. But this ratio was found be lesser in the males of Lakshadweep specimen (3.66). Bjornberg (1963) is considered this species as a typical indicator of warm tropical oceanic water.

Distribution: Tropical, Subtropical and North Temperate Atlantic, Mediterranean, Indo-Pacific, East china Sea, Japan Sea, South and North Pacific. In Arabian Sea, this species was first reported by Sewell in 1947 (http:// copepods. obs-banyuls.fr/en).

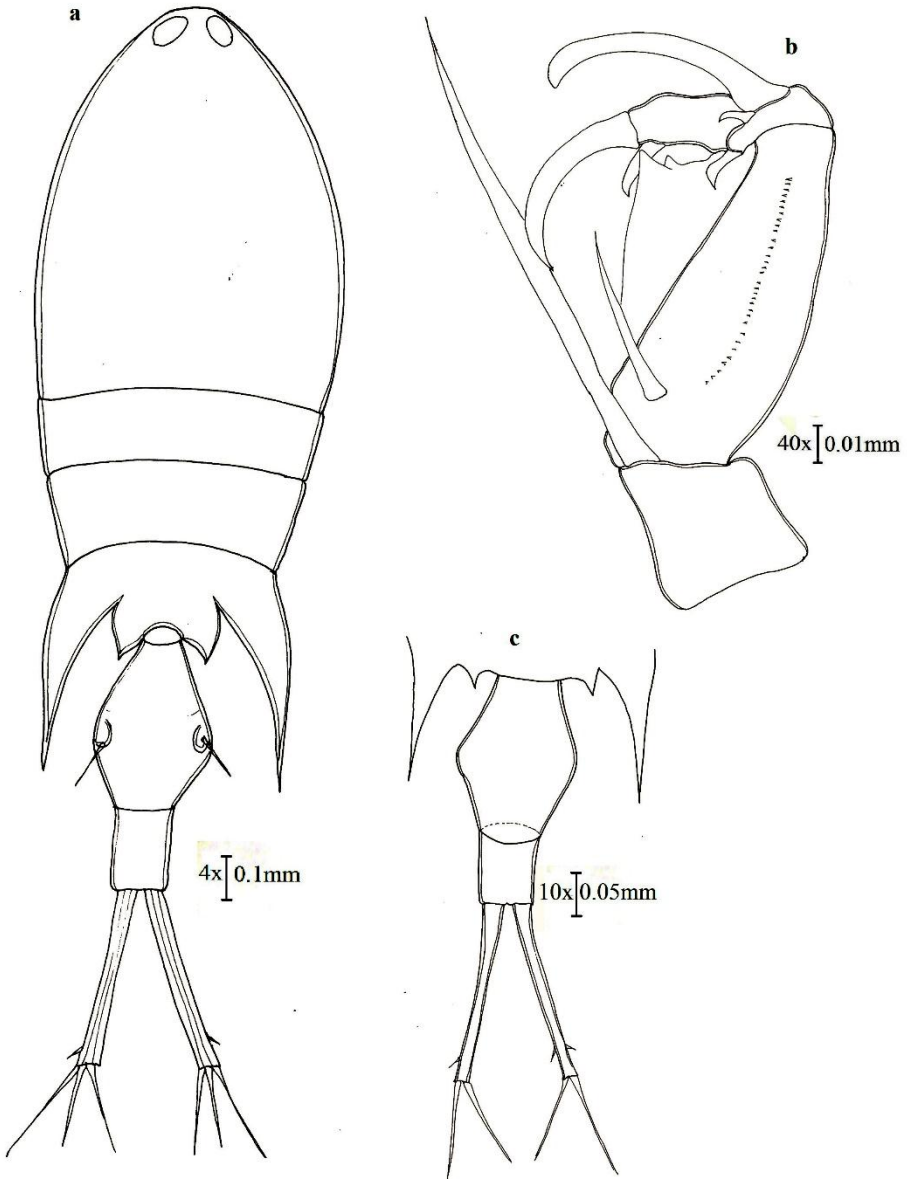


Fig.2. *Corycaeus speciosus* female. a, Habitus(dorsal);b, A2;c,urosome

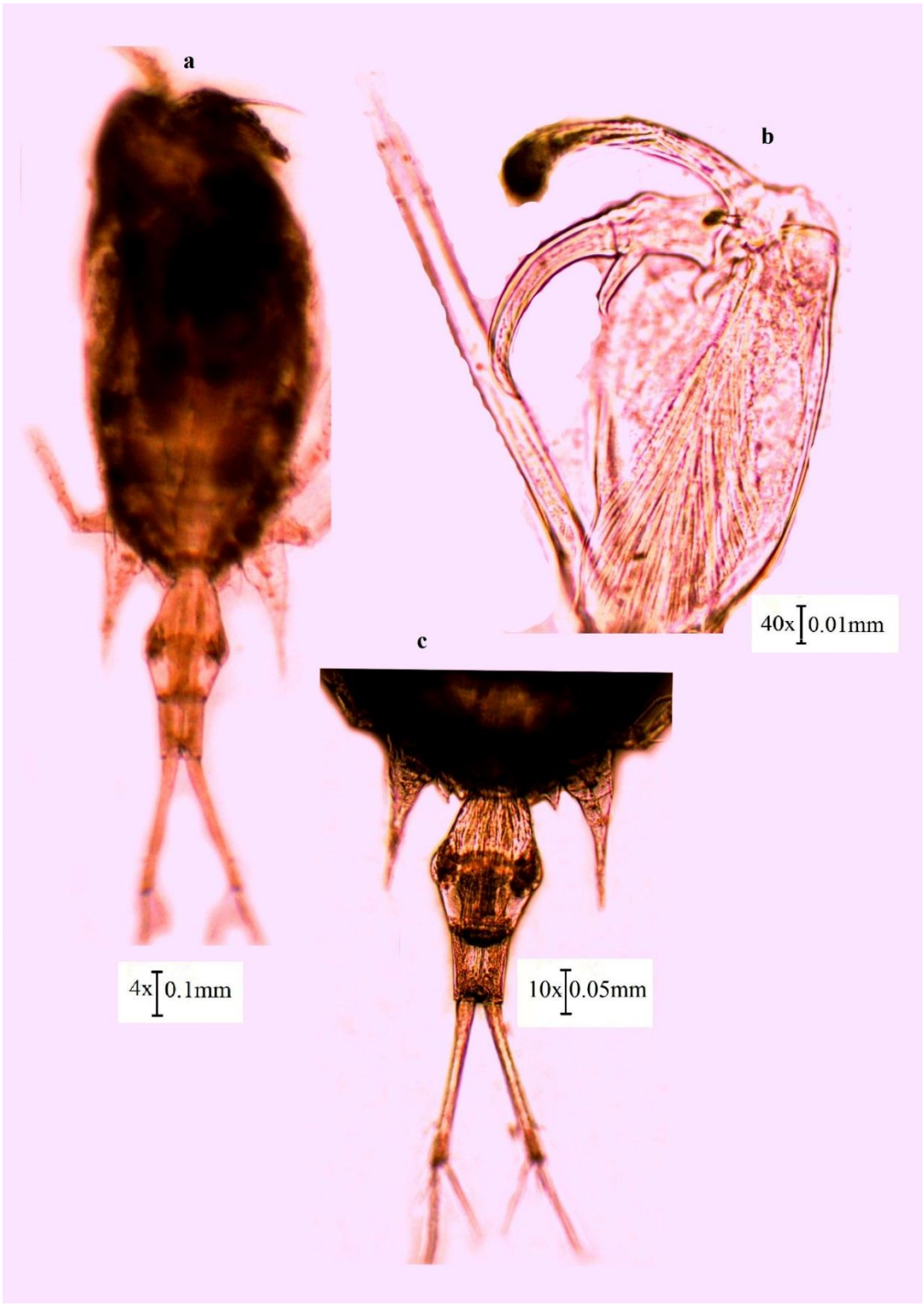


Plate.2. *Corycaeus speciosus* female. a, Habitus(dorsal);b, A2

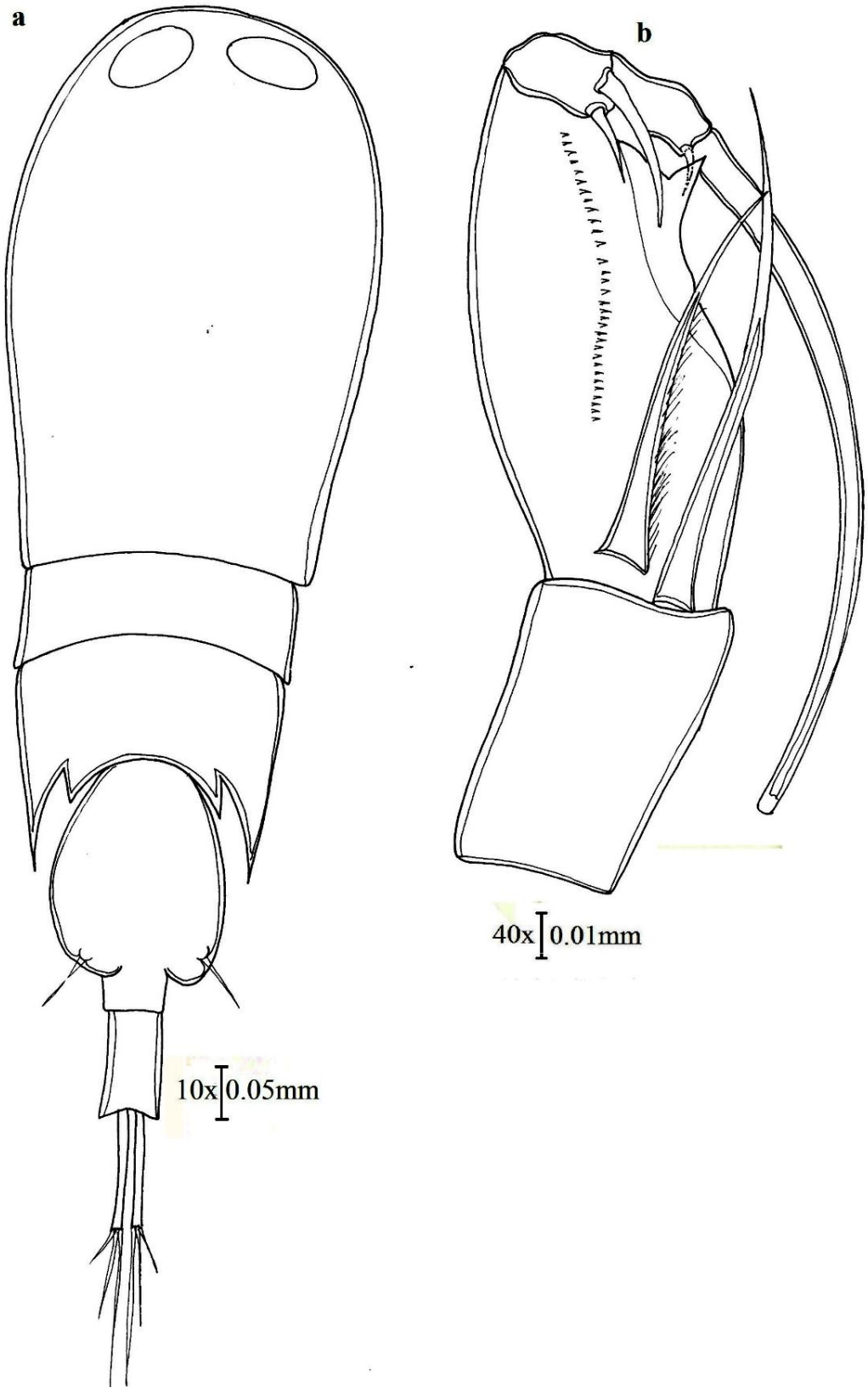


Fig.3. *Corycaeus speciosus* male. a, Habitus;b,A2(antenna)

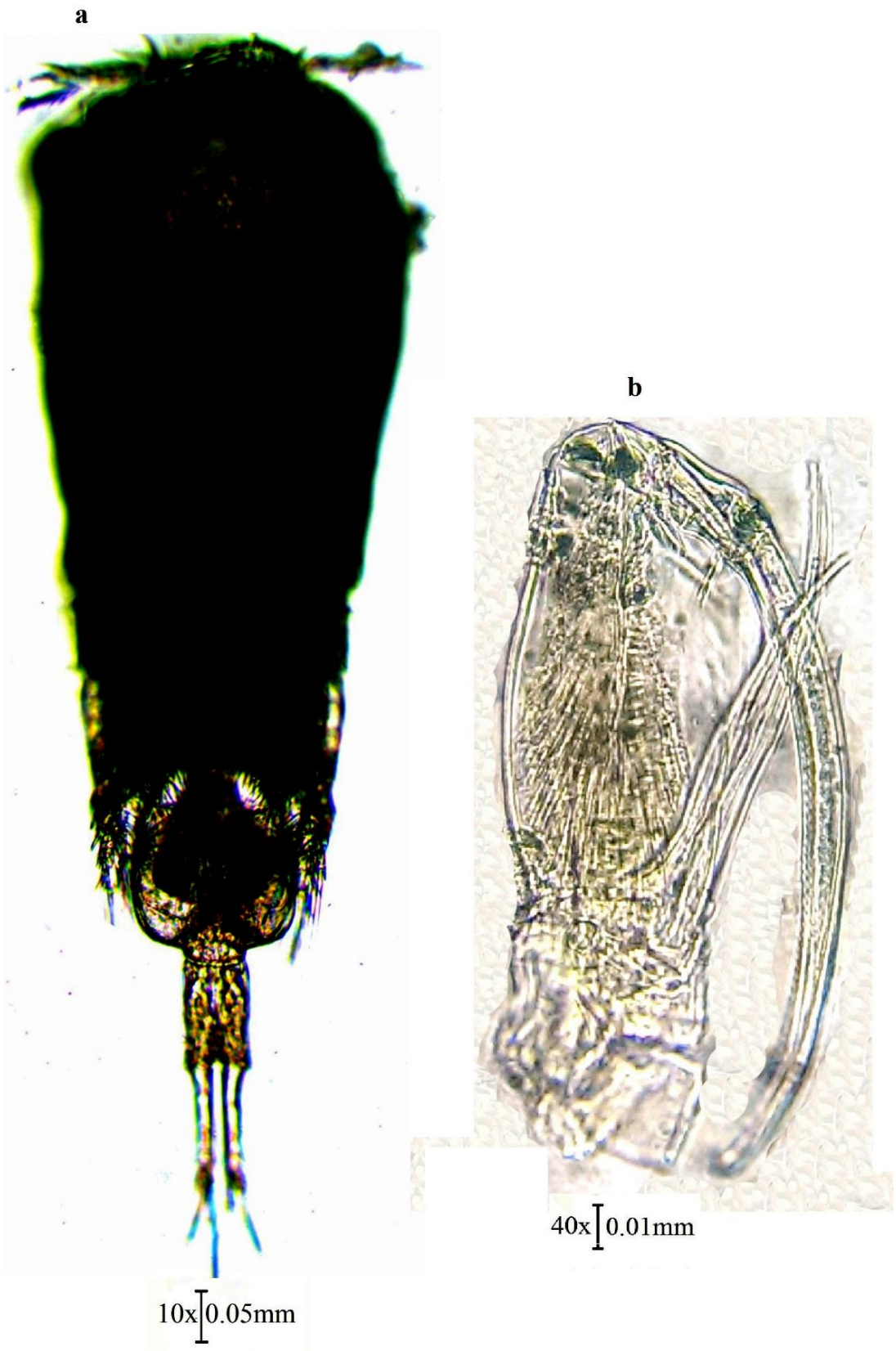


Plate.3. *Corycaeus speciosus* male. a, Habitus;b,A2 (antenna)

Corycaeus clausi F.Dahl,1894

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti (Refer Table 3.1 and 3.2).

Female (Fig.4, Plate 4): Length 1.50-1.6mm.Prosome, broad, 2.06 times as long as wide and 1.57 times as long as urosome.GS is as long as wide. CR more than thrice as long as wide at the proximal. Proportional lengths of the urosomal segments and CR are 2.5:2.2:3.2 (Fig.4a).Antenna (A2) four segmented with coxobasal setae longer than endopodal setae. Lateral margin of the first endopodal segment adorned with a row of minute spines.2nd endopodal segment with two spines, one larger and one smaller.3rd endopodal segment also with two spines, one larger which is drawn out as a claw and one smaller (Fig.4c).

Male (Fig.5, Plate 5): Length 1.37-1.5mm.Prosome 1.80 times longer than wide and 1.69 times longer than urosome. Proportional lengths of the urosomal segments and CR is 3.6:1.4:2.5.GS 1.6 times as long as wide. CR about 2.5 times as long as wide at the proximal end (Fig.5a). Antenna (A2) four segmented with coxobasal setae longer than endopodal setae. Lateral margin of the first endopodal segment adorned with a row of minute spines.2nd endopodal segment with two spines, one larger and one smaller.3rd endopodal segment also with two spines, one larger which is drawn out as a claw extending upto the coxobasal segment and one smaller (Fig.5b).

Remarks : The diagnostic feature of *C.clausi* is the presence of a row of minute spines on the lateral portion of first endopodal segment of the A2.Comparing the measurements, armature and spine ornamentation of the specimens collected from various islands of Lakshadweep clearly established that the present specimens belong to *C.clausi.* Sewell (1947) considered this species as only to be a variety of *C.crassiusculus.* Boxshall and Halsey considered this as full generic status pending phylogenetic revision of the whole family at the generic level.

Distribution: Epi-mesopelagic, recorded from temperate waters of the Atlantic and rarely from the Indo-pacific (http:// copepods. obs-banyuls.fr/en).

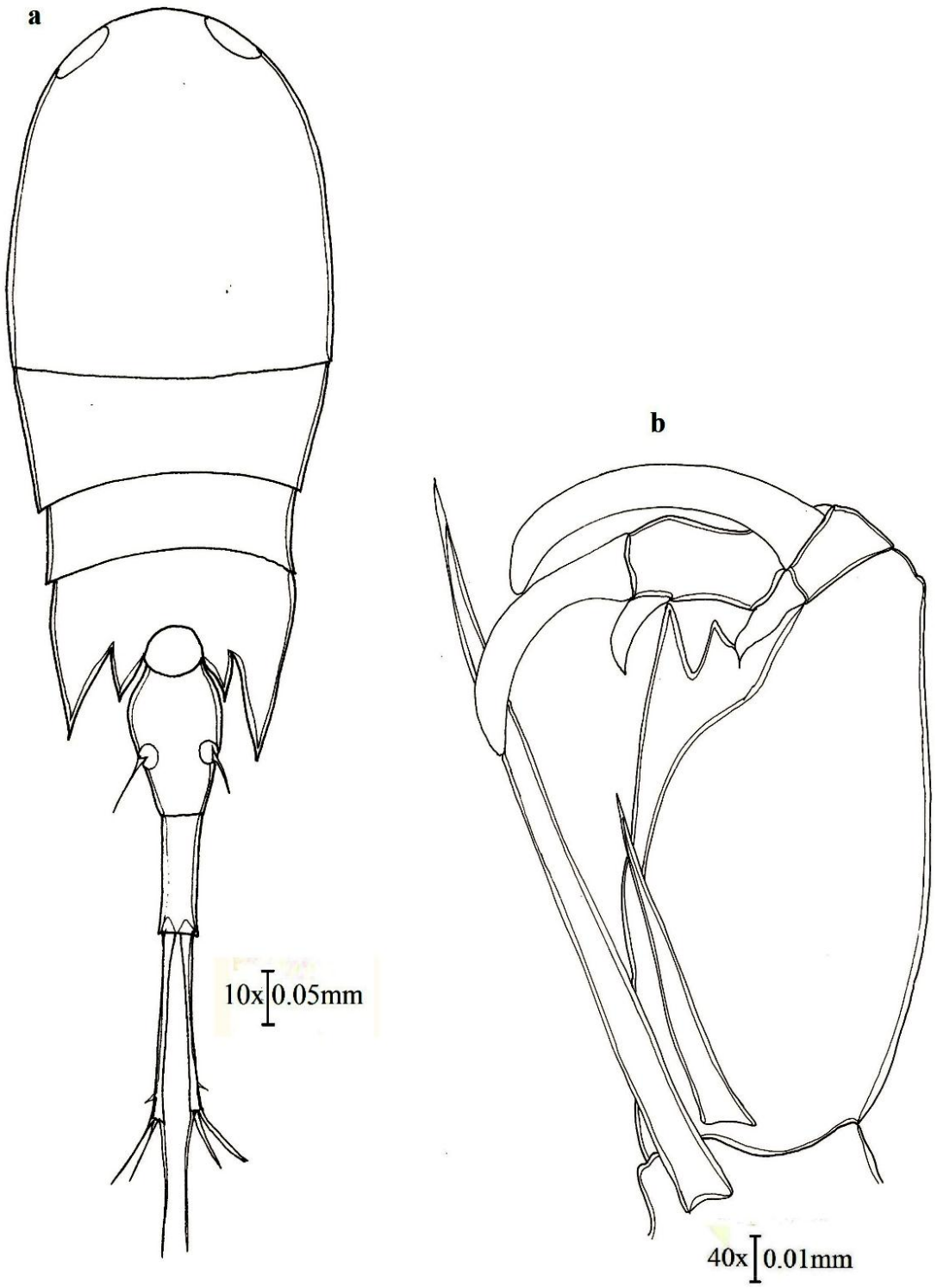


Fig.4.*C.clausi* female.a,Habitus (Dorsal);c,A2.

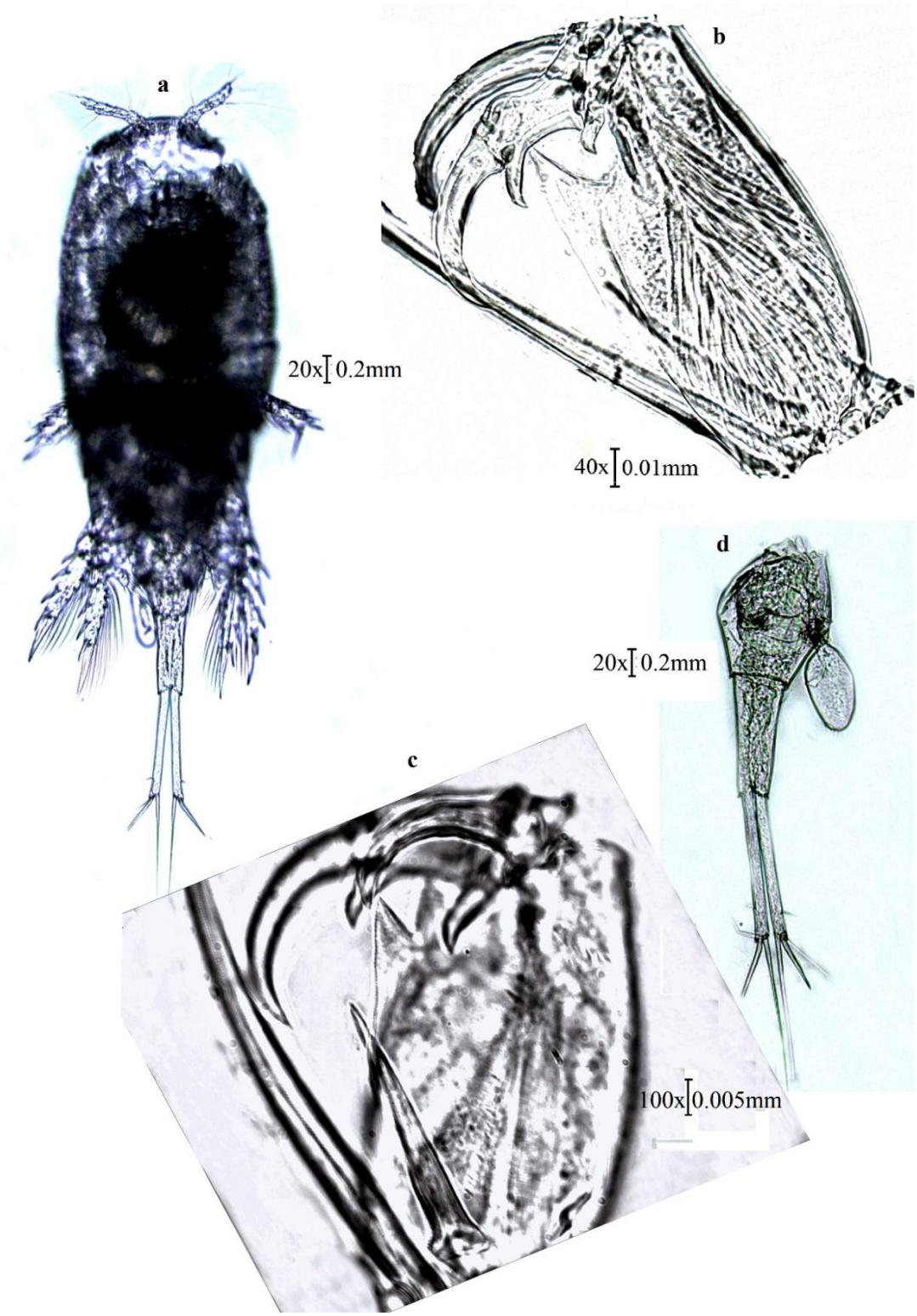


Plate.4.*C. clausi* female. a,Habitus (Dorsal);b and c,A2; d,Urosome

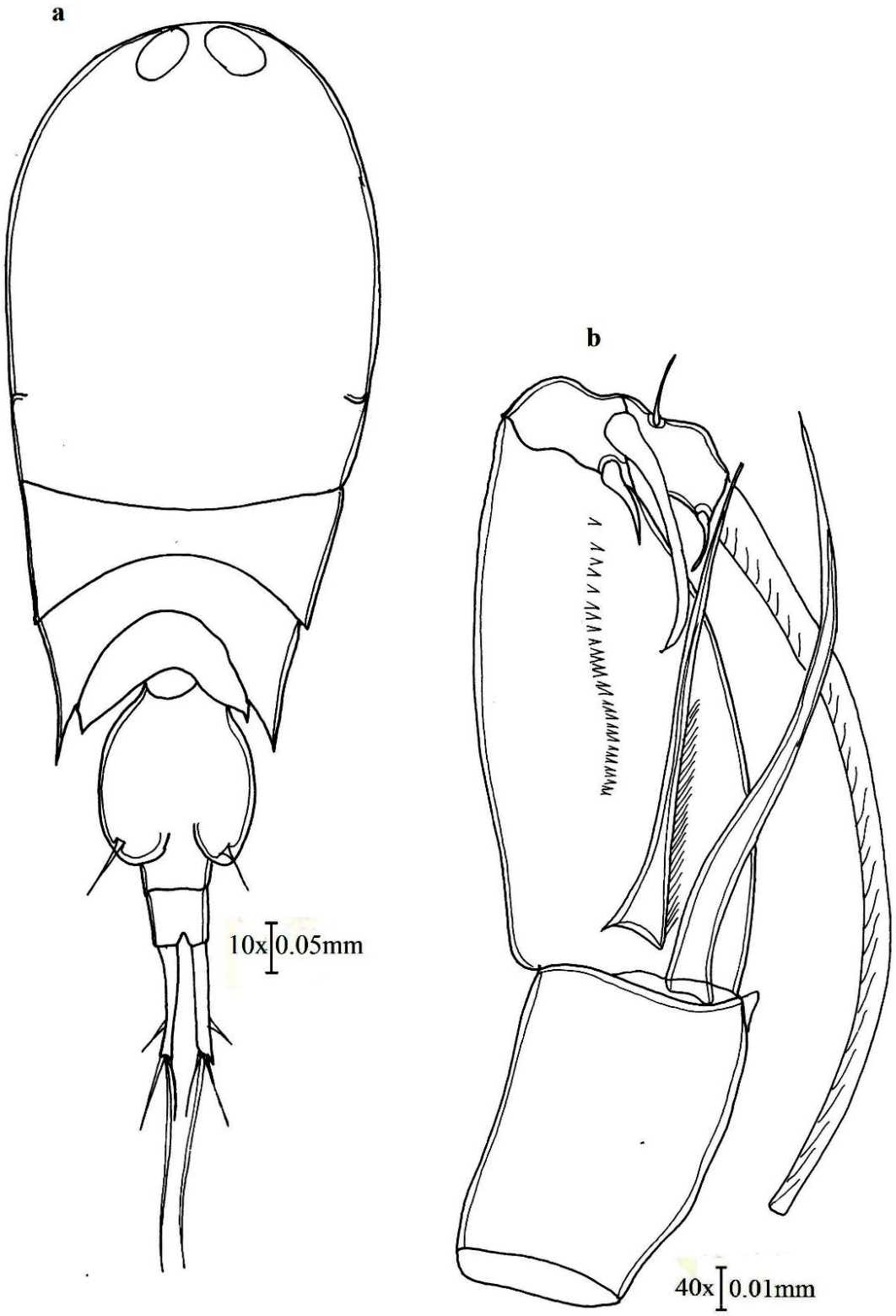


Fig.5.*C.clausi* male. a,Habitus (Dorsal);b,A2

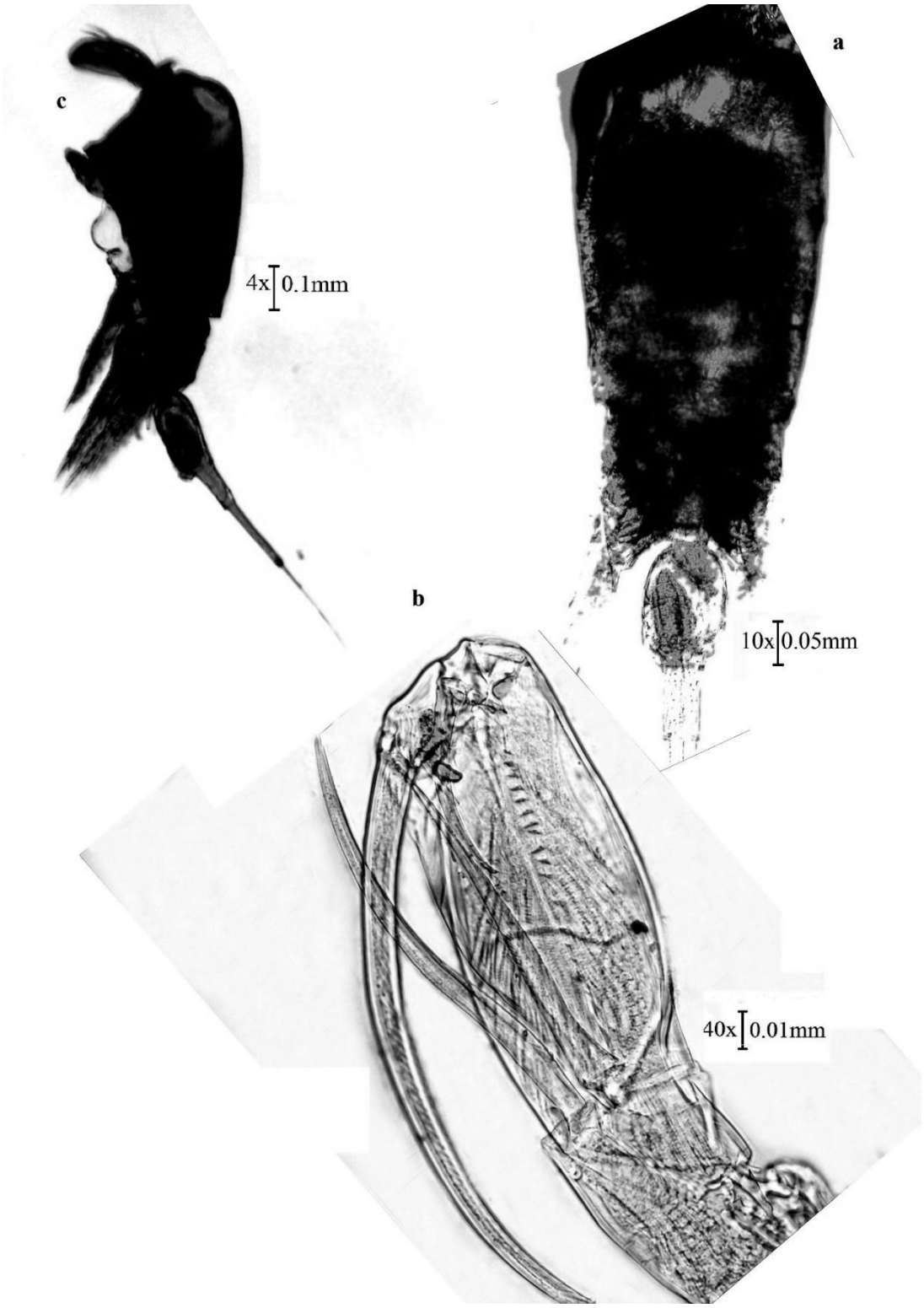


Plate.5.*C.clausi* male. aand c, Habitus (Dorsal and lateral);b,A2.

Corycaeus vitreus Dana, 1849

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti and Bangaram (Refer Table 3.1 and 3.2).

Male (**Fig.6, Plate.6)** Total length 1.06-1.15mm.Prosome 1.75 times longer than wide and 1.46 times as long as urosome. Urosome 2 segmented 3.9 times longer than wide. Genital double somite 1.33 times longer than wide.AS 2.97 times as long as wide.CR slightly divergent at its base, 1.92 times as long as wide. Ratio of urosomal somites and CR 2.5:0.75:1.25 (Fig.6a, c).Antenna (A2) four segmented with coxobasal setae shorter than endopodal setae.2nd endopodal segment with two elements, one long and one short at base.3rd endopodal segment drawn out a long terminal claw extending upto coxobasis (Fig.6d).

Remarks: F.Dahl (1894), M.Dahl(1912) defined the characters of the male specimens of this species. Only Farran (1936) reported female specimens till date. He opined that the male of *C.vitreus* differs from that of *C.crassiusculus* and *C.clausi* by its short head which is broad anteriorly and tapers posteriorly and short AS. He collected *C.vitreus* from New Zealand but reported it as female of *C.crassiusculus.* Later he reported a specimen collected from Great Barrier reef as the female specimen of *C.vitreus* for the first time. He opined that the female of *C.vitreus* to be more than that of *C.crassisuculus.* Only male specimens were observed. When Tanaka's male specimens were compared with the Lakshadweep specimen, some of the characters were comparable even with slight variations. They included 1)PR:UR ratio being lower in Lakshadweep specimen than that of Tanaka (1.46 vs 1.5) ; 2)Length width proportion of CR being less in Lakshadweep specimen (1.92 vs 5); 3) AS wider at the proximal end than at distal end; 4)ornamentation of A2.

Distribution: Ocean and Coastal, Pacific Ocean, Coast of Western Australia (http:// copepods. obs-banyuls.fr/en).

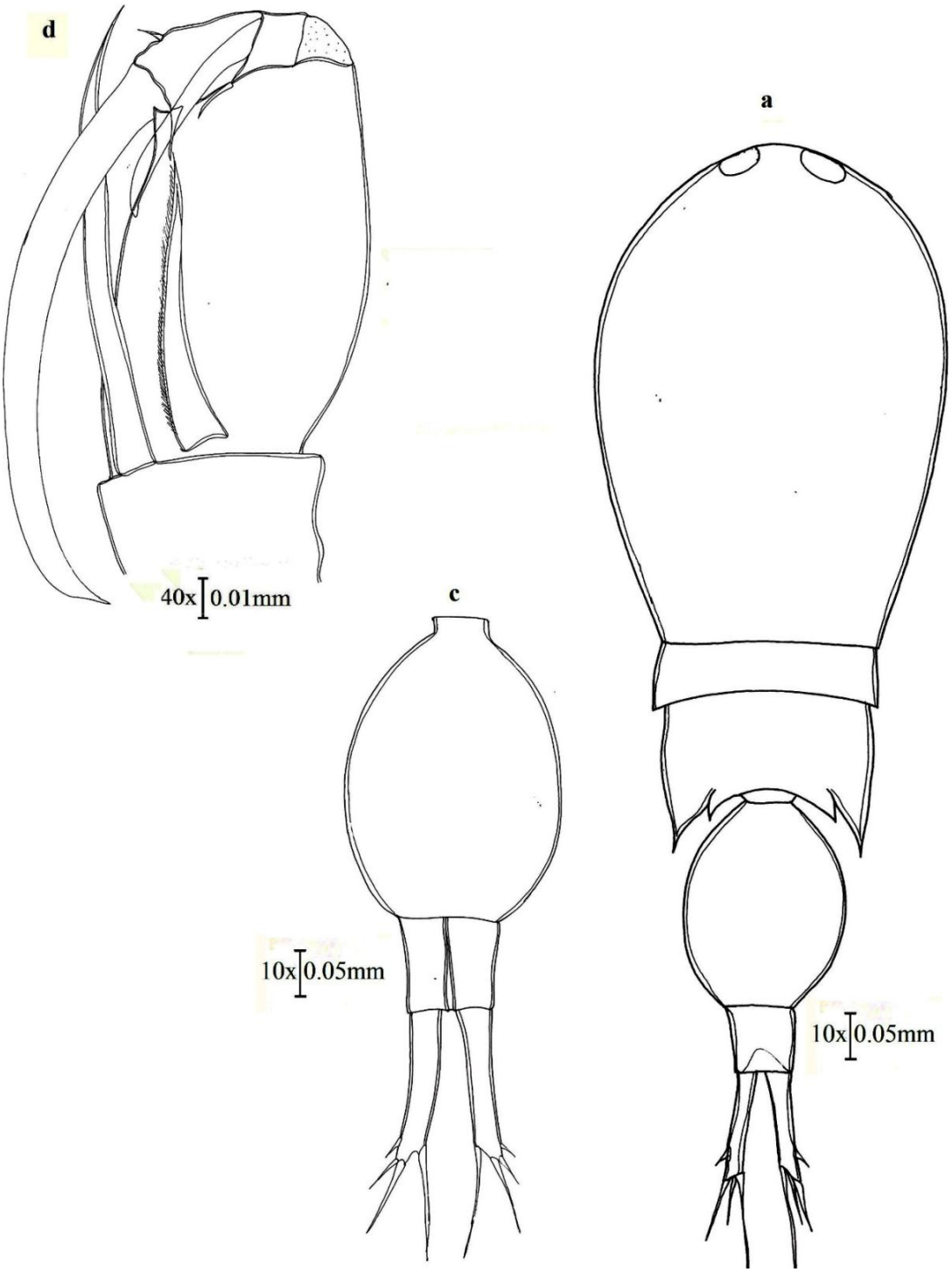


Fig.6*C. vitreus* male.a,Habitus;c,Urosome;d,A2.

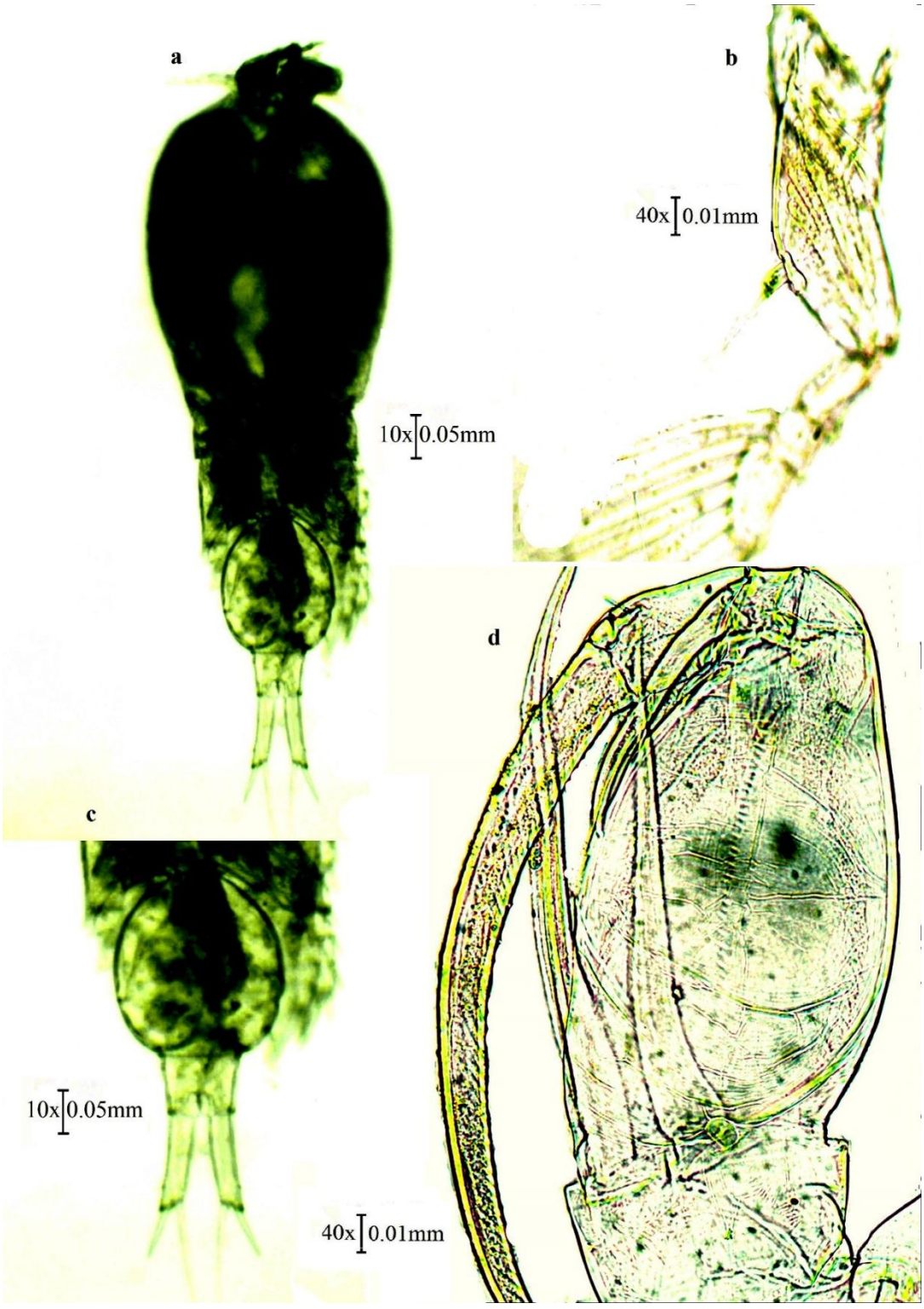


Plate.6. *C. vitreus* male.a,Habitus;b,P4;c,Urosome;d,A2.

Urocorycaeus lautus Dana, 1848

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Agatti, Minicoy (Refer Table 3.1 and 3.2).

Male (Fig.7, Plate.7) Total Length 1.48-1.6mm.Prosome frontal margin arc shaped, 2.34 times as long as wide and 1.16 times as long as urosome. Urosome two segmented. Proportional lengths of GS: AS: CR is 2.8:2:5.2. GS bulgy double somite, 2.33 times as long as wide. Rectangular shaped AS, 3.33 times as long as wide which is not as long as GS; Slender, long and slightly divergent CR which is 9.89 times as long as wide. CR longer among the urosomal segments and 1.08 times as long as the rest of the urosomal segments (Fig.7a).P4 with two setae (one long and one rudimentary) in the endopodite (Fig.7b).

Remarks: The male specimens of *U.lautus* can be recognized by the presence of 2 setae (1long and 1 rudimentary) in the P4 endopodite; UR differentiated into AS and GS; length ratio of CR to rest of the urosome. The present specimen agrees with the above said distinct characters. The length ratio of CR to rest of the abdomen (1.02) is also comparable with the previous descriptions like 1.2 (Farran,1911);1.3 (Dahl.M,1912);1.2 (Mori,1937);1 (Dakin and Colefax,1940);1.3 (Tanaka,1957);1.49 (Motoda,1963).All these confirms the taxonomic integrity of *U.lautus* male in Lakshadweep sea.

Distribution: Tropical, Subtropical and North Temperate Atlantic, Mediterranean, Caribbean Sea, Indo-Pacific, East China Sea, Japan Sea ,Pacific Ocean(http:// copepods. obs-banyuls.fr/en).

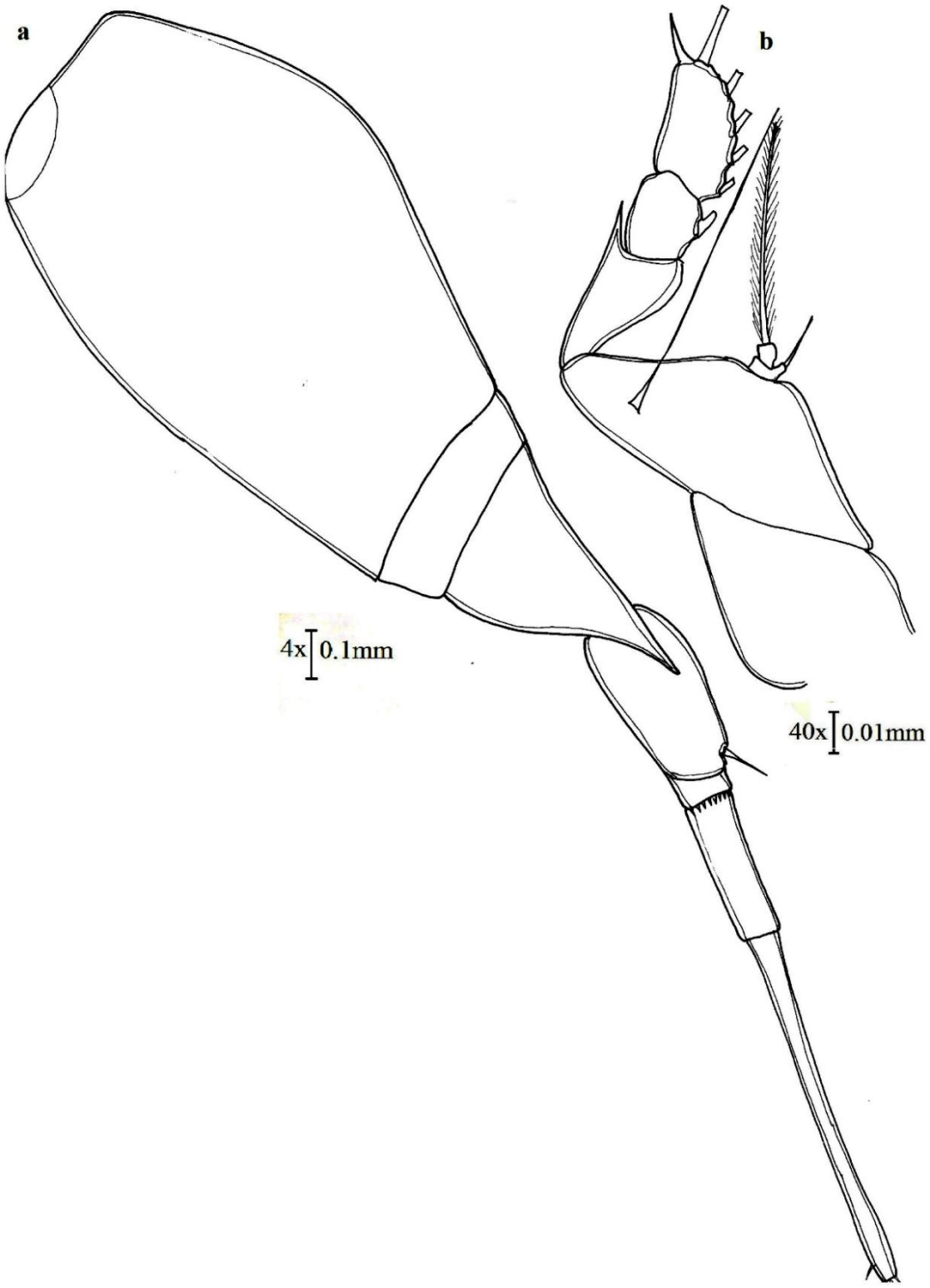


Fig.7. *U. lautus* male.a,Habitus (lateral view);b,P4.

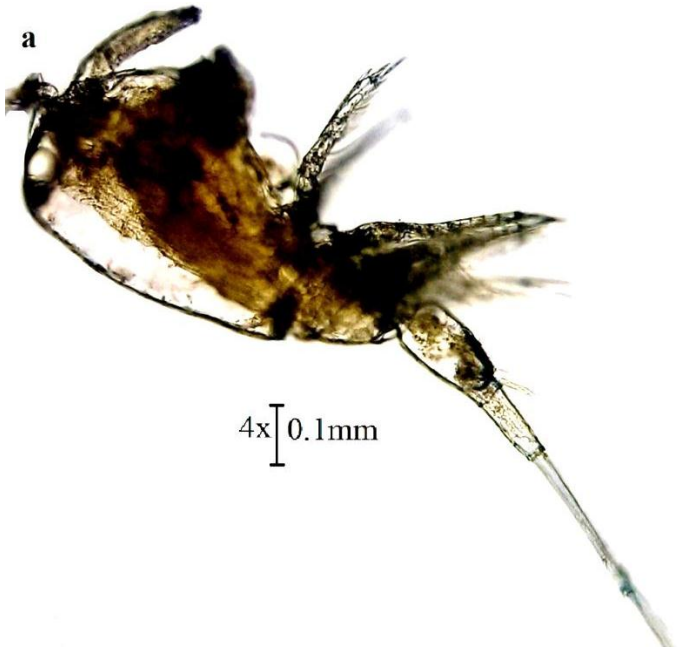


Plate.7. *U. lautus* male a,Habitus (lateral view);

***Urocorycaeus furcifer* Claus, 1863**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Agatti, Kalpeni, Minicoy(Refer Table 3.1 and 3.2).

Male **(Fig.8,Plate.8)** Total Length 1.28-1.35mm.Prosome frontal margin arc shaped, 2.44 times as long as wide. Prosome 1.38 times as long as urosome. Urosome three segmented. GS bulgy double somite, 1.65 times as long as wide. Rectangular shaped AS, 2.33 times as long as wide which is not as long as GS; Slender, long and slightly divergent CR which is 5.25 times as long as wide.CR longer among the urosomal segments. Proportional lengths of GS: AS: CR is 4:2.1:4.2 (Fig.8a).Antenna (A2) four segmented with coxobasal setae only slightly longer than endopodal setae which is unipinnate. Proximal lateral margin of the first endopodal segment ornamented with minute spines.2nd endopodal segment with two elements, one longer than the other.3rd endopodal segment with two elements; one long drawn out as a terminal claw and other being too short at the base (Fig.8b).P4 endopodite with only one setae (Plate.8c).

Remarks: The most distinct character of the genus *Urocorycaeus* is that the CR in both sexes are lengthy measuring at least twice the length of the rest of the UR and almost parallel, slightly divergent at the distal ends. Another distinguishing character of male specimen of *U.furcifer* from that of its allied species *U.longistylis*

is the differentiation of UR into GS and AS. Here in the present specimen from Lakshadweep islands has this differentiation very well that confirms its taxonomic identity. In the present specimens, proportional lengths of Urosomal segments is found to be 40:21:42. This is at variance with the description given by Cravigon, 1964 (30:12:58).Tanaka, 1957 reported only female specimens.

Distribution: Recorded from Indo-Pacific, northern coast of South America, Mediterranean and Sargassum Seas (http:// copepods. obs-banyuls.fr/en).

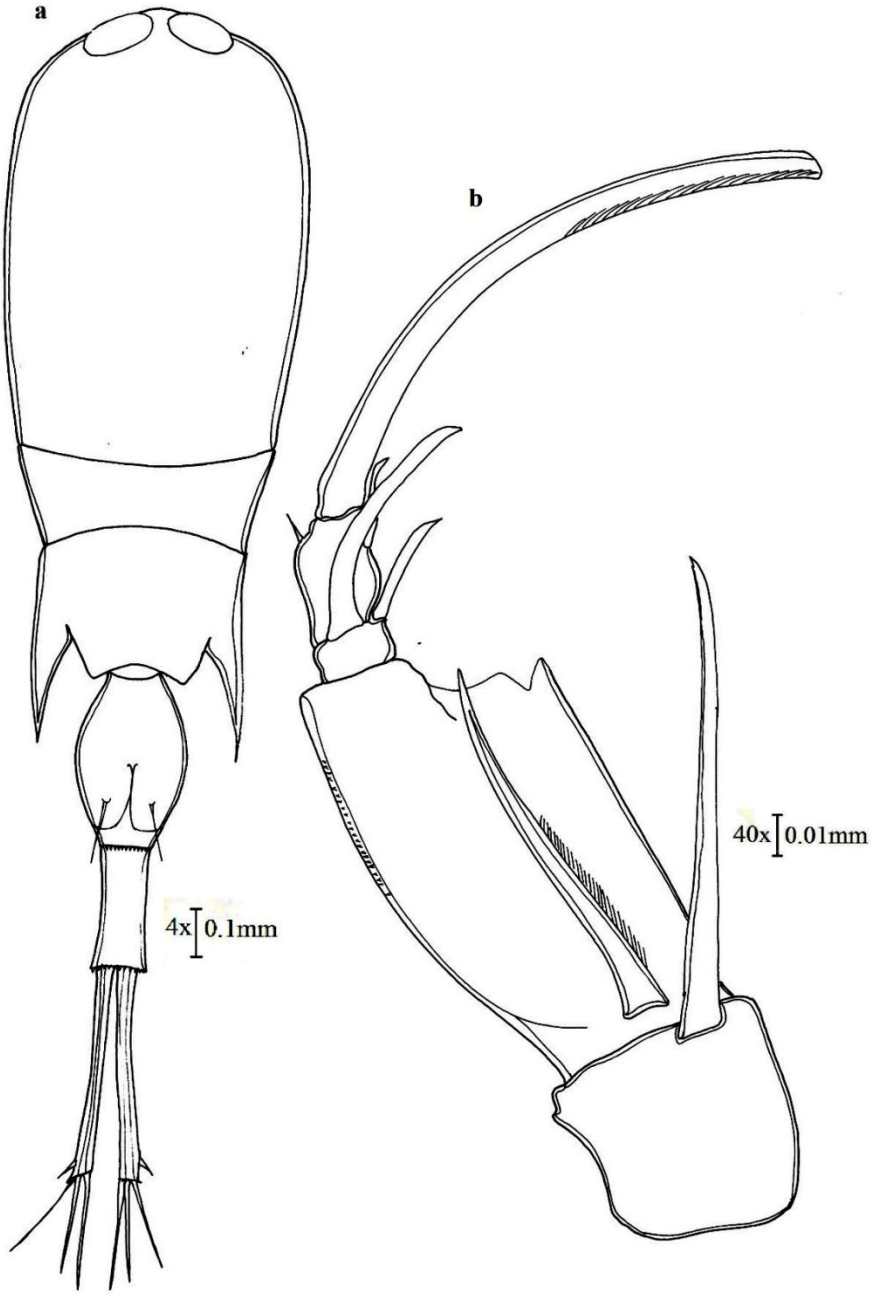


Fig.8.*U.furcifer* male.a,Habitus; b,A2.

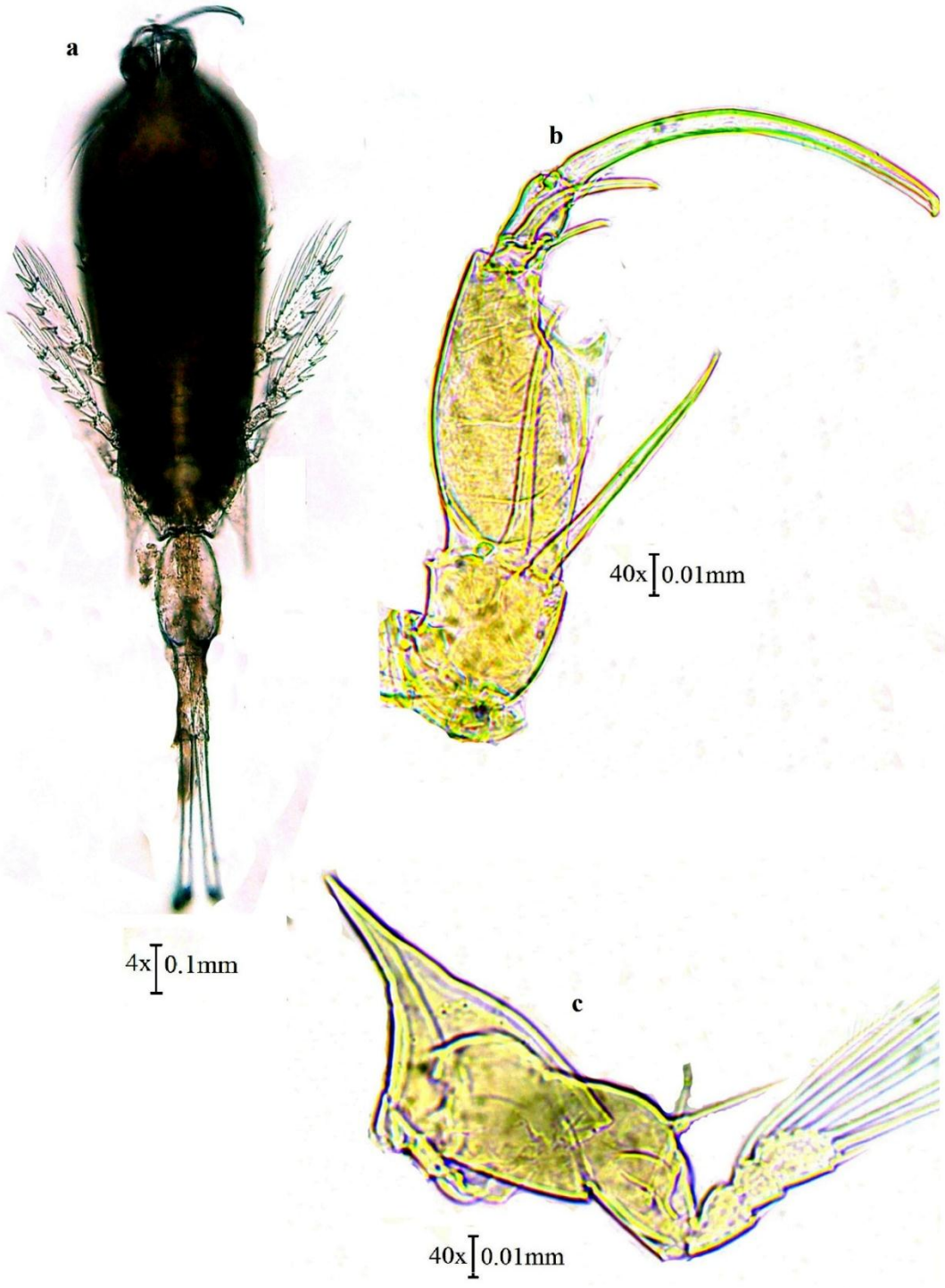


Plate.8*. U.furcifer* male. a,Habitus; b,A2;c,P4.

Onychocorycaeus catus Dahl F,1894

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Bangaram, Agatti (Refer Table 3.1 and 3.2).

Female (**Fig.9,Plate.9):** Body cylindrical, tapering posteriorly. Total length 0.65-0.66mm. Prosome four segmented, more than twice as long as urosome including caudal rami about 1.75 times as long as wide. Urosome two segmented with divergent caudal rami. Genital somite oval, 1.5 times as long as maximum width at anterior mid region, longer than AS and CR combined; AS rectangular shaped, about 1.3 times as long as wide at base; distal margin bears spinules ventrolaterally; 3.9 times shorter than genital somite and 1.3 times shorter than caudal rami. Caudal rami divergent, 1.67 times longer than wide at base, about 0.35 times shorter as long as genital somite and 1.38 times as long as anal somite (Fig.9a,b). A2 four segmented with coxa and basis with strong unipinnate setae on inner distal margin.Endopod three segmented and unequal in length; 1st segment bearing short unipinnate seta on ventral proximal margin much shorter than coxobasal seta, inner distal margin formed into two stout teeth. 2nd segment short bearing two elements a) curved stout short spine arising from outer distal margin and is longer than the other and b)comparatively smaller spine arising from the inner margin;3rd segment cylindrical, 1.2 times as long as wide at base, armed with a curved terminal claw and a short spine arising from the inner distal margin (Fig.9c).

Remarks: When compared with the descriptions of (Tanaka,1957)from Japanese waters, females of *O.catus* from Kavaratti waters, Lakshadweep showed almost similar length ratio of PR:UR (including CR) where PR being more than two times the length of UR (4.9:1.9 vs. 9:4).However, a few morphological variations from the former description were also there regarding the total body length being smaller (0.65mm vs 0.93-1mm), length width ratio of the anal somite being slightly different (4.5:3.5 vs 7:8), length width ratio of the CR being smaller (1.67 vs. 4) and length proportion of the GS: AS: CR being much large (177.5:45:62.5 vs. 58:20:22).The present study provides a detailed description on the morphometry

ofA1,A2,Urosome,P1-P4On the contrary, females of *O.catus* described by (Motoda, 1963) from Hawaiian waters differed from those of the Kavaratti specimens in the proportional lengths of PR: UR (including CR) where PR about twice the length of UR in Hawaiian waters vs. more than twice in Kavarathi specimen and the total body length being larger(1.14 mm vs.0.65mm) whereas the morphological characteristics such as GS longer than AS and CR combined; AS 1.3 times as long as wide (4.5:3.5) and slightly shorter than CR, were found to be similar. In contrast, from the descriptions of female *O.catus* by (Karanovic, 2003) from Australian waters, the body length seems larger being 1.06mm when compared to 0.65mm of Kavarathi specimen. Variations also appear in the length width ratio of prosome which being larger in Kavaratti specimen from that of Australian specimen (1.75 vs. 1.0) as well the details like surface of the cephalic shield of the prosomites with numerous small sensilla and cuticular pores. While Karanovic(2003) explains that genital somite is only slightly longer than wide in Australian specimen, Kavarathi specimens varies from it by the genital somite being 1.5 times longer than the maximum width and anal somite about 0.8 times as long as wide in Australian specimen which is smaller to that of Kavaratti specimen (0.8 vs.1.3). Anal somite 3.9 times shorter than genital somite in Kavaratti specimen while that of Australian specimen is only 0.4 times as long as genital somite, which explains another variation.

Distribution: Recorded from the Indo-pacific Ocean, Great Barrier Reef Sea, Arabian Sea and very common in the warm waters of Japan(http:// copepods. obs-banyuls.fr/en).

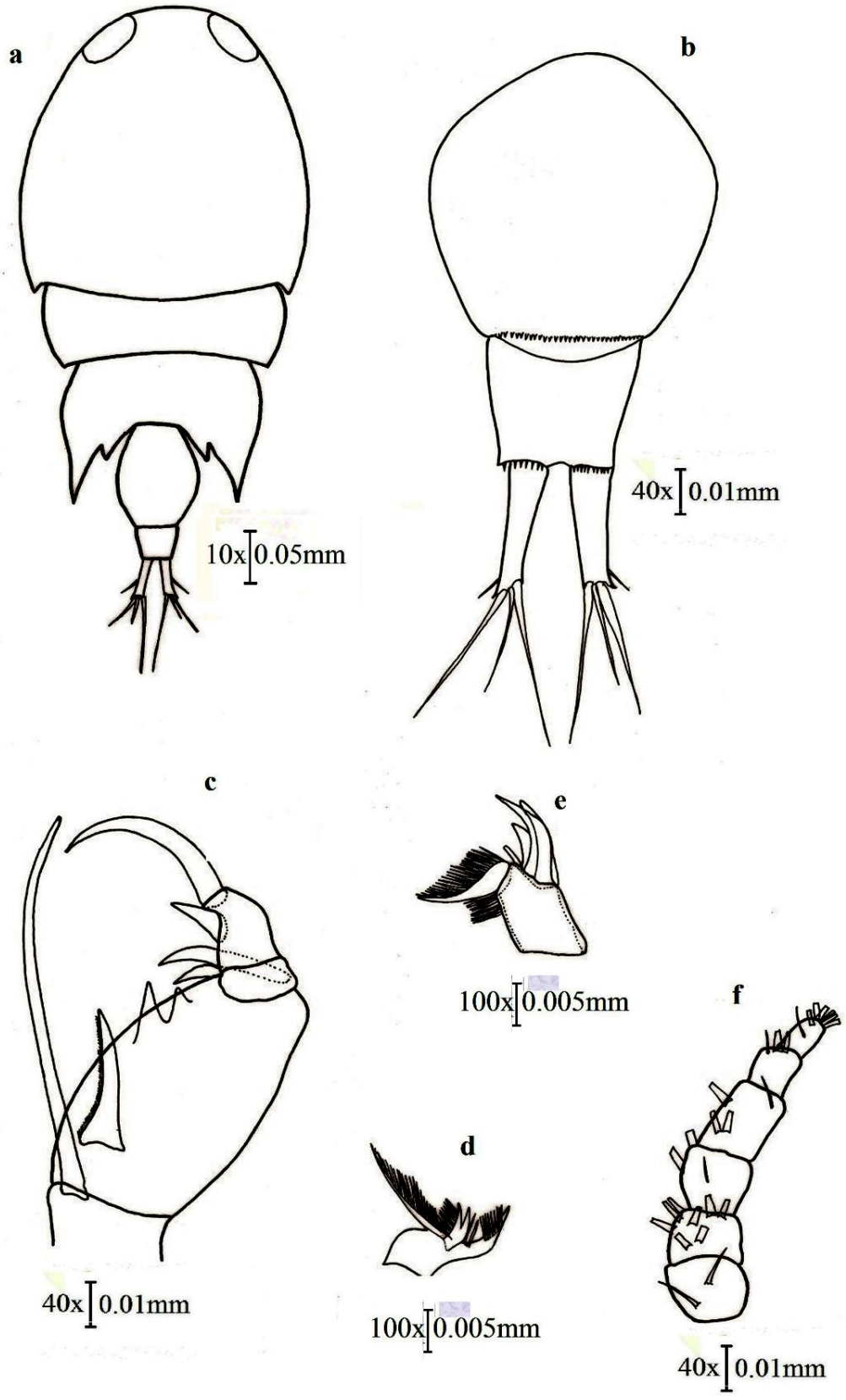


Fig.9.*O.catus* female.a,Habitus;b,Urosome;c,A2;d,maxilla;e,maxillule;f,A1

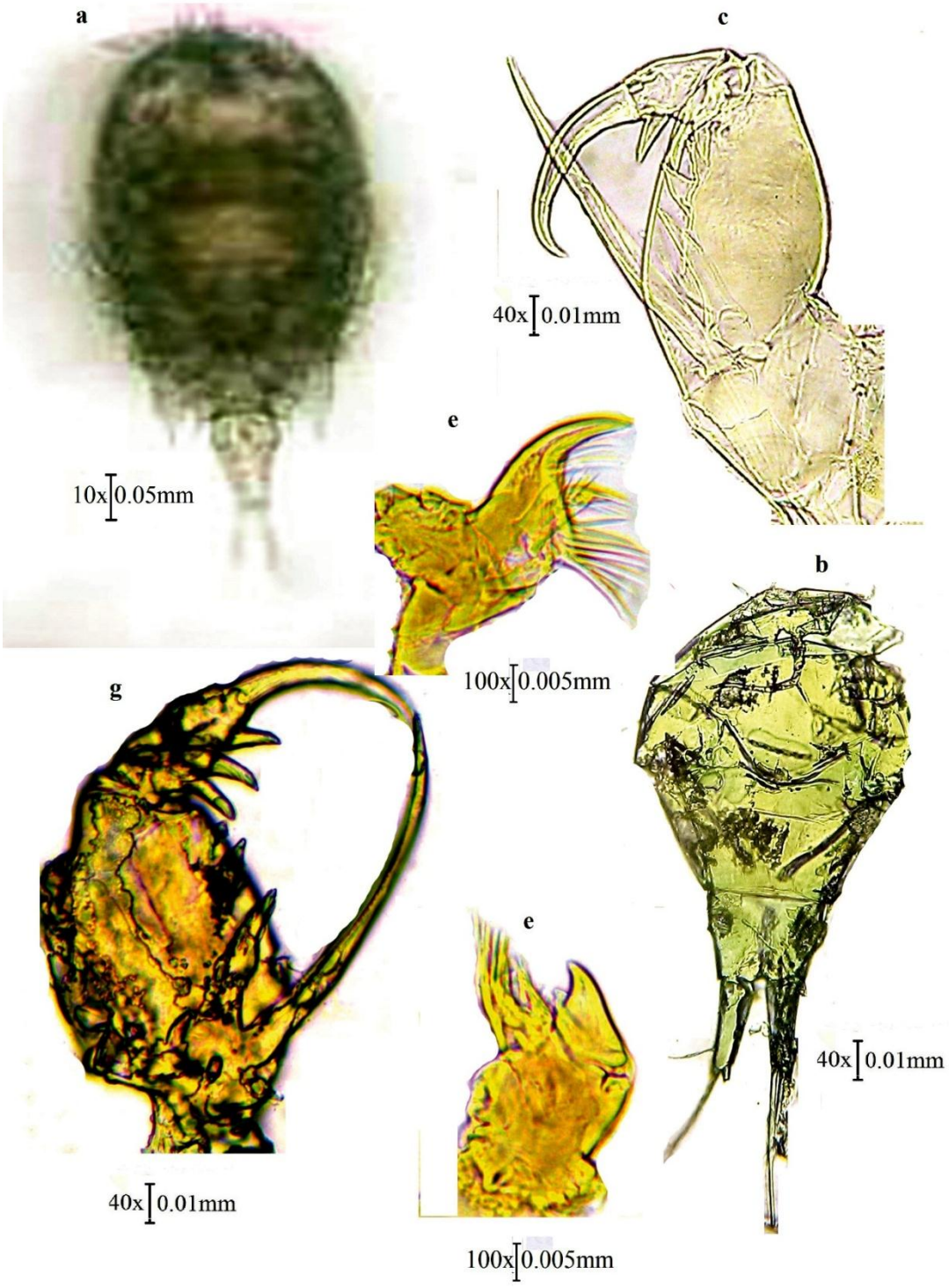


Plate.9.*O.catus* female. a,Habitus;b,Urosome;c,A2;d,maxilla;e,maxillule;f,A1

Onychocorycaeus agilis Dana, 1849

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female (**Fig.10, Plate.10):** Total length1.34-1.38mm.Prosome robust, twice as long as wide. Prosome 1.66 times as long as urosome. Slender CR. Urosome 3 segmented. Proportional lengths of GS: AS: CR is 0.9:0.85:1.1(Fig.10a).Broad 1st endopodal segment of A2 bears two spine like process at the inner distal margin whose level is slightly displaced from that of second endopodal segment. Coxobasal setae thrice as long as endopodal setae. 2nd endopodal segment bears two spines.3rd endopodal segment also bears two elements, one short and the other as a terminal claw (Fig.10b).

Male(**Fig.11, Plate.11):** Total length 0.7-0.8mm. Prosome 1.83 times as long as wide and 1.76 times as long as urosome. Slender CR. Urosome three segmented. Proportional lengths of GS: AS: CR is 2:1.3:2 (Fig.11a).Broad 1st endopodal segment of A2 bears two spine like process at the inner distal margin whose level is slightly displaced from that of second endopodal segment. Coxobasal setae longer than endopodal setae. 2nd endopodal segment bears two slender spines.3rd endopodal segment also bears two elements, one short and the other as a terminal long claw (Fig.11b).

Remarks: C. *gracilicaudatus* of Giesbrecht (1891, 1892) was synonymized with male specimen of *O.agilis* of Dana, F. Dahl (1894) and M. Dahl, 1912. Eventhough Scott (1909) presented only a brief note on the female specimen characters, his *C. gracilicaudatus* was also considered synonymous to *O.agilis.* The diagnostic features like 1) swelling of the GS at the middle and almost as long as furca (0.81:1); 2)AS slightly shorter than CR (0.85:1.1) and more than twice (3.4) as long as wide; 3) Coxobasal setae 2.6 times as long as endopodal setae; 4) first endopodal segment of A2 bears 2 spine like process at the inner distal margin, of the female specimens of *O.agilis* from Lakshadweep waters matches with the depictions of previous works. This undoubtedly proves the taxonomic status of *O.agilis.*

Distribution: Warm waters of Japan, tropical regions of Atlantic, South and North Pacific, Caribbean Sea and Indian Ocean (http:// copepods. obs-banyuls.fr/en).

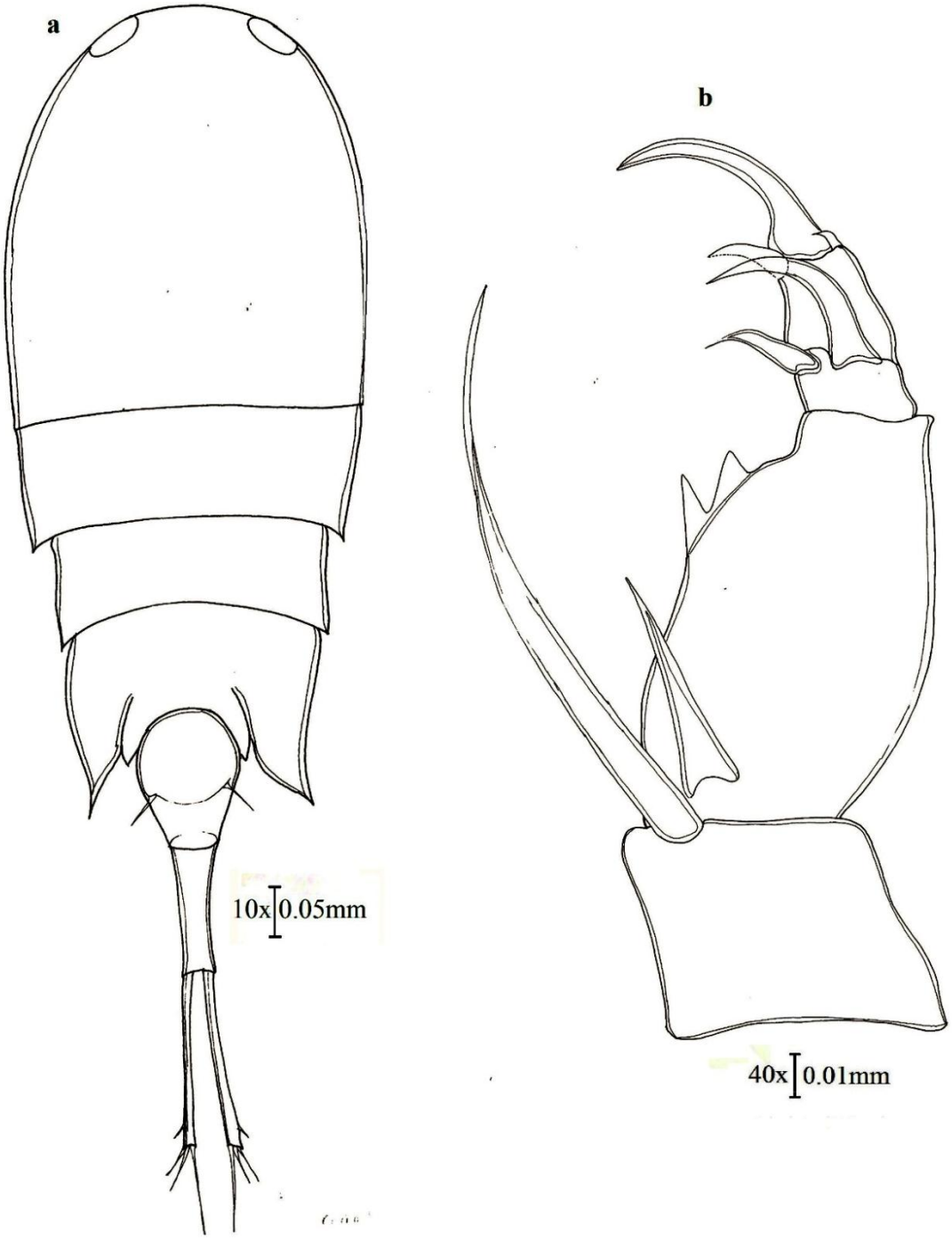


Fig.10. *O.agilis* female.a,Habitus;b,A2.

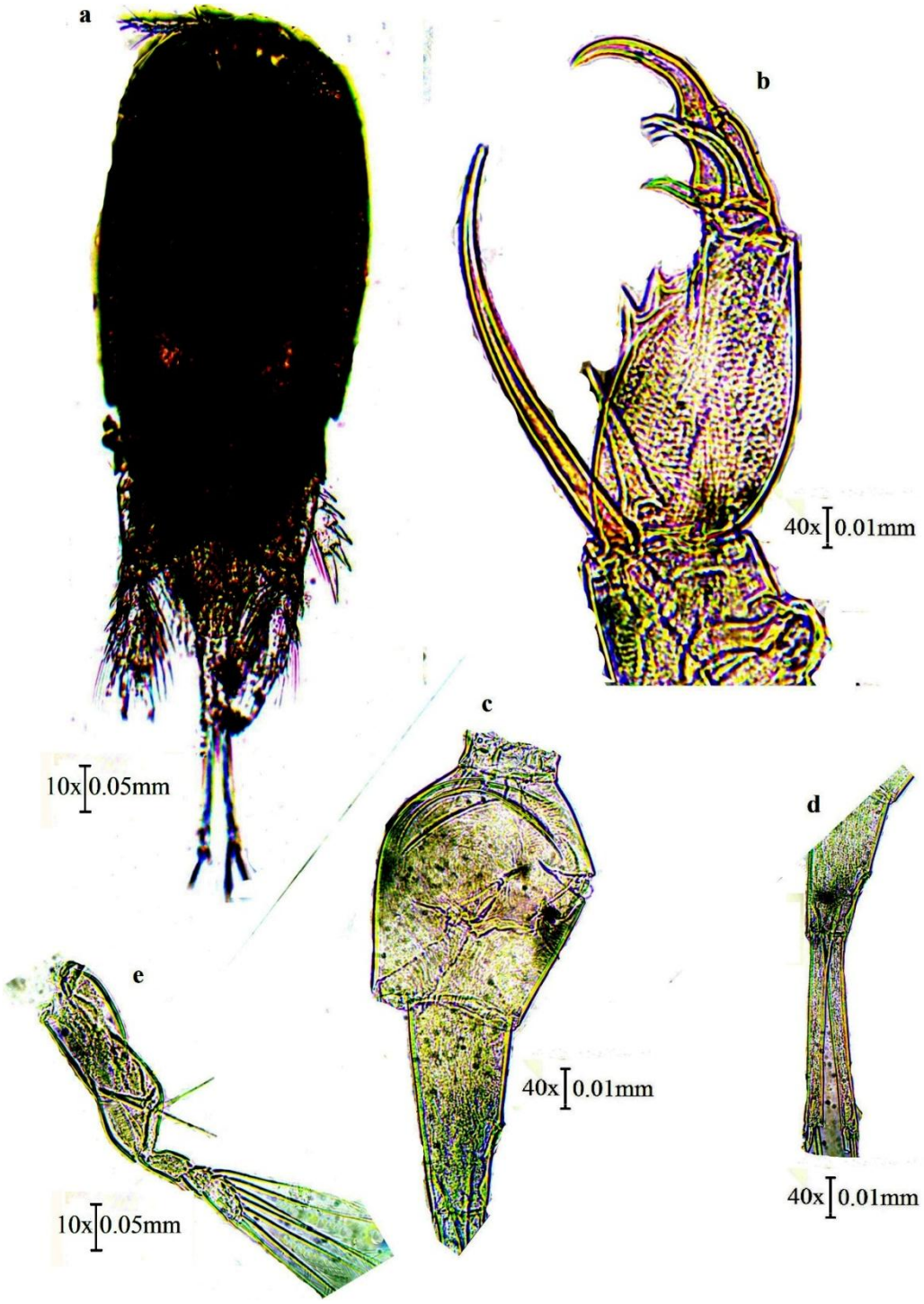


Plate.10. *O. agilis* female.a,Habitus;b,A2;c,Urosome;d,CR;e,P4

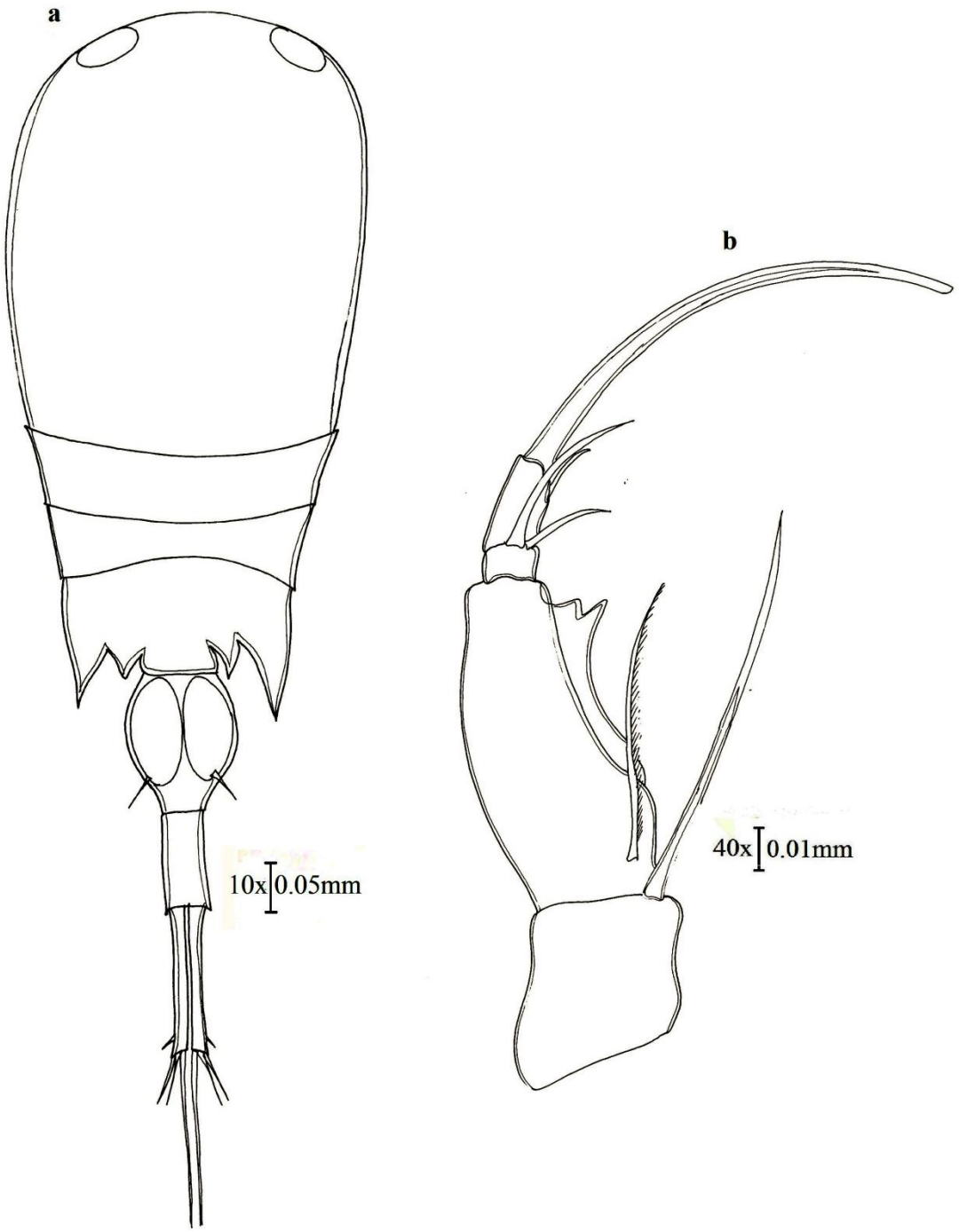


Fig.11. *O.agilis* male.a,Habitus;b,A2.

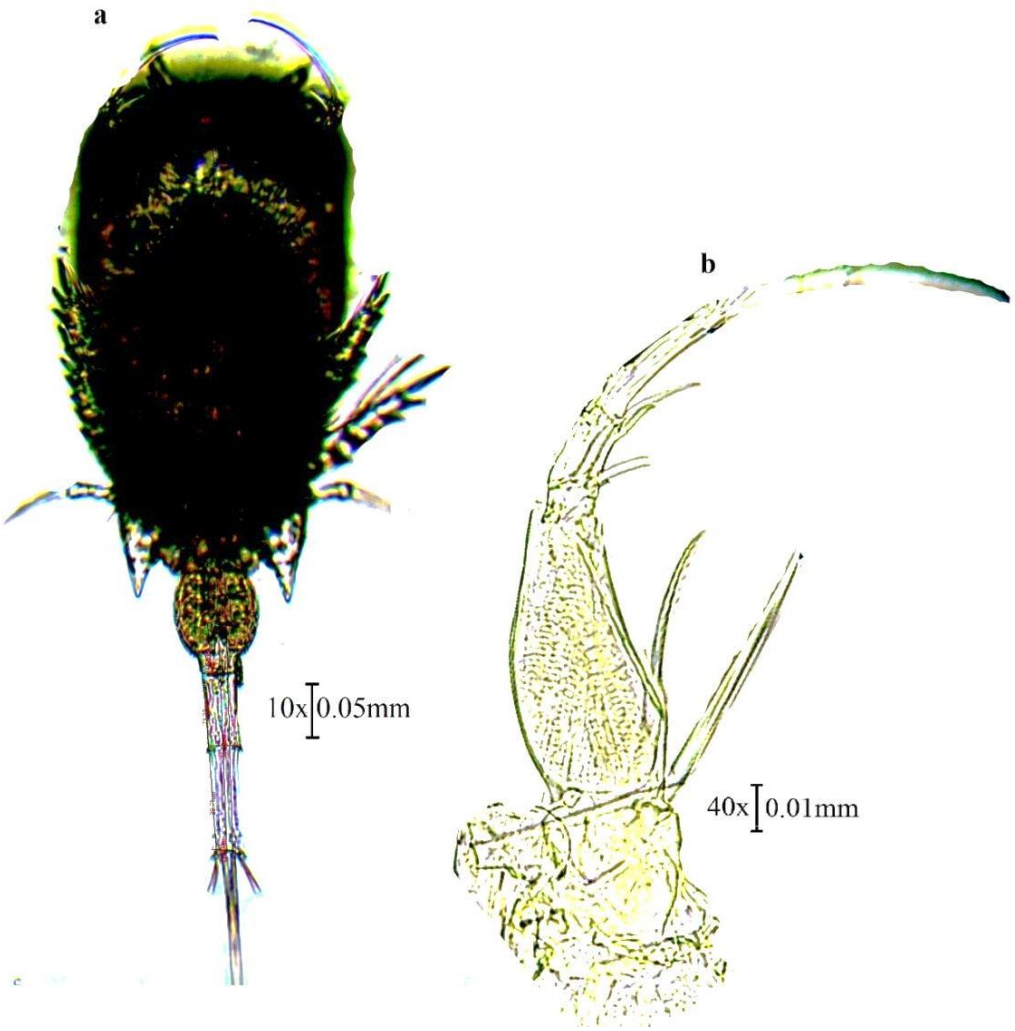


Plate.11. *O.agilis* male a,Habitus;b,A2.

Onychocorycaeus giesbrechti Dahl ,1894

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female (**Fig.12, Plate.12):** Total Length 1.05mm.Large prosome 1.73 times as long as wide and 2.13 times as long as urosome. Trimmed CR. Urosome two segmented. GS ovate 1.33 times as long as wide. Ventral surface of the GS with a median hook. AS slightly divergent at base,1.6 times as long as wide.CR 1.16 times as long as wide .Proportional lengths of GS: AS: CR is 1:0.4:0.35 (Fig.12a).A2 four segmented.1st endopodal segment about 1.7 times as long as wide at base bearing short endopodal seta on ventral proximal margin 2.58 times shorter than

coxobasal setae; inner distal margin formed into two stout teeth. 2nd segment short bearing two elements; 3rd segment cylindrical, armed with a curved terminal claw and a short spine arising from the inner distal margin (Fig.12b).

Male **(Fig.13, Plate.13)** Total Length 0.967mm.Prosome robust,2.15 times as long as wide. Prosome 1.22 times as long as urosome. Trimmed CR. Urosome two segmented. GS ovate 1.25 times as long as wide. AS with parallel lateral margins, 2.57 times as long as wide.CR 4.2 times as long as wide. Proportional lengths of GS:AS:CR is 1.25:0.9:2.1 (Fig.13a,c). A2 four segmented.1st endopodal segment bears endopodal seta shorter than coxobasal setae; inner distal margin formed into stout teeth. 2nd segment short bearing two elements; 3rd segment cylindrical, armed with a curved terminal claw and a short spine arising from the inner distal margin (Fig.13b).

Remarks : *C.giesbrechti* female described by Tanaka differs from those described by Dahl in the proportional lengths of the abdominal segments and CR (46:28:28 for latter and 41.5:17.25:19.5 for former) and in the more robust GS. The male specimens of Tanaka closely resembles *C.agilis*. But the shape of the 4th thoracic segment that is more tapered, slender GS with a small ventral hook and the large cylindrical part are the most distinguishing characters when compared with from those of *C.agilis*. *O.giebrechti* described during the present study and proportions of the relative segments and the body size were almost equal to those of previous descriptions. The diagnostic features like 1) Ovoid PR in female and robust PR in male; 2) GS ovate in both male and female; 3) A median hook in the ventral surface of both male and female 4) Length width proportions of the PR,GS and AS of the specimens of *O.giebrechti* from Lakshadweep waters matches with the depictions of previous works. This proves the taxonomic status of *O.giebrechti.*

Distribution: South Africa, Tyrrhenian Sea, Adriatic Sea, Ionian Sea, Aegean Sea, Thracian Sea, Lebanon Basin, Suez Canal, Red Sea, Madagascar, Indian ocean, China Seas (http:// copepods. obs-banyuls.fr/en).

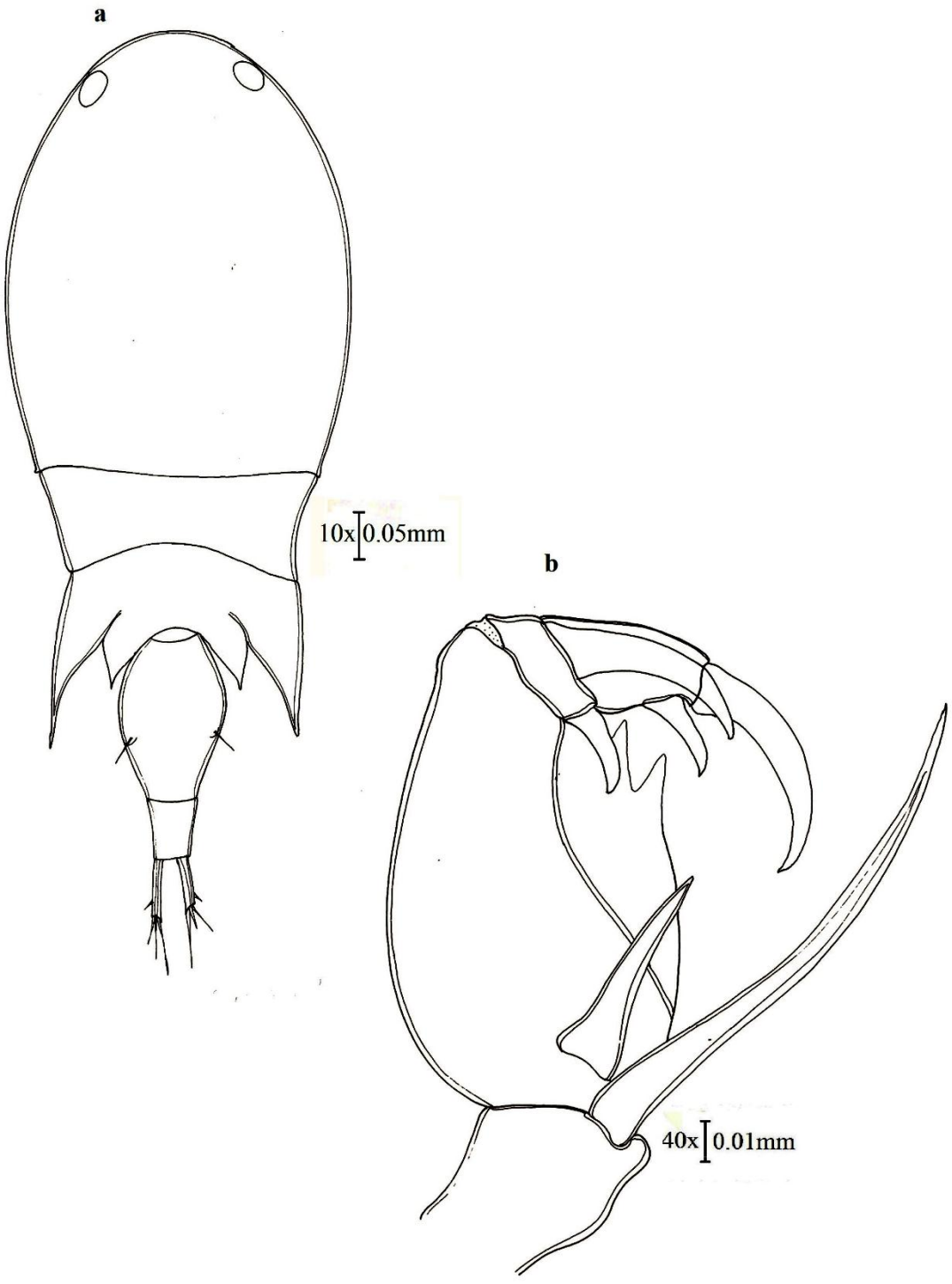


Fig.12.*O.giesbrechti* female.a,Habitus;b,A2.

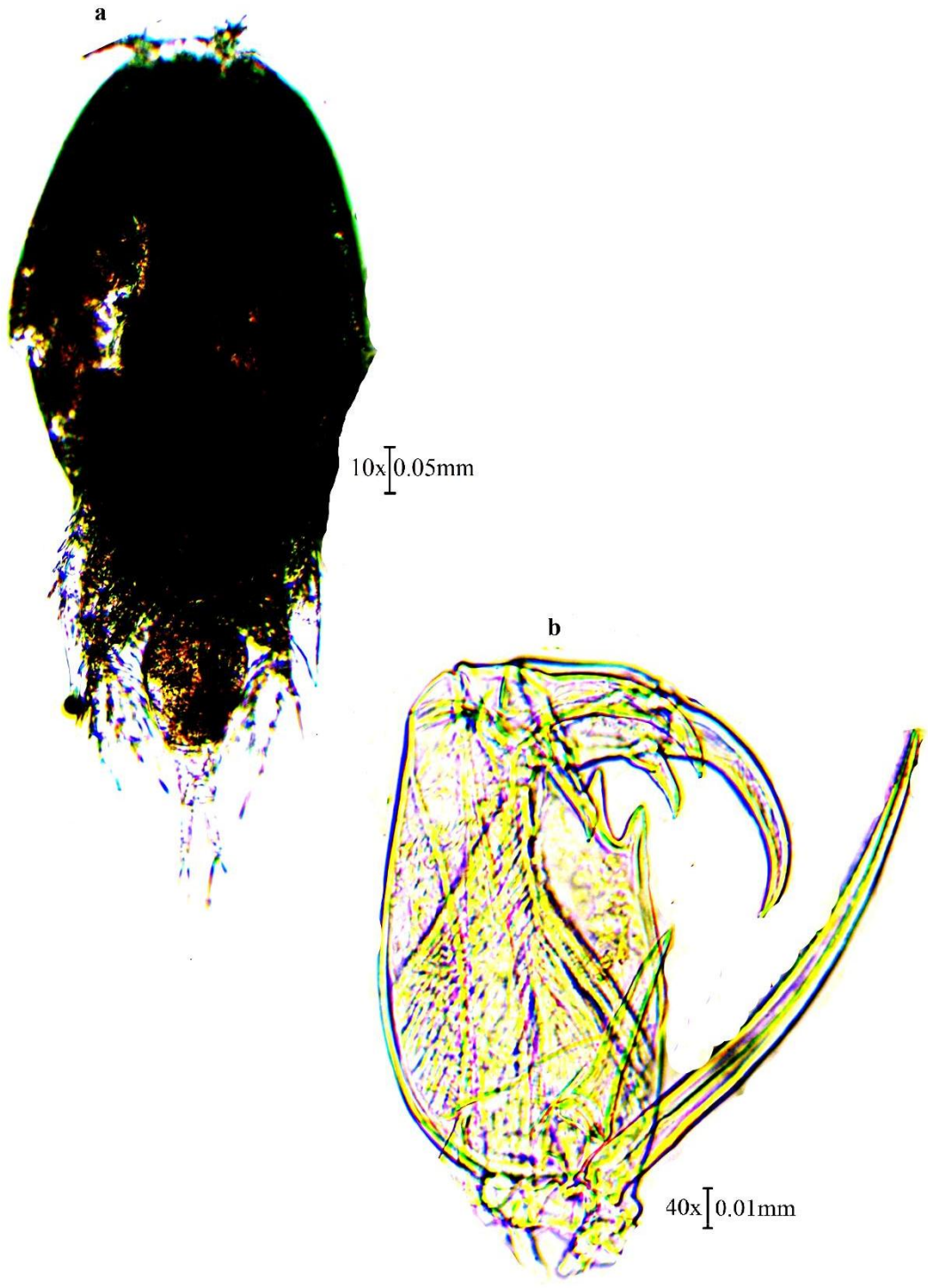


Plate.12.*O. giesbrechti* female.a,Habitus;b,A2.

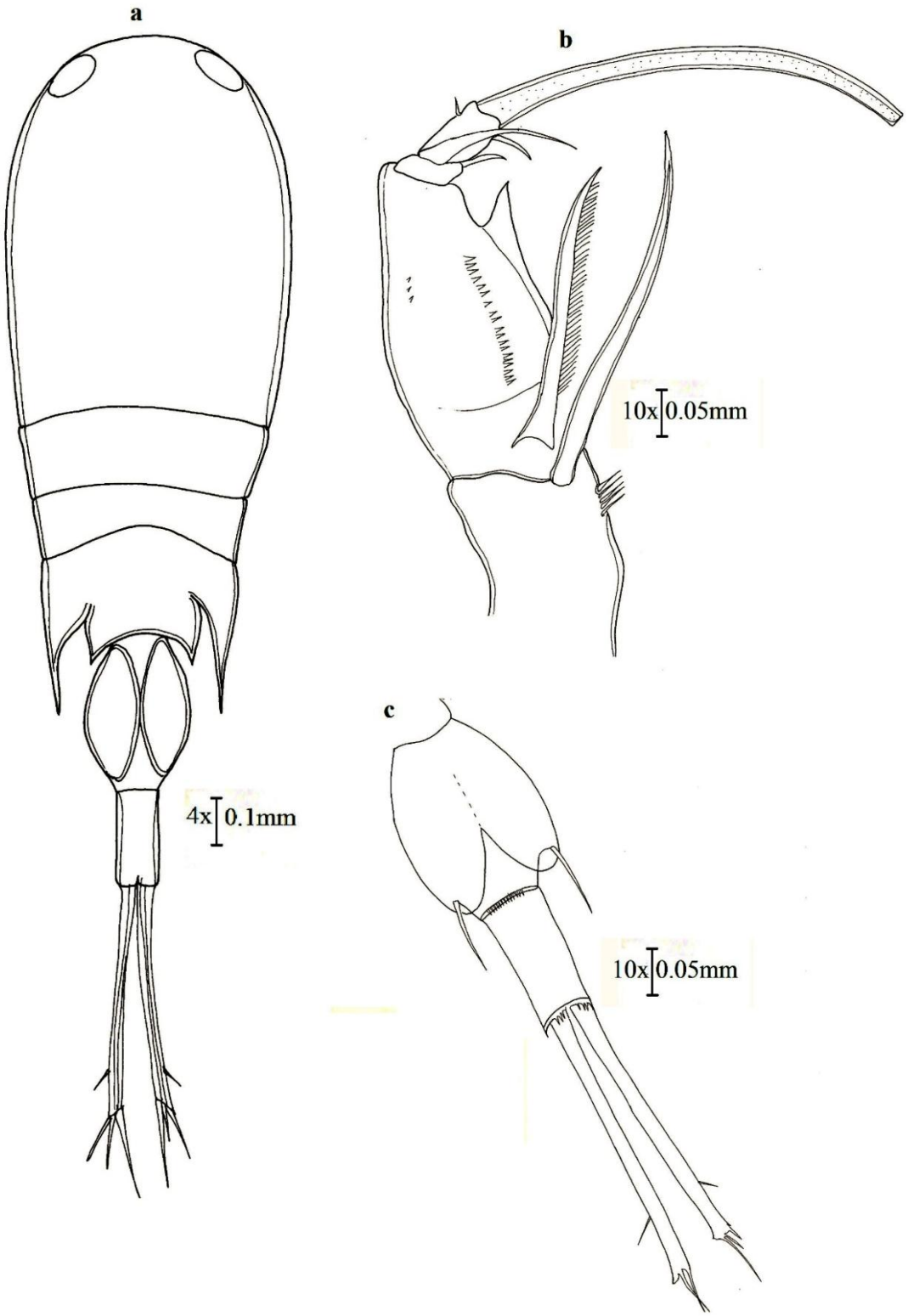


Fig.13.*O. giesbrechti* male.a,Habitus;b,A2;c,Urosome.

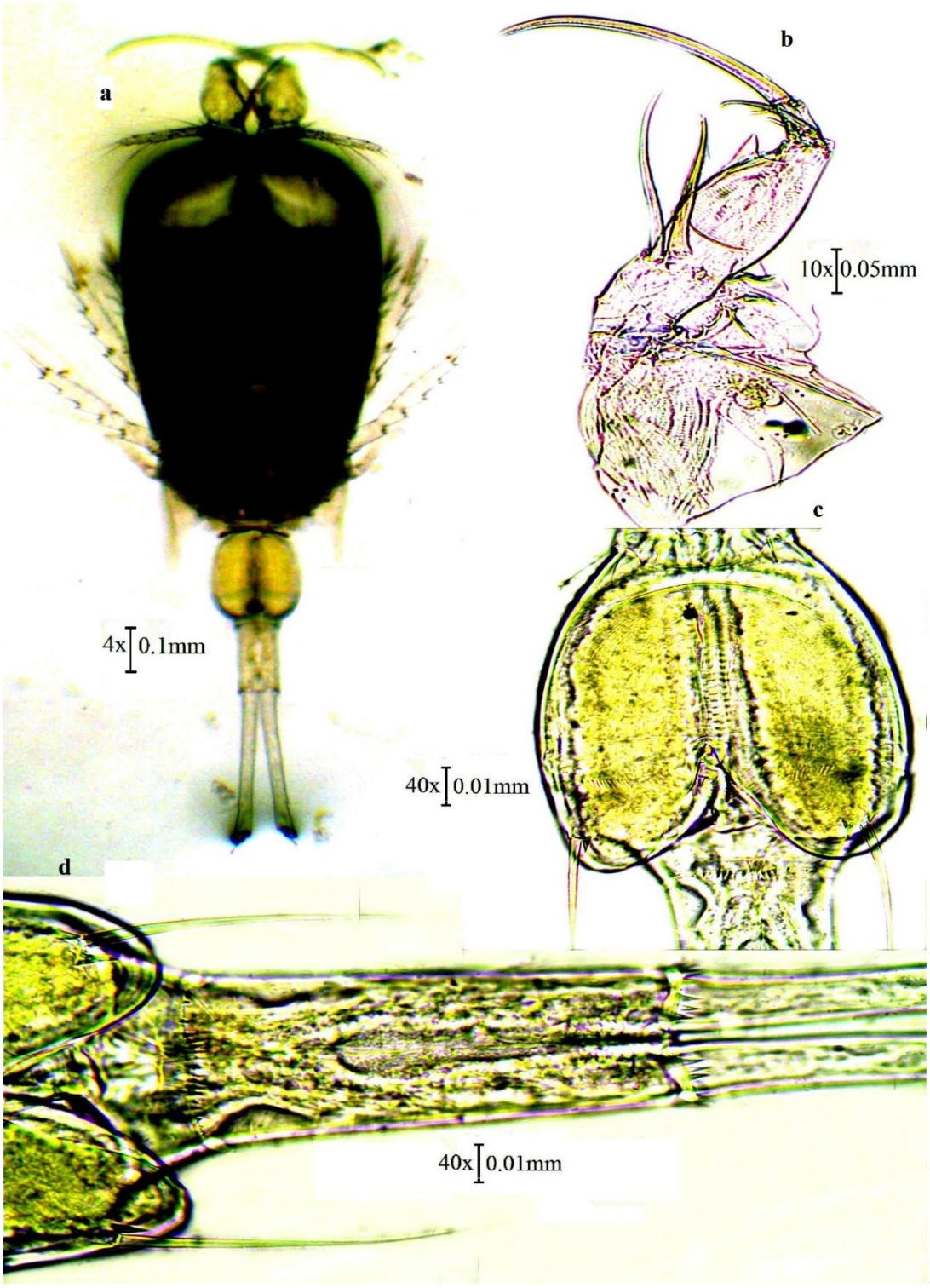


Plate.13.*O.giesbrechti* male.a,Habitus;b,A2;c,GS;d,Urosome.

Onychocorycaeus latus Dana,1849

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Male **(Fig.14, Plate 14)** Total length 0.813mm. Prosome robust with two unequal lateral flaps at the distal margin but less wider than proximal margin, 1.97 times as long as wide. Prosome 1.59 times as long as urosome. GS elongate ovate and extended anteriorly 1.67 times as long as wide. Ventral surface of the GS with no median hook. AS with parallel lateral margins, 2.5 times as long as wide.CR 3.53 times as long as wide.GS1.45times shorter than AS & CR combined. Proportional lengths of GS: AS: CR is 0.72:0.45:0.6 (Plate.14a).A2 four segmented.1stendopodal segment bears a uniramous endopodal setae which is shorter than coxobasal setae. 2nd endopodal segment bears two unequal setae at its inner distal margin.3rd segment armed with a long terminal claw and a short spine arising from the inner distal margin (Fig.14 P4 endopod with one setae**.**

Remarks: Dana's *C.laticeps* was synonymized with this species. *O.latus* species is definitely identified by the ornamentation of A2, number of spines in P4 endopod and anteriorly extended GS. Male specimens differs from female in the appearance of lateral flaps and its width at the distal margin of PR as well as overall shape of PR.A2 in both sexes is almost similar.

Motoda (1963) got only male specimens from Oahu Island. When compared, Lakshadweep specimens agreed with the features like GS shorter than AS & CR combined; body length; A2 ornamentation; A2 terminal claw exceeding the combined length of 1st and 2nd segments; but varied in AS length width ratio being slightly more (2.5) than Oahu specimen which was only 2.3 times. In contrast ,Dahl (1912) mentioned on the GS length being approximately as long as CR & AS combined but is Lakshadweep specimen the same was shorter about 1.45 times. However, GS being almost twice as long as wide in Dahl's specimen was comparable with the present specimen (1.67).

Distribution: Mediterranean, Japan Sea, South and North Pacific Ocean(http:// copepods. obs-banyuls.fr/en).

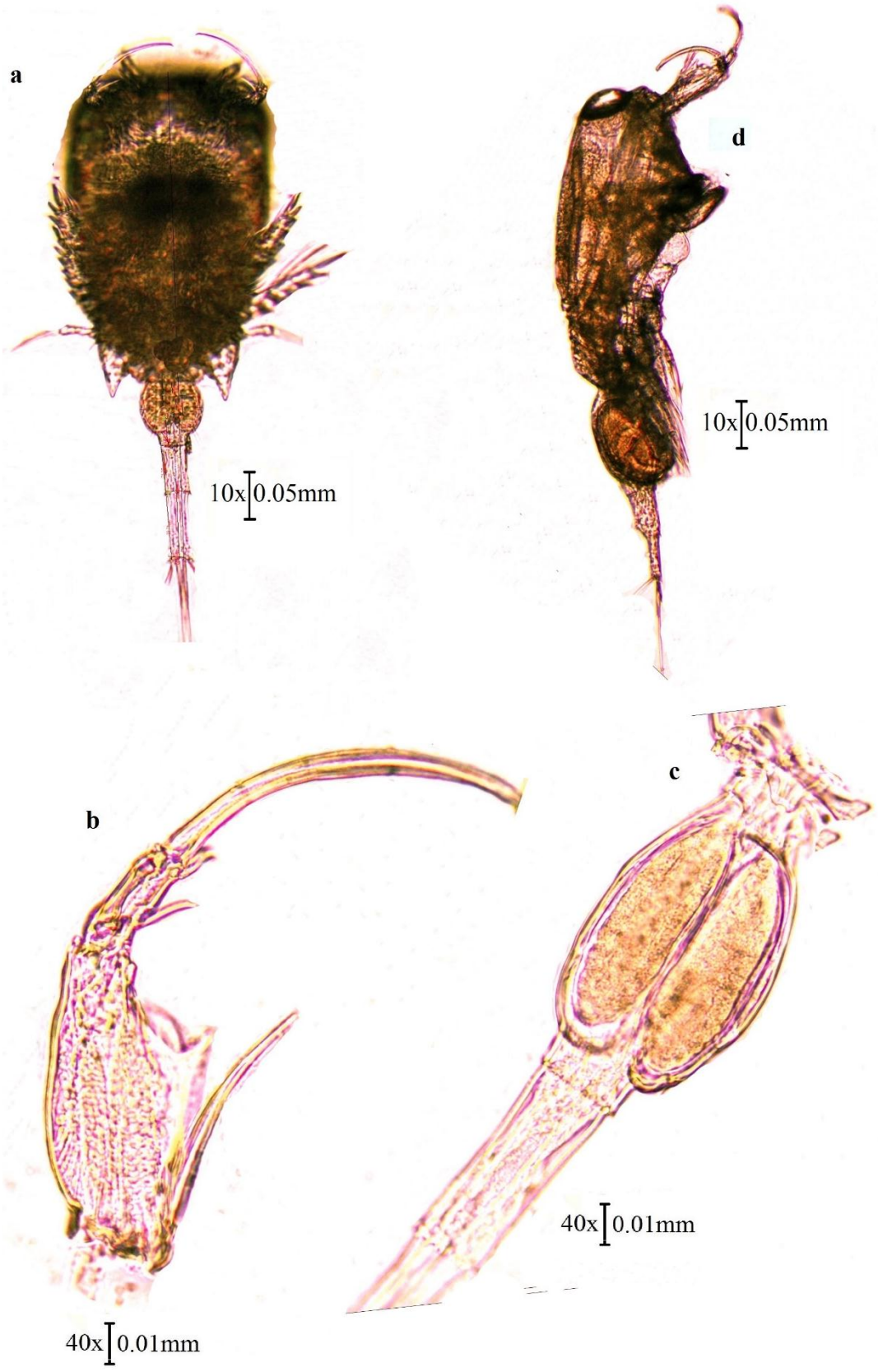


Plate.14. *O.latus* male.a,Habitus;b,Habitus (lateral);b,A2;c,Urosome.

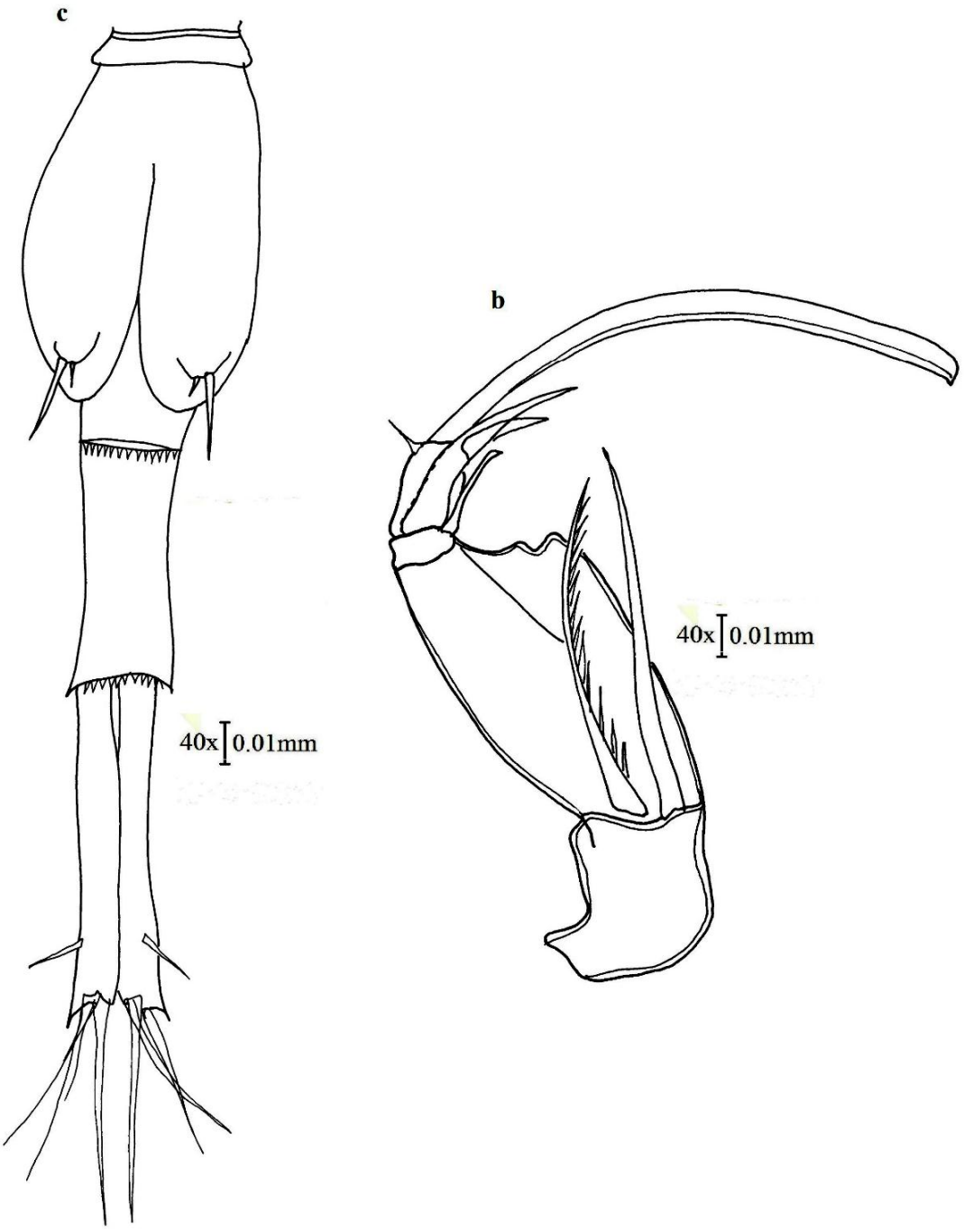


Fig.14. *O.latus* male.a,A2; c,Urosome.

Onychocorycaeus pumilus Dahl.M,1912

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female (Fig.15, Plate.15) Total Length 0.671-0.68mm.Prosome 1.56 times as long as wide. Urosome 2.8 times as long as wide. Presence of wing like expansion of the 3rd thoracic segment upto GS and small posterior protuberance of 4th thoracic segment (Fig.15a). A2 four segmented. Coxobasal setae longer than endopodal setae.1st endopodal segment bears a short spine at inner distal margin.2nd segment is short bearing two spine like process.3rd segment bears two spines ,one at inner distal margin and the other drawn out as a terminal claw (Fig.15b).

Remarks: Tanaka (1960) and Dahl (1912) could only report male species whereas female species were reported by Chen and Zang (1974); Sewell (1947).However Sewell had already reported *O.pumilus* from Arabian Sea which is a part of Indian Ocean. Wing like expansion of the 3rd thoracic segment upto GS and small posterior protuberance of 4th thoracic segment is mainly a characteristic of Onychocorycaeus genus and obviously of *O.pumilus* too. Tanaka regarded both *O.medius* and *O.pumilus* as identical species. After Tanaka, Farran's specimen of pumilus from the Great Barrier reef were more similar to *O.pumilus* itself than to *O.medius.* Anyhow, its presence in extreme North Pacific is said to be surprising and Boxshall & Halsey considers this subgenus as full generic status pending phylogenetic revision.

Distribution: South Africa, Ibero-moroccan Bay,Suez Canal, Red Sea, Arabian Sea, Madagascar, Indonesia-Malaysia, Sarawak-Bintulu coast, Bismarck Archipelago, Philippines, China Seas, Taiwan, Japan (Kuchinoerabu Island.), Japan, Australia (North West Cape, Great Barrier), New Caledonia, off Hawaii, Pacific Ocean(http:// copepods. obs-banyuls.fr/en).

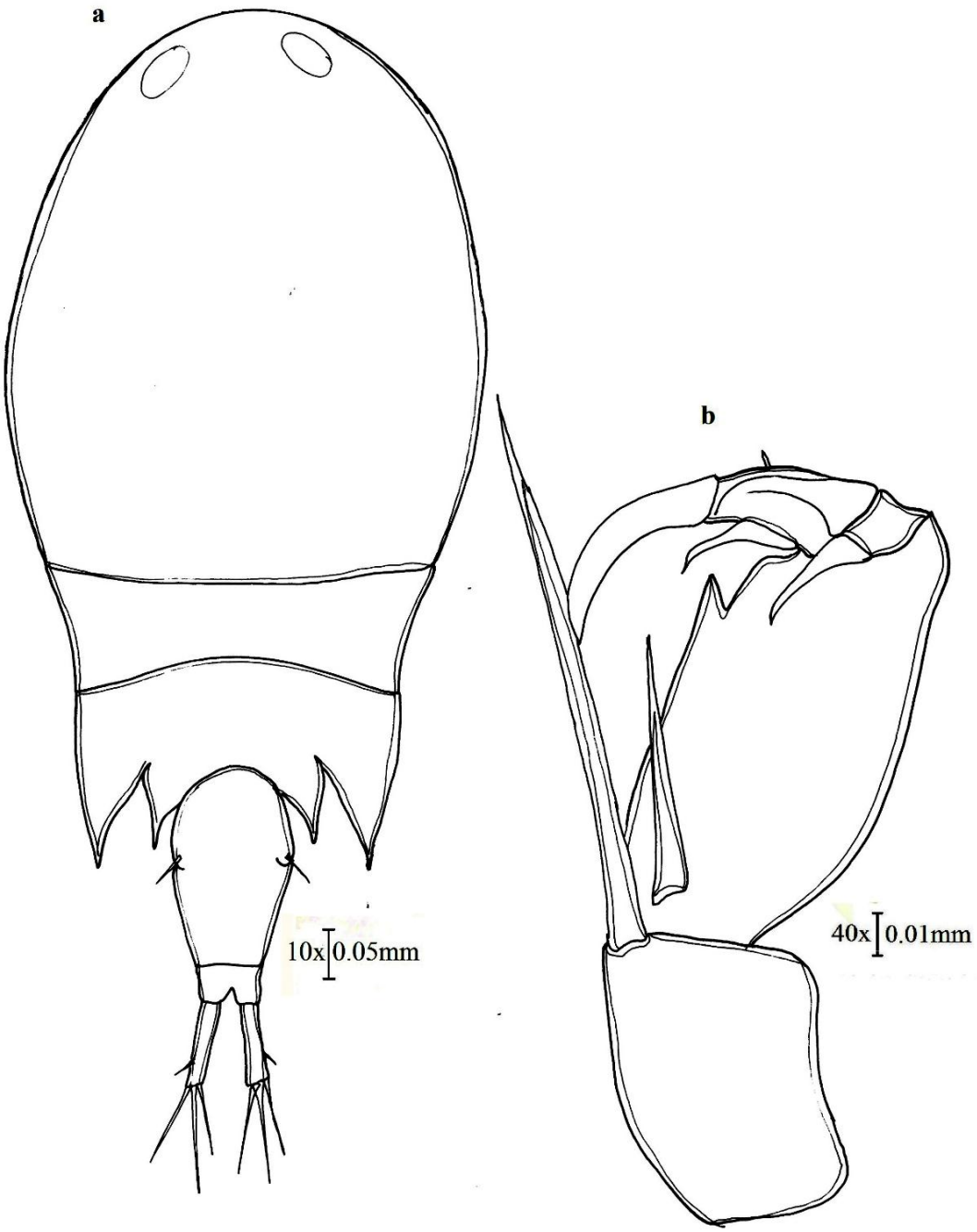


Fig.15. *O.pumilus* female.a,habitus; b,A2.

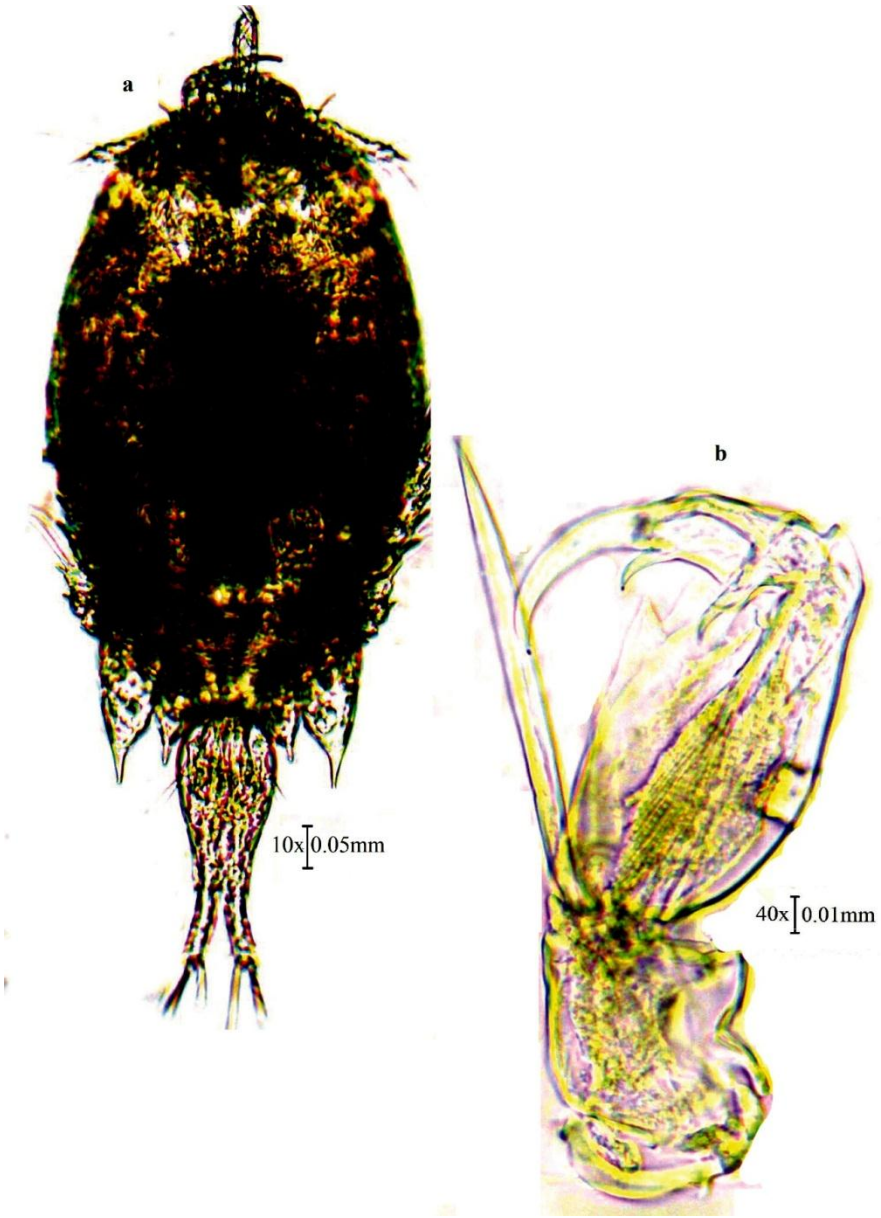


Plate.15. *O.pumilus* female.a,Habitus; b,A2.

***Onychocorycaeus pacificus* Dahl.F,1894**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.16,Plate.16)** Total Length 1.12-1.15mm.Large prosome 1.96 times as long as wide and 1.52 times as long as urosome.3rd pedigerous somite with lateral pointed lateral flaps but 4th pedigerous somite with short blunt flaps. Urosome two segmented. GS ovate 1.14 times as long as wide. AS slightly divergent at base, 3 times as long as wide.CR 6.1 times as long as wide .Proportional lengths of GS: AS:

CR is 1.25:1.05:1.85 (Fig.16a). A2 four segmented. Coxobasal setae longer than endopodal setae.1st endopodal segment bears a short spine at inner distal margin.2nd segment is short bearing two spine like process.3rd segment bears two spines,one at inner distal margin and the other drawn out as a claw (Fig.16b).

Remarks: Sewell considers *O.pacificus* and *O.ovalis* as local races of the same species. In Sewell's specimen, the ratio of PR: UR was found to be 1.94 and that of Lakshadweep specimen being 1.52. Even with slight variation, this was comparable. The ornamentation of A2; number of spines in P4 endopod; shape of urosomal segments all these confirmed the morphological identity of *O.pacificus* female specimen.

Distribution: Indian Ocean, Pacific Ocean, Japanese waters (http:// copepods. obs-banyuls.fr/en).

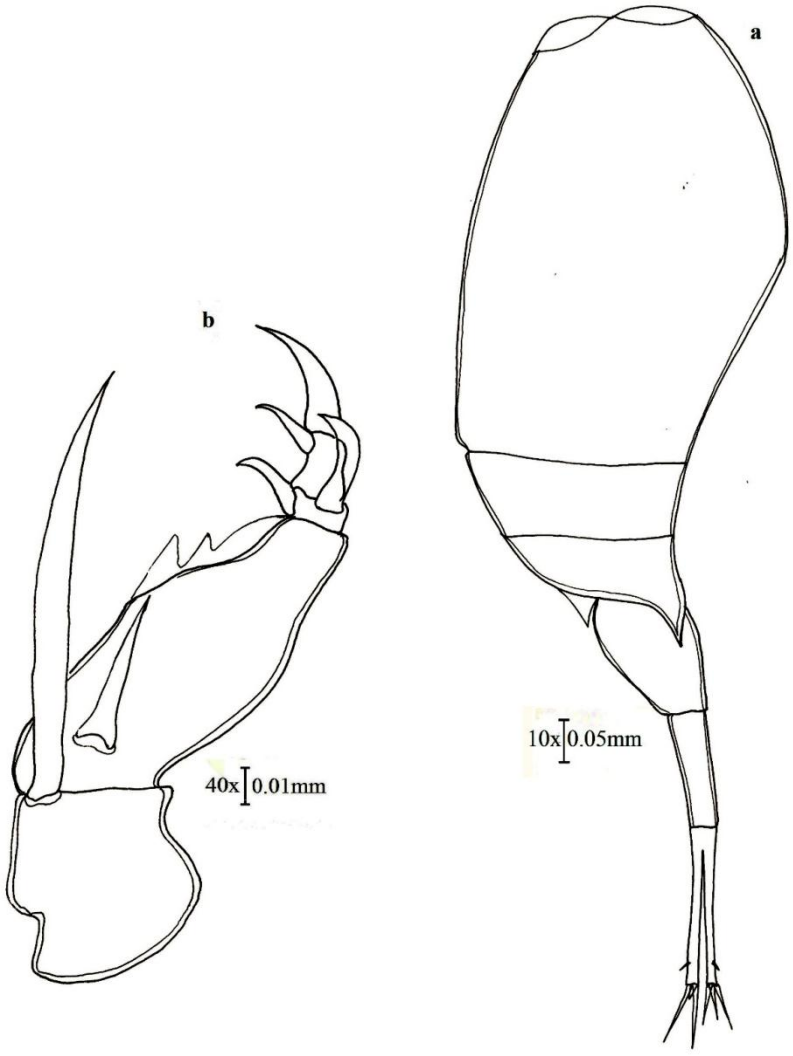


Fig.16. *O.pacificus* female.a ,Habitus (lateral);b,A2.

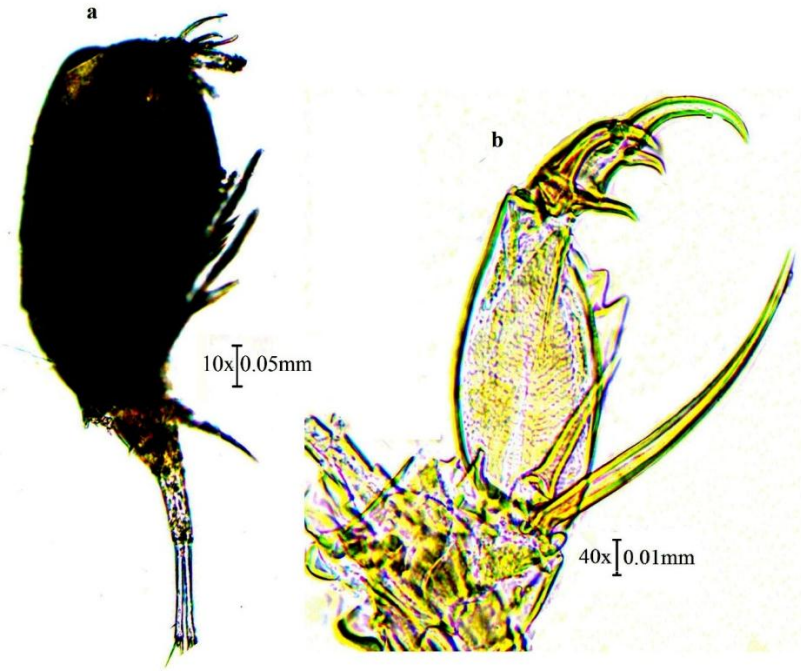


Plate.16. *O.pacificus* female.a ,Habitus (lateral);b,A2.

***Ditrichocoryceus andrewsi* Farran,1911**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.17,Plate.17)**: Total body length 1-1.07mm. Prosome, frontal margin arc shaped, with two large separate cuticular lenses; about 1.97 times longer than urosome and 2.15 times as long as wide. Urosome three segmented with slightly divergent caudal rami. GS somite broadish oval and widest at the middle and 1.34 times longer than wide. AS 1.66 times long as wide. CR about 1.38 times longer than wide. Proportional lengths of the GS:AS:CR is 3.5:2:1.8.GS is as long as anal somite and caudal rami combined (Fig.17a).Antenna four-segmented bearing three endopodal segments.1st endopodal segment robust,bears unipinnate setae shorter than coxobasal setae. Outer distal margin produced into a spine. 2nd endopodal segment, shortest of the three, bears two elements.3rd endopodal segment armed with a long robust terminal claw and a short spine at its base (Fig.17b).

Male **(Fig.18,Plate.18)**:Total body length 0.712-0.8mm.Urosome conspicuously narrower than urosome.Prosome, frontal margin arc shaped, with two large separate cuticular lenses.; about 1.5 times longer than urosome and 1.46 times as long as wide. Proportional lengths of the urosomal somites and CR is 7.6:3.6:4.Genital segment is as

long as anal somite and caudal rami combined (205:102.5:105). Urosome three segmented with slightly divergent caudal rami. Genital double somite broadish oval and widest at the middle and 1.52 times longer than wide. Anterior margin bears a ventral hook which is evident in the lateral view.P6 represented by a genital flap;armed with short,stout naked setae. AS 1.5 times long as wide. CR long and divergent, about 5 times longer than wide (Fig.18a).Antenna four-segmented bearing three endopodal segments. 1st endopodal segment robust and barrel shaped bears unipinnate setae shorter than coxobasal setae. Outer distal margin produced into a spine. Midventral surface vertically adorned with denticles gradually increasing in length at distal end.2nd endopodal segment, shortest of the three, bears two elements. 3rd endopodal segment armed with a long robust terminal claw extending upto coxobasis with a blunt tip and a short slender spine at its base (Fig.18b).P4 endopod reduced into a knob like segment with two plumose setae arising from it, one slightly longer than the other (Plate.18e).

Remarks: Genus *Ditrichocorycaeus* M. Dahl(1912) is characterized by the procession two setae on endopod of P4 and is divided into two groups based on relative lengths of the caudal ramus of which the first group has short caudal rami almost equal to anal somite but shorter than genital somite and the second group is characterized by the possession of caudal ramus longer than both anal somite and genital somite (Dahl 1912;Tanaka 1957). The male specimen of *D.andrewsi* belongs to the first group. The combination of general morphological features such as shape of the genital double somite, presence of ventral hook; slight swelling about the middle lateral margins of the second thoracic segment: width length ratio of the genital segment; presence of median longitudinal row of spinules /denticles in the first endopodal segment; total body length; PR:UR ratio is consistent with the description of *D.andrewsi* male by Tanaka(1957).However variations were also noticed, from the illustrations given by Tanaka (1957)of Japanese waters in proportional lengths of the Urosomal somites and CR greater (58:21:21) as compared to Kavaratti specimens (7.6:3.6:4); length width ratio of the CR being less than that of Kavaratti specimen (4 vs.5). *Corycaeus trukicus* Mori is the synonym of *D.andrewsi* in the short caudal rami whose length is almost equal to that of anal somite, short wing like process on posterior ends of metasomal somite 3 in the male. Although P4 and caudal setae are considered as important identification keys to the genus *Ditrichocorycaeus,* the same has not been described by Tanaka (1957).

Distribution: Pacific coast, Japanese waters, Indo-Pacific Ocean, Truk Island (http:// copepods. obs-banyuls.fr/en).

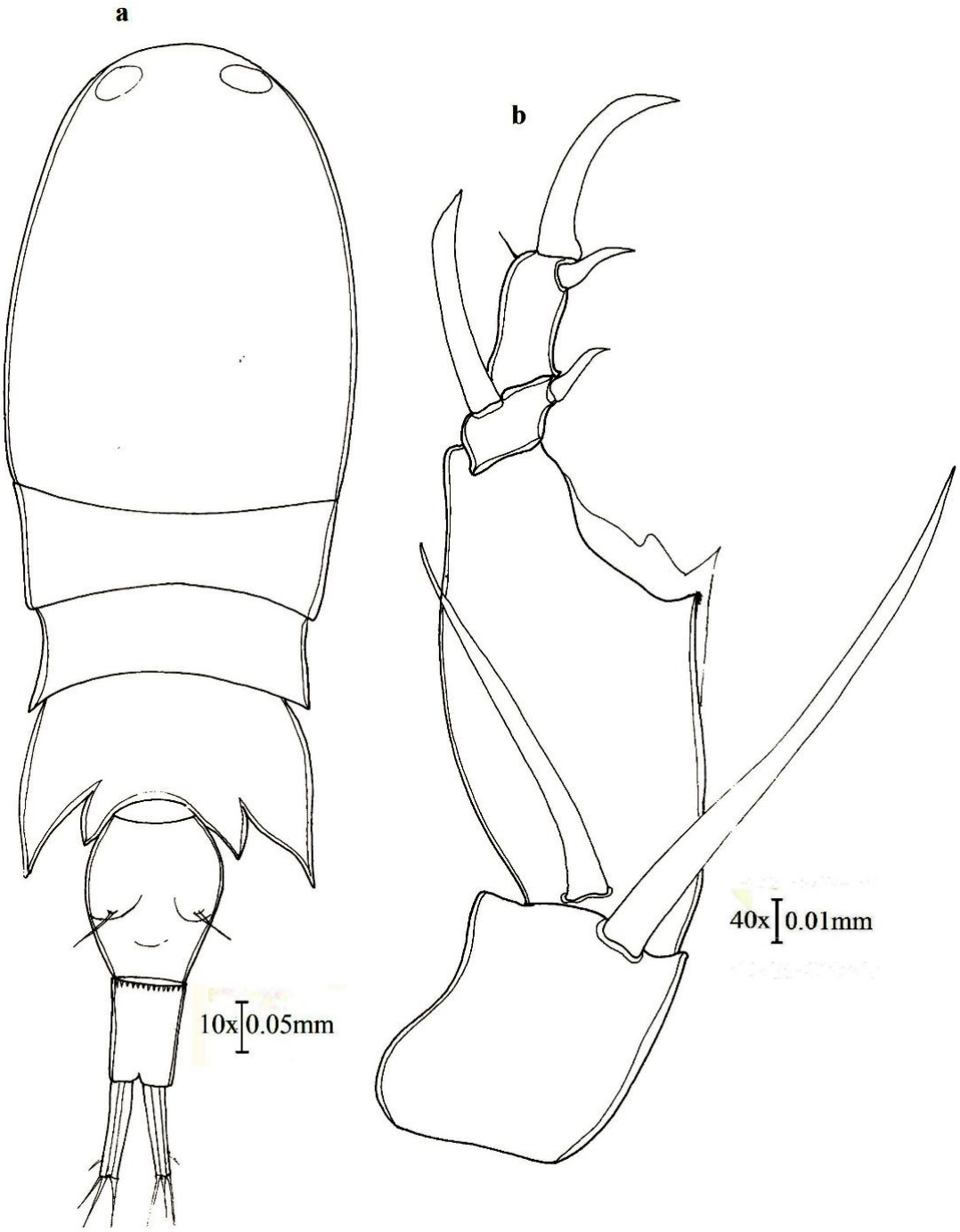


Fig.17. *D.andrewsi* female.a,Habitus;b,A2.

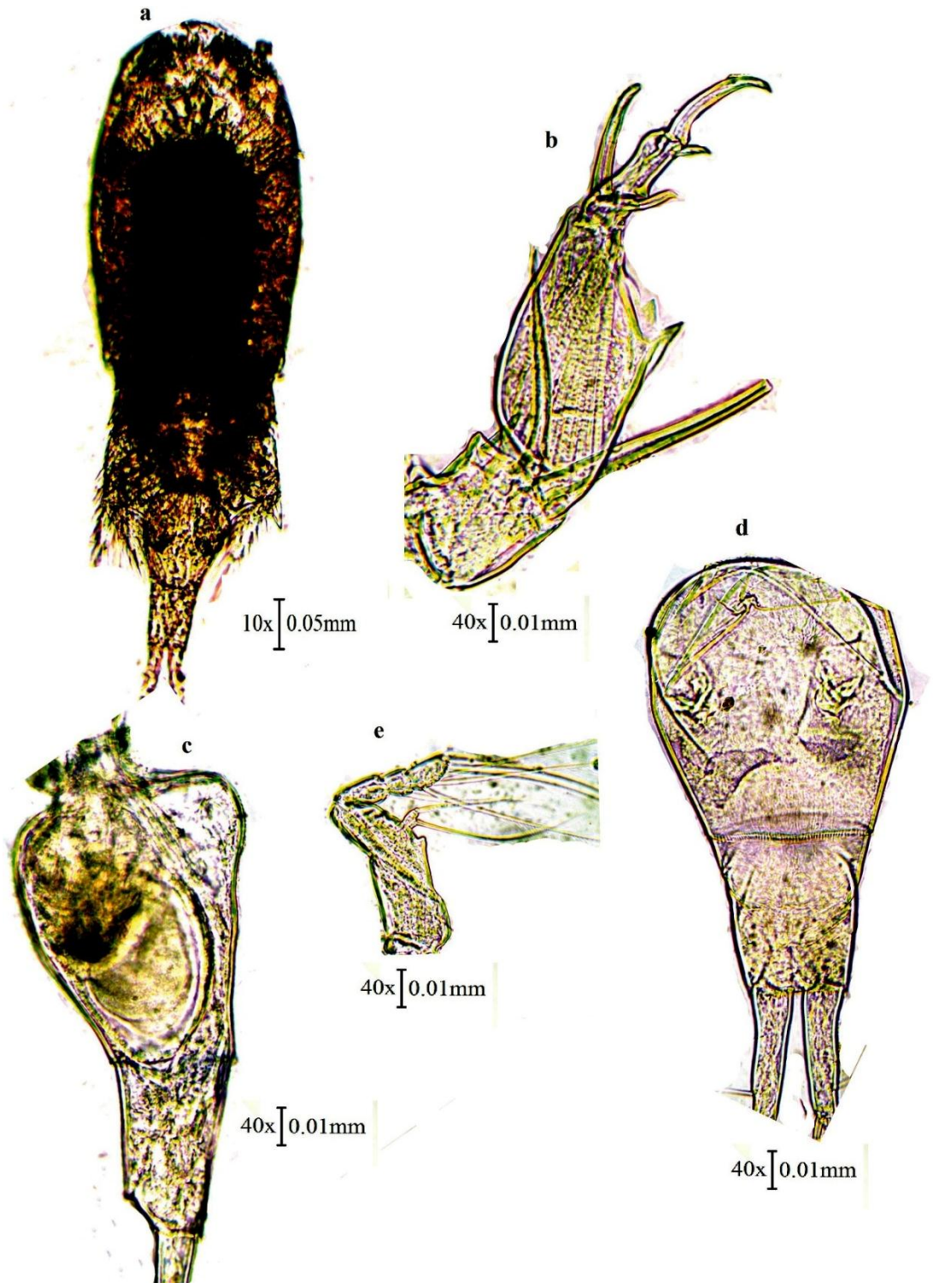


Plate.17. ***D.andrewsi*** **female.a,Habitus;b,A2;c,Urosome (lateral); d, Urosome (Dorsal);e,P4.**

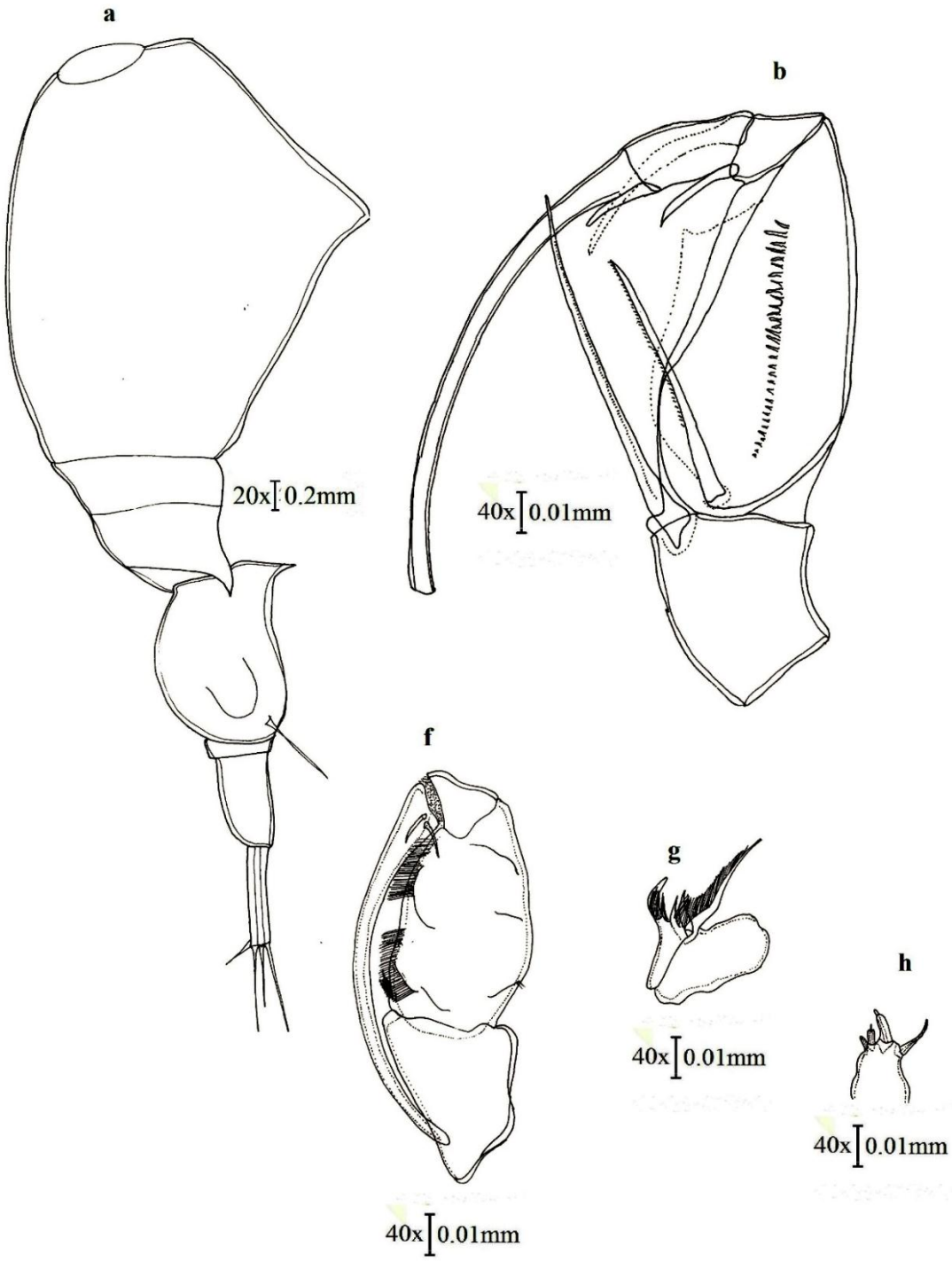


Fig.18A *.D.andrewsi* male.a,Habitus;b,A2;f,maxilliped;g,maxilla;h,maxillule

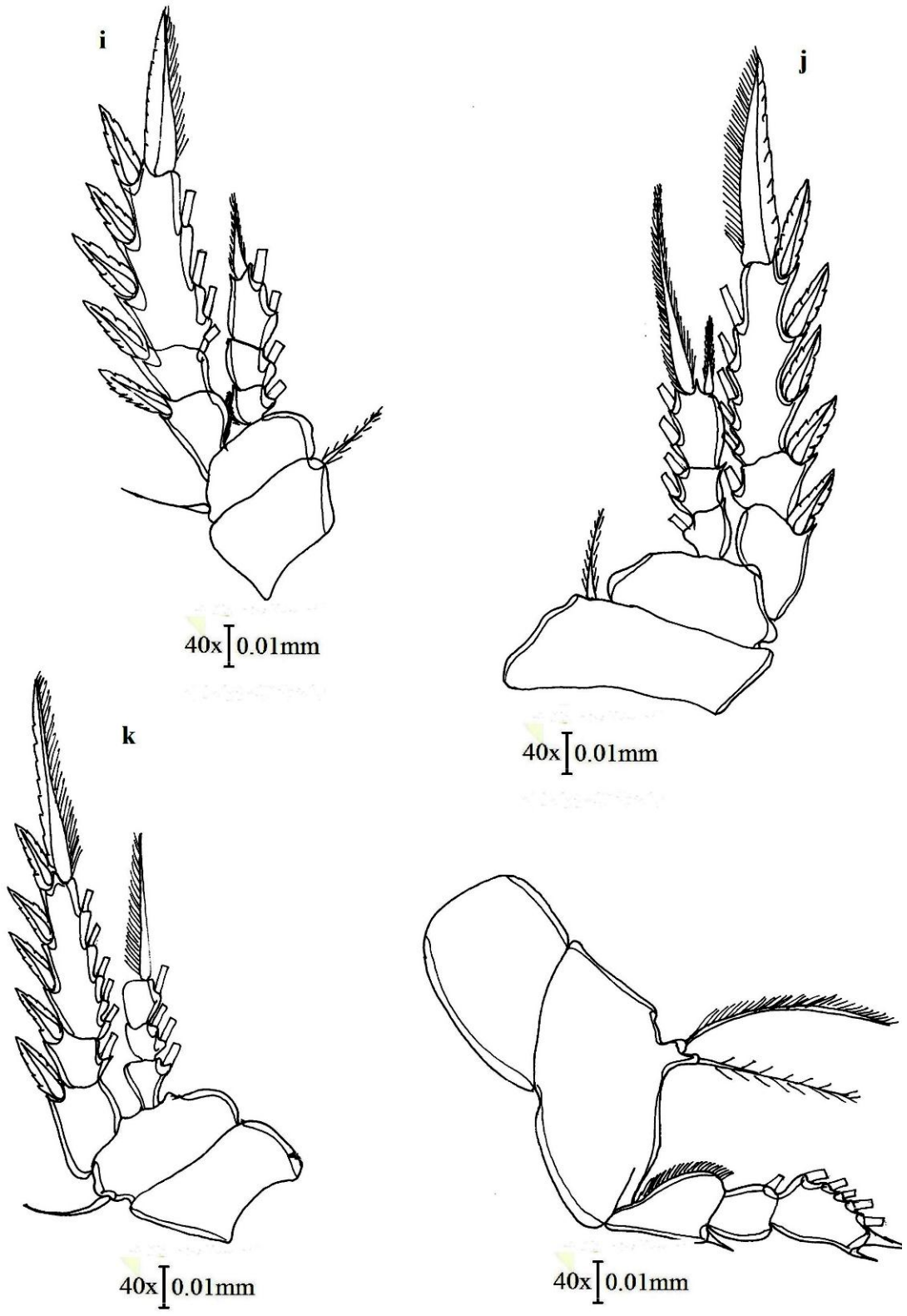


Fig.18 B. *D.andrewsi* male.1,P1;j,P2;k,P3;l,P4.

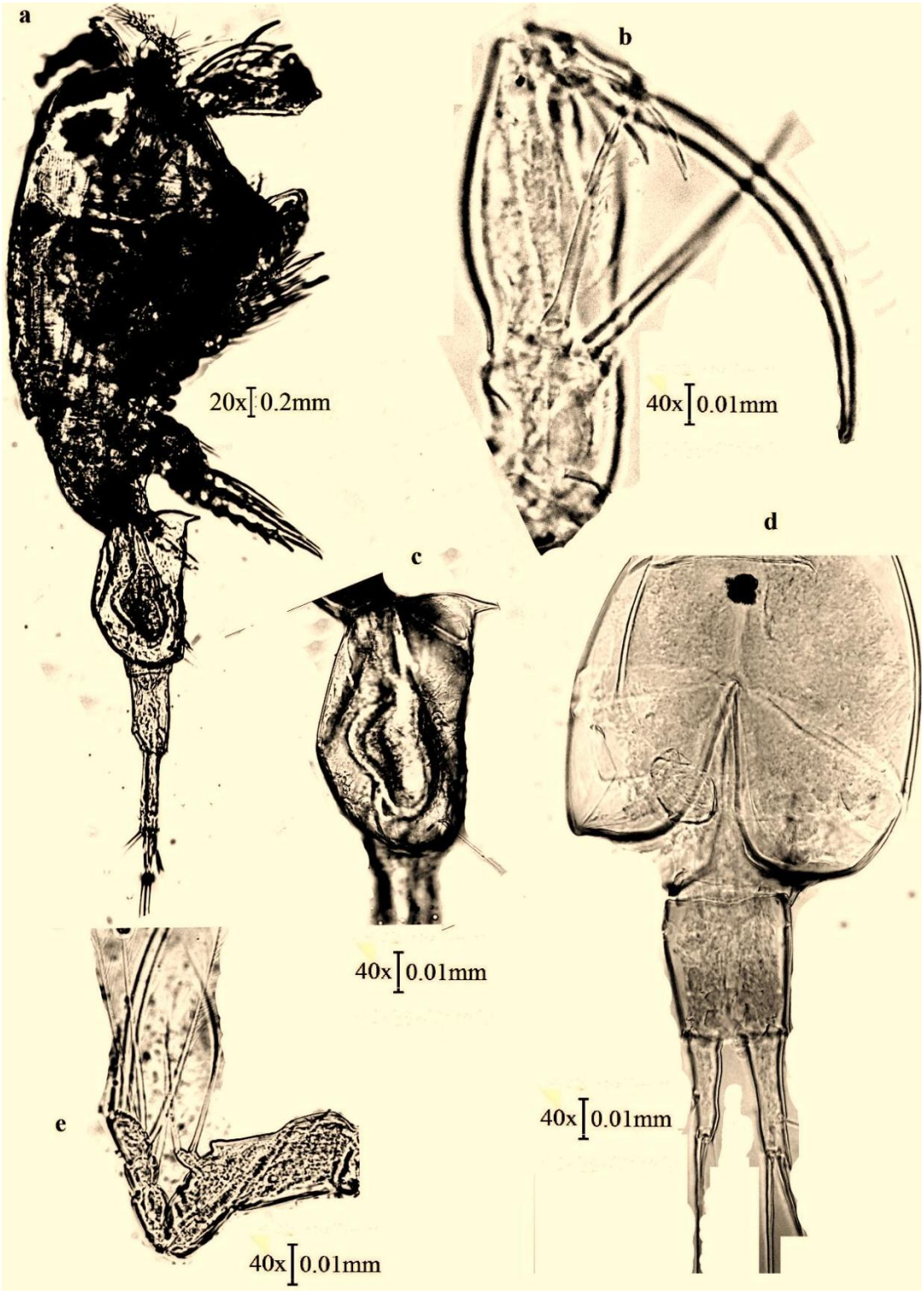


Plate.18. *D.andrewsi* male. A,Habitus;b,A2; c,GS;d,Urosome;e,P4.

Ditrichocoryceus affinis McMurich,1916

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni,Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.19,Plate.19)** Total body length 0.95-1mm.Prosome five segmented with 4th metasomal segment produced into lateral flaps. Prosome 2.27 times as long as wide and 1.8 times as long as urosome.Genital segment double somite 1.06 times as long as wide.AS 1.41 times as long as wide.CR 1.73 times as long as wide (Fig.19a,b).A2 four segmented with three endopodal segments.1st endopodal segment bears short setae which is shorter than coxobasal setae.2nd endopodal segment ,short, bears two spines and 3rd endopodal segment adorned with a claw like process and a short spine. Proportional lengths of GS:AS:CR is 5.8:2.6:5.2 (Fig.19c).

Remarks: Davis (1949) considers *Corycaeus japonicus* to be the synonym of *D.affinis. D.affinis* can be identified by CR shorter than urosome, two segmented urosome, ventral keel is not protruded, P4 endopod with two setae and divergent CR.Tanaka (1957) reported length width ratio of CR for female to be 9 and 1.7 times its AS. But Lakshadweep specimen exhibited slight variation but comparable with CR length width ratio as 1.73 and CR:AS ratio as 2. As per Kang et.al (1990) from Korean waters, CR was 7-8 times its width which varied with Lakshadweep specimen (1.73).He also mentioned on the GS being as long as CR & bears a ventral process was consistent with the present study female specimen. Male specimens were not observed during the study period.

Distribution: Distributed in the inland waters of Japan, Korean waters Namibia, Red Sea, Gulf of Oman; Straits of Malacca, G. of Thailand, Hong Kong, China Seas, Korea Strait, Japan Sea, Japan, Kuchinoerabu Island,Ariake Bay, Seto Inland Sea, Tanabe Bay, Tokyo Bay, Charlotte Queen Is., British Columbia, Vancouver Is., Nitinat Lake, Strait of Georgia, San Francisco Estuary, W Baja California (Magdalena Bay), Gulf of California (http:// copepods. obs-banyuls.fr/en).

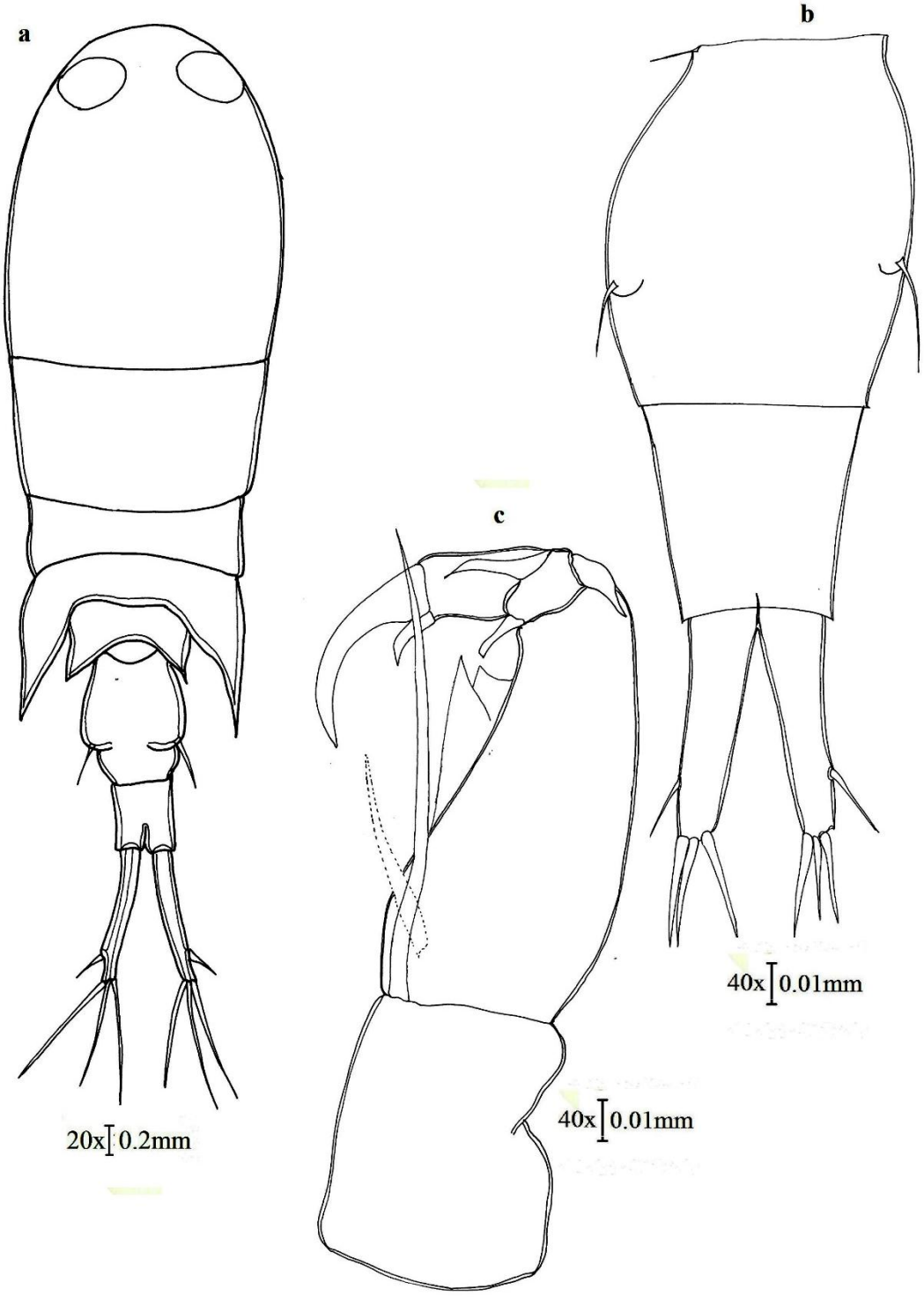


Fig.19. *D.affinis* female.a,Habitus;b,Urosome;c,A2.

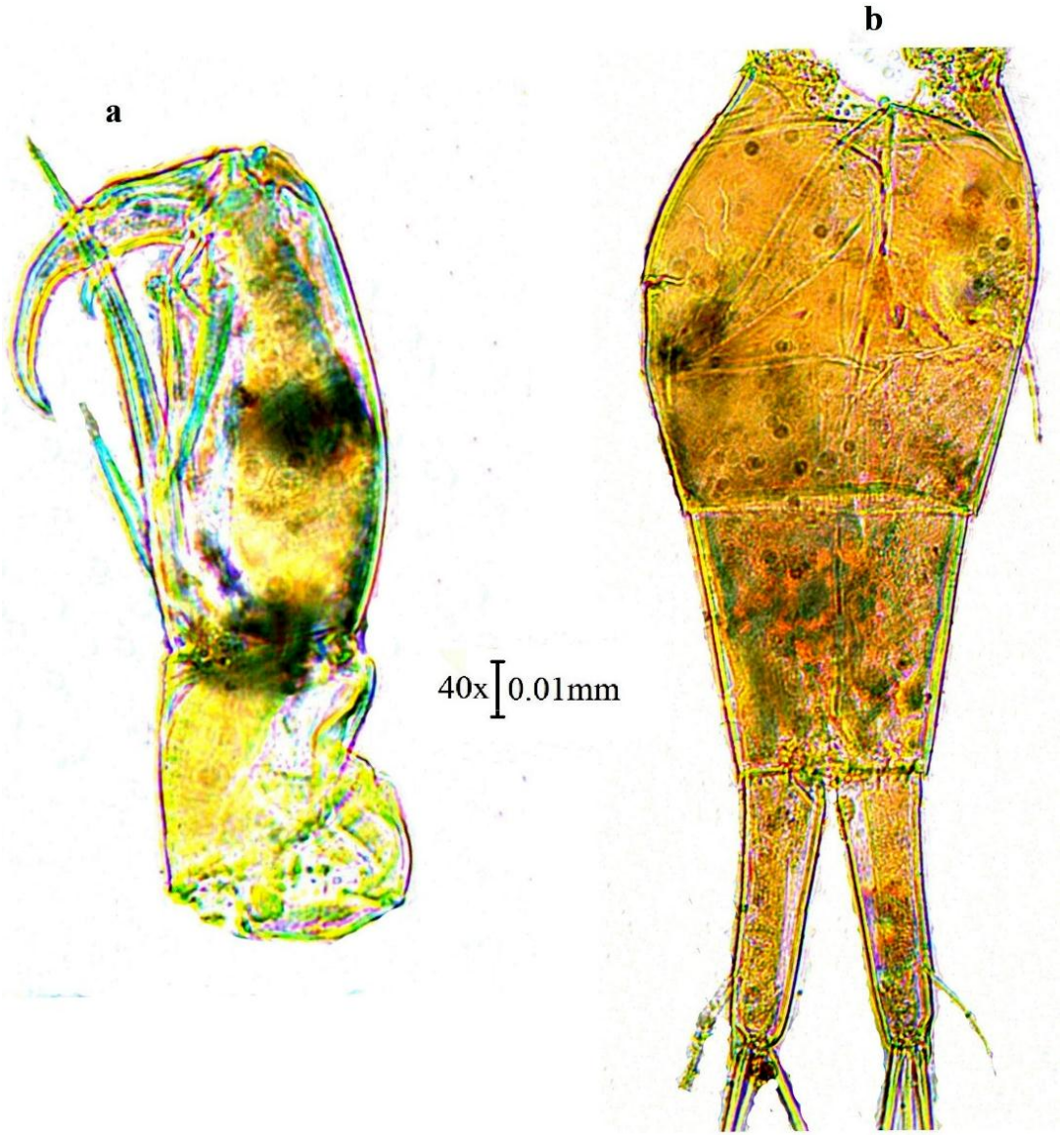


Plate.19. *D.affinis* female. A, Habitus; b,Urosome.

Ditrichocoryceus dahli Tanaka,1957

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Male **(Fig.20, Plate.20)** Total body length 0.687-1.09mm .Prosome frontal margin arc shaped, with two large separate cuticular lenses; prosome about 1.31 times longer than urosome;1.96 times as long as wide (Fig.20a). GDS broadish oval and widest at the middle 2.2 times as long as wide; AS 3.28 times as long as wide. Urosome two segmented with slightly divergent caudal rami at the base.

Proportional lengths of the urosomal somites and CR is 1.65:1.15:2 Caudal rami long and divergent at the base, about 8 times longer than wide (Fig.20b).The shape of A2 is very peculiar.A2 four segmented with three endopodal segments.1st endopodal segment bears a unipinnate setae shorter than coxobasal setae.2nd endopodal segment 3 slender spines of which one is longer.3rd endopodal segment is drawn out as a long slender claw which extends upwards (Fig.20c).

Remarks and Discussion: As per Tanaka(1957),this species is synonymous to *D.lubbocki, D.tenius and D.africanus.* D.dahli can be distinguished by the length of the 3rd endopodal segment being longer, oval genital segment with a small ventral hook and long CR. When compared with previous descriptions, the present specimens showed variations as well as similarities with the original description of Tanaka(1957).Proportional lengths of urosomal segments and CR slightly varied (1.65:1.15:2) with that of Tanaka being 5.0:1.8:3.2.However CR length width proportion was similar being (8 vs 8) for Lakshadweep and Tanaka's specimen respectively. However no female specimen could be encountered in the present study. Recently in 2011 Al-Yamani and team reported box sexes of *D.dahli* from North western Arabian gulf. In that for the male sex, prosome less than twice as urosome was very much similar to Lakshadweep specimen (1.31); length of CR being more than GS was found be almost similar (3.0:1.8:3.8 vs 1.65:1.15:2) and CR being longer than AS.

Distribution: Epipelagic, Coastal and oceanic, Subtropical and tropical,Indian and Pacific Oceans (http:// copepods. obs-banyuls.fr/en).

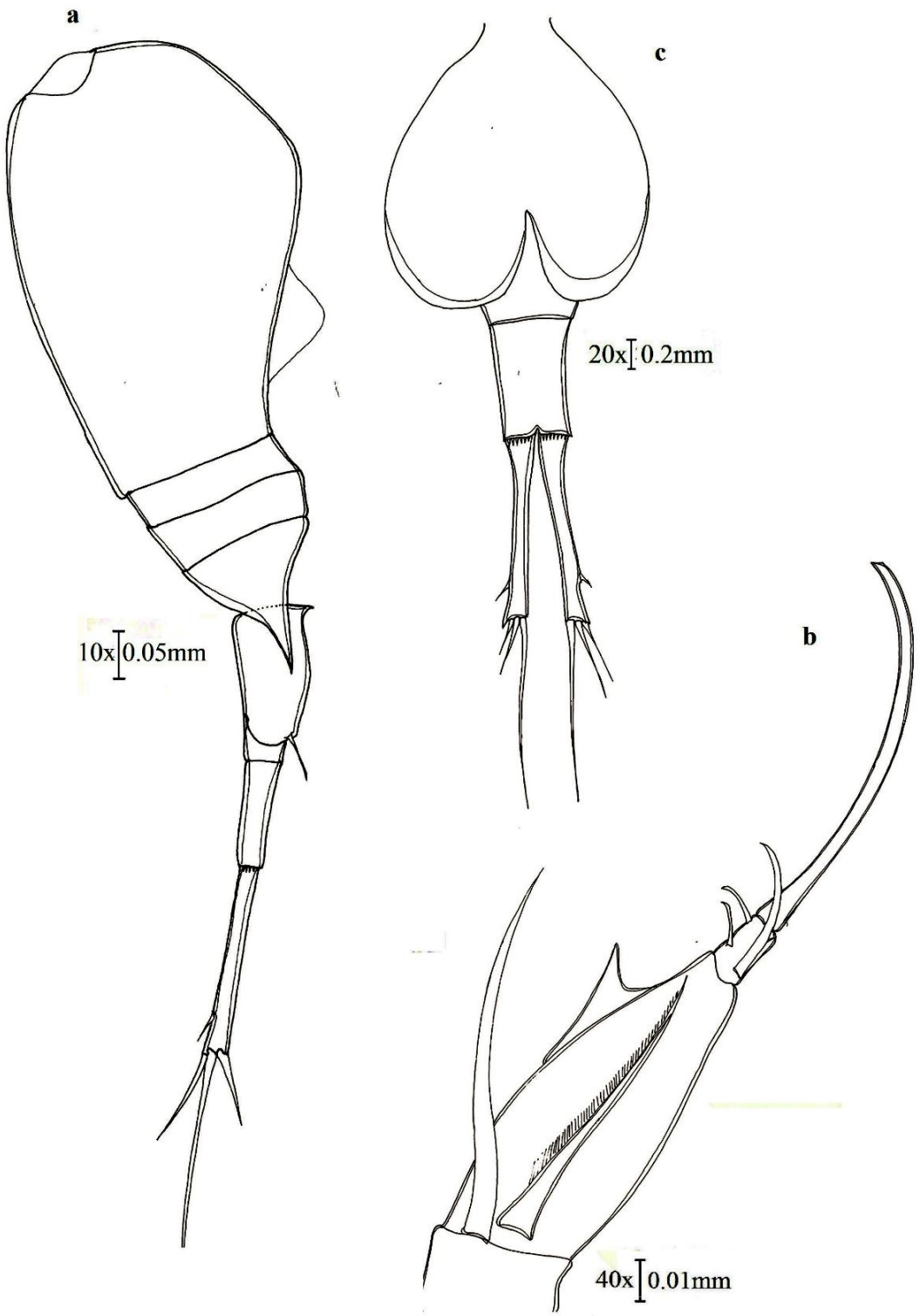


Fig.20. *D.dahli* male.a,Habitus (lateral); b,A2;.c, Urosome.

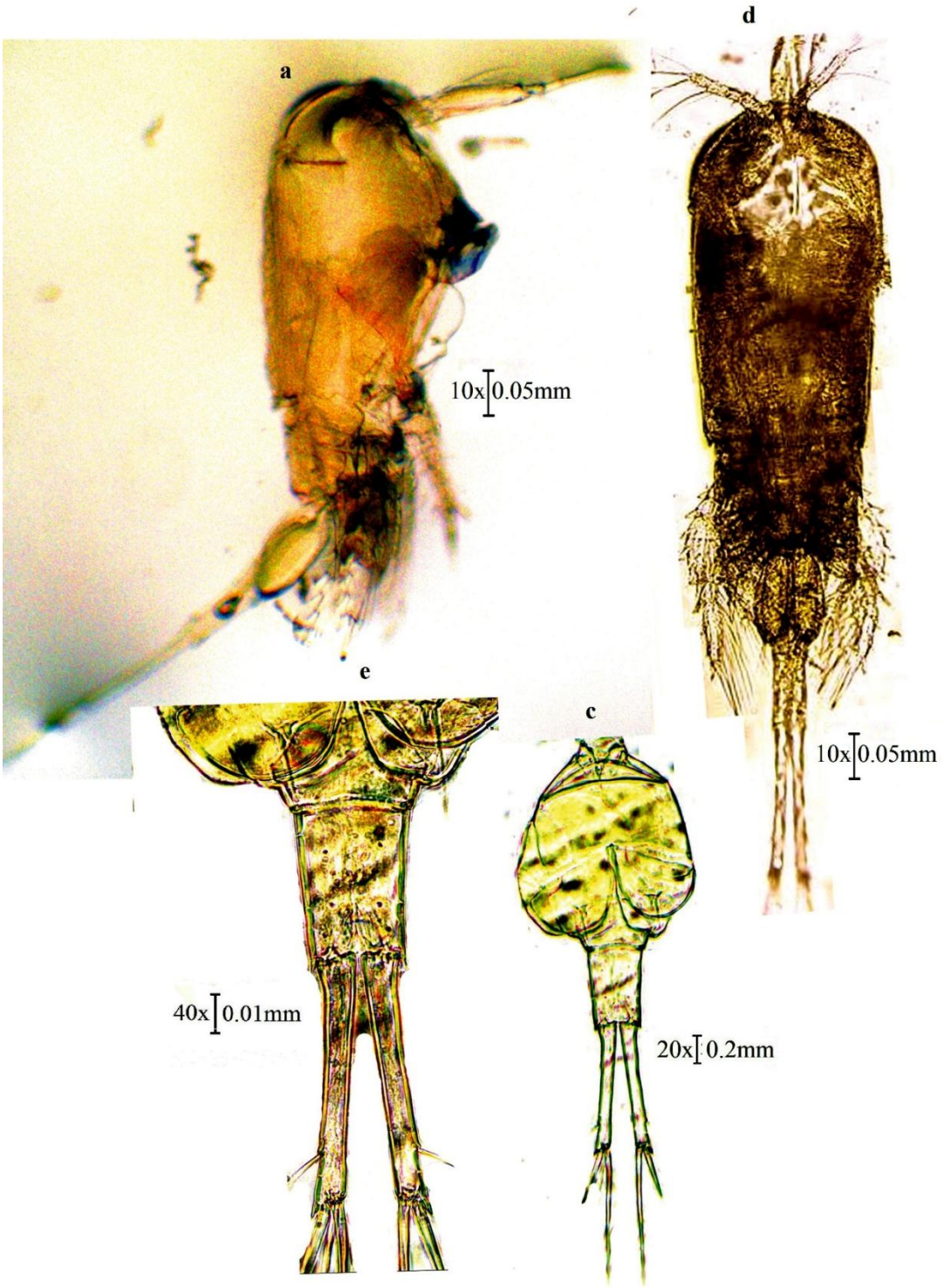


Plate.20. *D.dahli* male. A,Habitus (lateral);b,Habitus(dorsal);c,d,Urosome.

Ditrichocoryceus tenius Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.21,Plate.21)**Total body length 0.94-0.969mm.Prosome about 1.4 times longer than urosome; 1.79 times as long as wide. Urosome conspicuously narrower than prosome. GDS broadish oval and widest at the middle 1.68 times as long as wide; AS thrice as long as wide (3.1).Urosome two segmented with slightly divergent caudal rami at the base. Proportional lengths of the urosomal somites and CR is 1.85:1.4:1.75. Caudal rami long and divergent at the base, about 3.5 times longer than maximum width at base (Fig.21a). A2 four segmented with three endopodal segments.1st endopodal segment bears a setae shorter than coxobasal setae.2nd endopodal segment two spines of which one is longer.3rd endopodal segment bears two elements of which one is drawn out as a terminal claw and the other short at the base (Fig.21c).

Remarks: *D.tenius* in general manifestation it resembles *D.lubbocki* according to Scott(1909) who reported only female specimen. Two segmented urosome is a characteristic feature with long CR which is slightly divergent at the base. In Scott's specimen, CR are nearly twice as long as AS which is comparable to that of Lakshadweep specimen being 1.25 times as long as AS. Dahl (1912) also had the same opinion on CR:AS ratio which was twice longer than AS. The feature in which GS and AS combined longer than CR, of Dahl's female specimen were consistent with the Lakshadweep specimen. Giesbrecht (1892) also reported only female specimens. The present study also encountered only female specimens.

Distribution: Indian and Pacific Ocean (http:// copepods. obs-banyuls.fr/en).

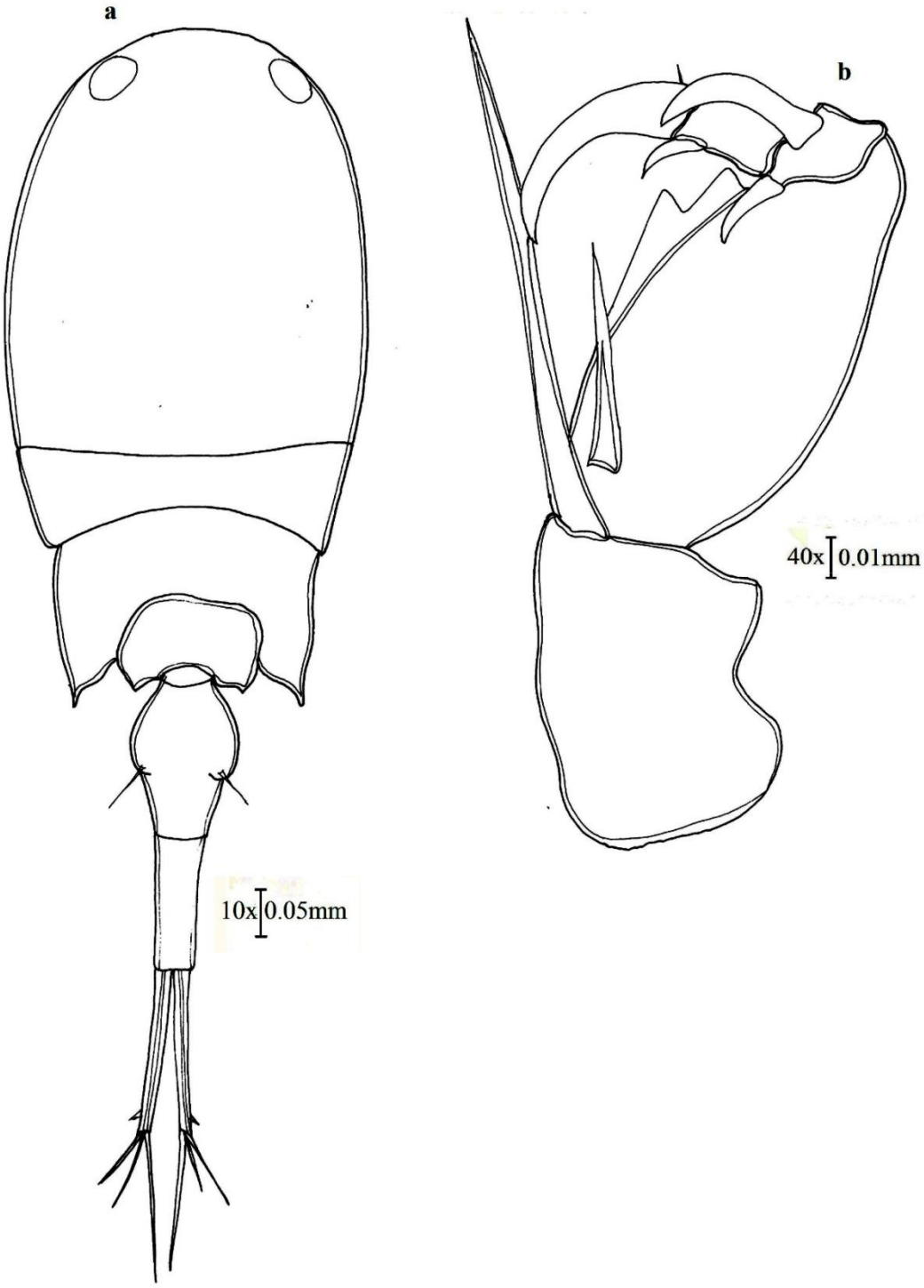


Fig.21. *D.tenius* female. a,Habitus;b,A2.

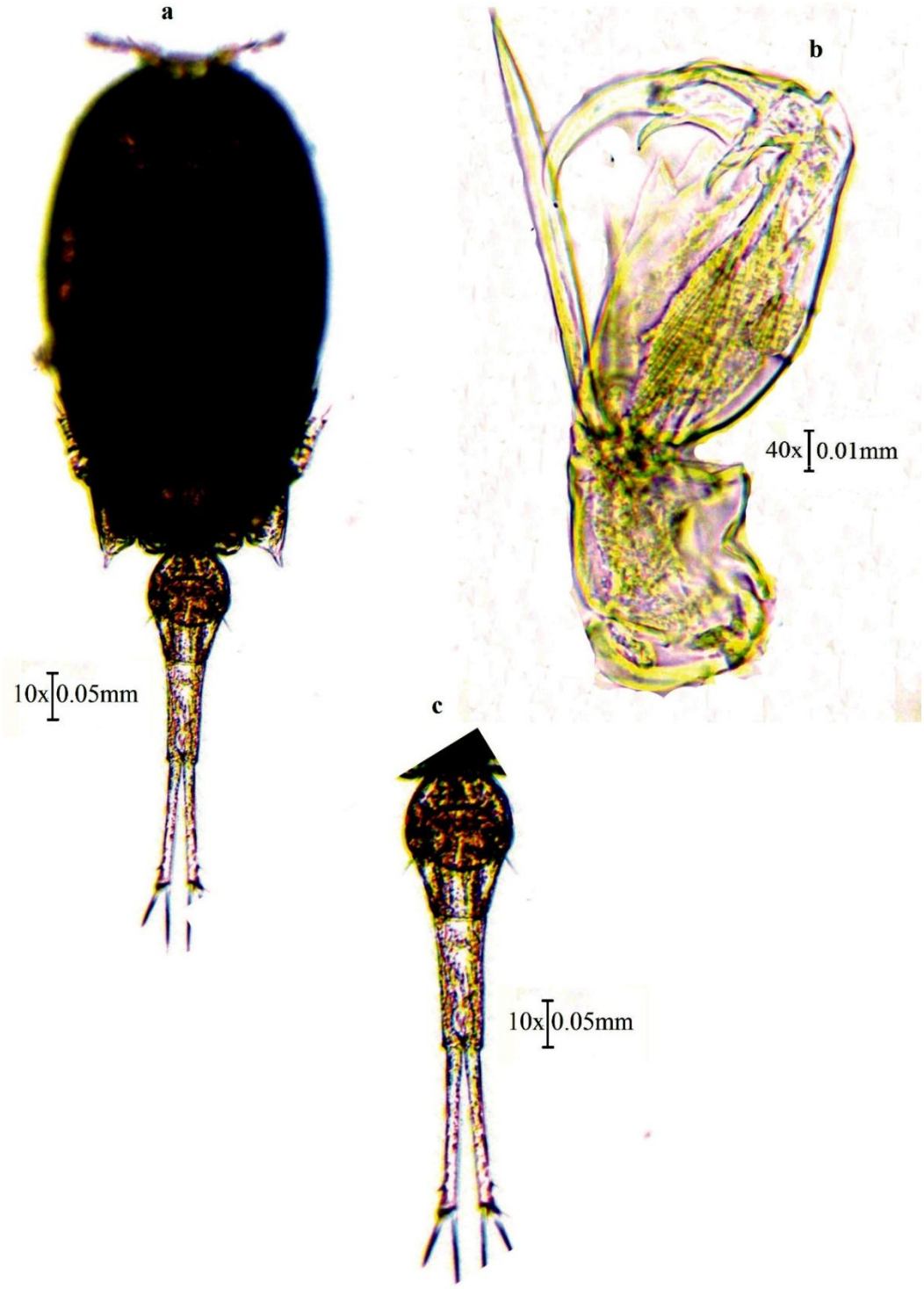


Plate.21. *D.tenius* female. a,Habitus;b,A2; c,Urosome.

Ditrichocorycaeus subulatus Herrick,1887

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.22,Plate.22**).Total length 0.89-0.9mm.Prosome 1.76 times as long as wide and 1.96 times as long as urosome. 3rd prosomal segment produced into lateral flaps; Two segmented urosome 2.90 times as long as wide. Oval shaped GS, 1.24 times as long as wide.AS rectangular shaped,0.69 times shorter than GS and 0.94 times shorter than CR.CR being 4.75 times longer than wide. Proportional lengths of GS:AS :CR 1.3:0.9:0.95 (Fig.22a,c). A2 four segmented with three endopodal segments.1stendopodal segment with endopodal setae shorter than coxobasal setae.2nd endopodal segment with two spines.3rd endopodal segment,cyclindrical, bears two elements of which one is drawn out as a terminal claw and the other short at the base (Fig.22b).

Remarks: Wilson, 1949 synonymised it as *Corycaeus americanus*. According to him, characters like 3rd metasomal segment produced into lateral flaps agreed with the present description. However, variations also existed in the length ratio GS: AS being lower (1.44) for Lakshadweep specimen than that of former (2).He also mentioned on CR being longer than other two segments combined also varied in the present study specimen. Nevertheless, the ornamentation of A2 and P4 endopod with two setae also confirmed the identity of *D.subulatus* female specimens as we could not come across any male specimens.

Distribution: Epipelagic, Coastal and oceanic, Subtropical and tropical, Indian and Pacific Oceans (http:// copepods. obs-banyuls.fr/en).

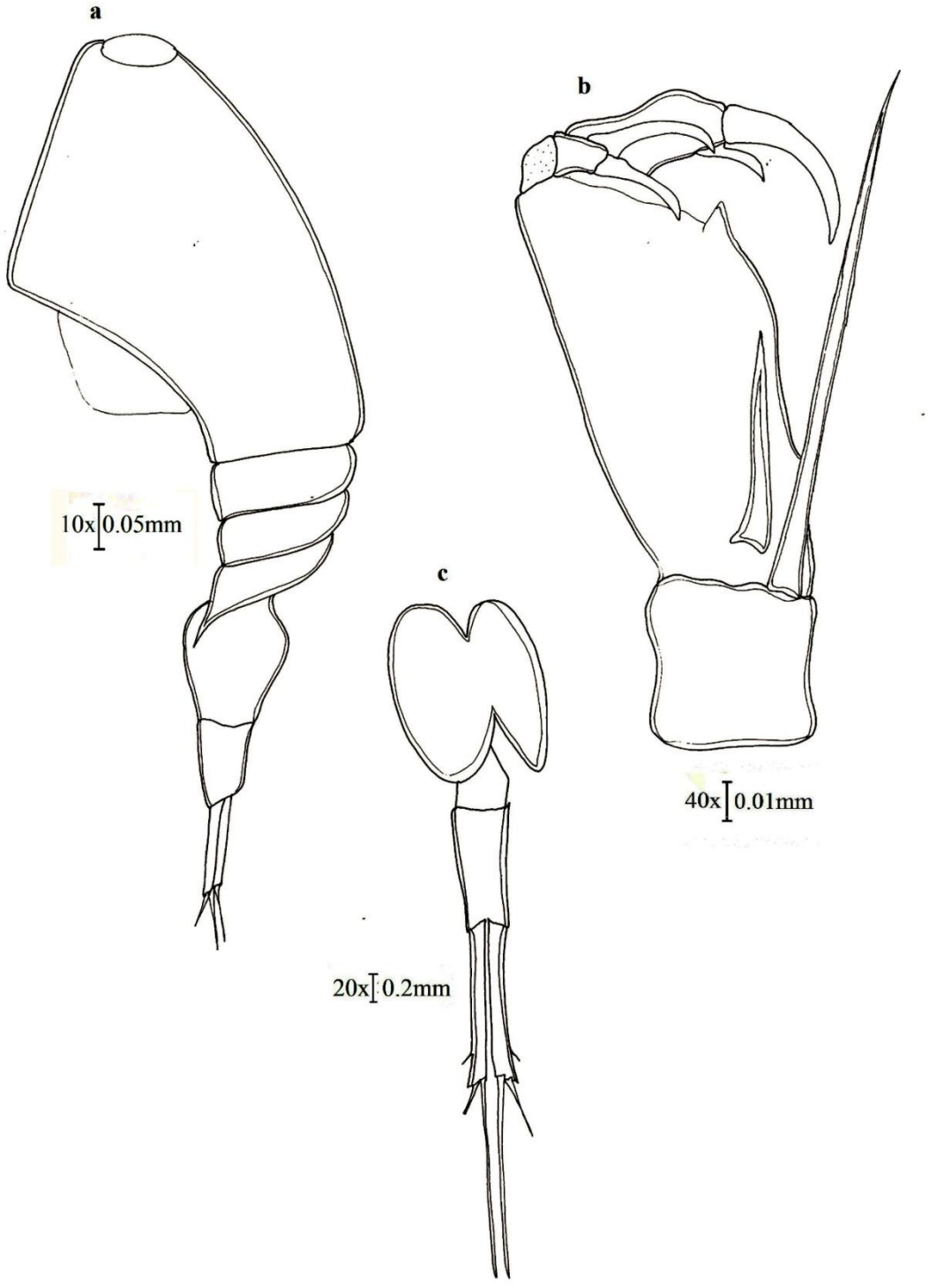


Fig.22. *D.subulatus* female.a,Habitus;b,A2; c,Urosome.

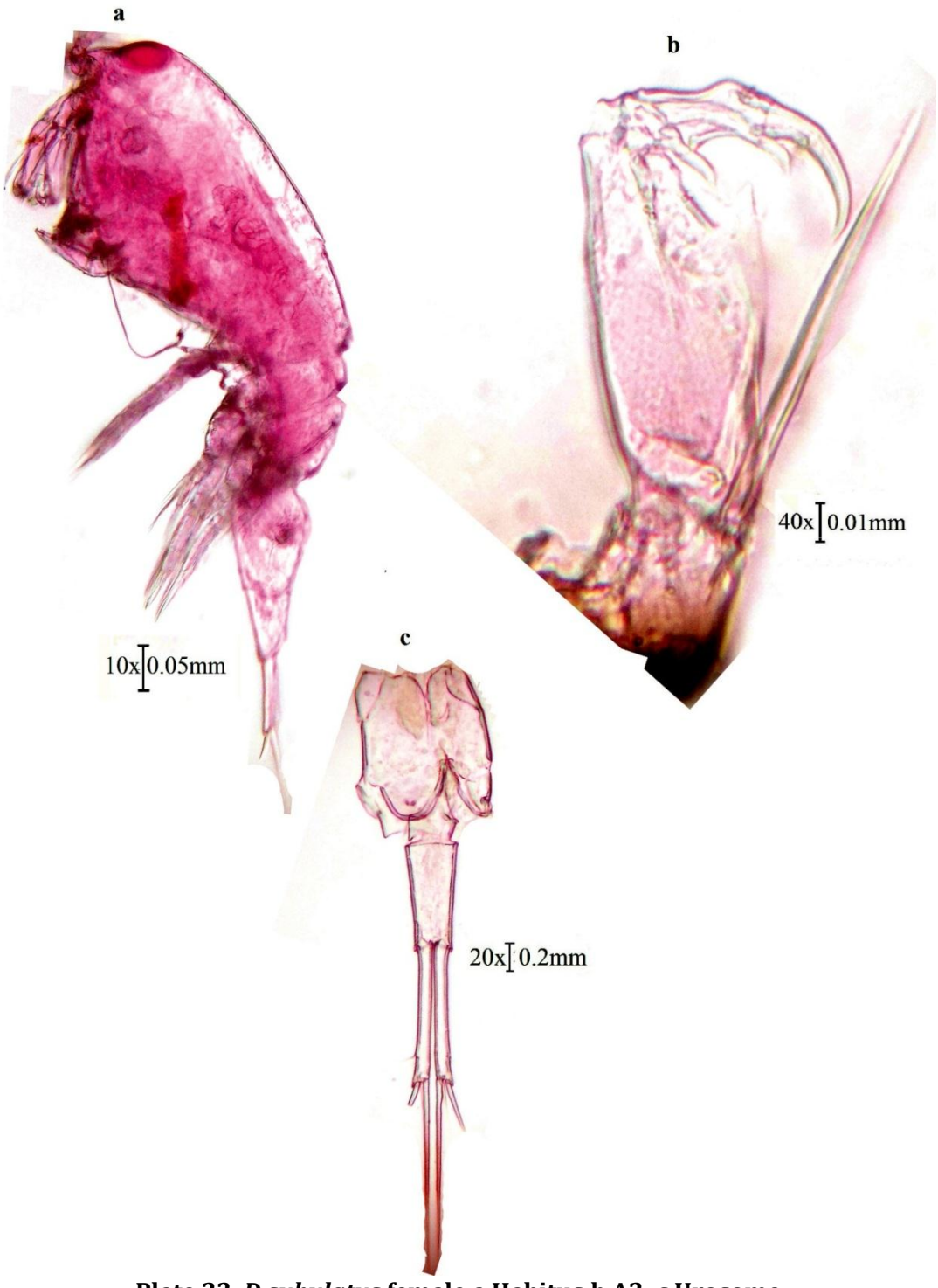


Plate.22. *D.subulatus* female.a,Habitus;b,A2; c,Urosome.

Ditrichocorycaeus lubbocki Giesbrecht ,1891

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.23, Plate 23**).Total length 0.94-0.99mm.Prosome 2.23 times as long as wide and 1.34 times as long as urosome. Urosome 4.72 times as long as wide. Posterior corner of the 3rd prosomal somite extend to the middle of the genital somite. A stout process arising from the 4th prosomal somite. Urosomal somite and CR in the proportional lengths 1.15:1.25:1.7 (Fig.23a,b). Ventral surface of GS is flat without a ventral hook. A2 four segmented with three endopodal segments. Inner margin of coxobasis partly ornamented with spines. First endopodal segment with unipinnate endopodal setae too shorter than coxobasal setae and outer lateral margin adorned with numerous denticles or spine.2nd endopodal segment with three spines.3rd endopodal segment bears two elements of which one is drawn out as a small terminal claw and the other short at the base (Fig.23c).

Remarks: *D.lubbocki* females agree well with the original description by Giesbrecht (1891) in its distinctive shape of GS/GDS which is distally swollen in dorsal view and absence of ventral hook. The absence of ventral hook was recorded as rounded eminence in figure by Sewell (1947), slightly round process by Chen *et al* (1974), Zheng *et al* (1982) and Wi *et al* (2013).Presence of two well-developed teeth on the distal segment of first endopodal segment of A2 with outer lateral margin adorned with numerous denticles and presence of spines at the inner margin of coxobasis very well agreed with previous description of Wi *et al* (2013).

Distribution: Epipelagic, coastal and oceanic,subtropical and tropical , Indian and Pacific Oceans (http:// copepods. obs-banyuls.fr/en).

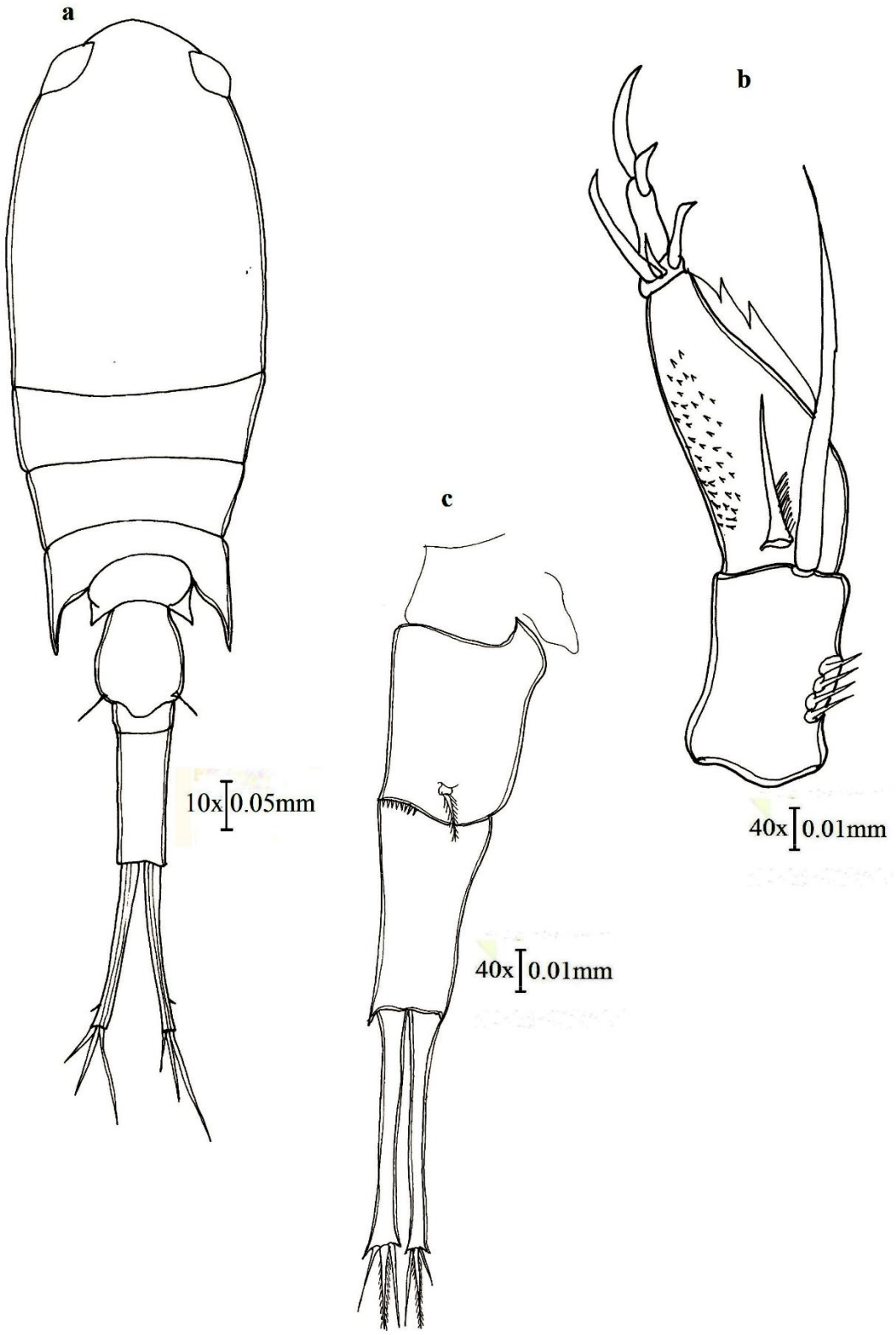


Fig.23. *D.lubbocki* female.a,Habitus;b,Urosome;c,A2.

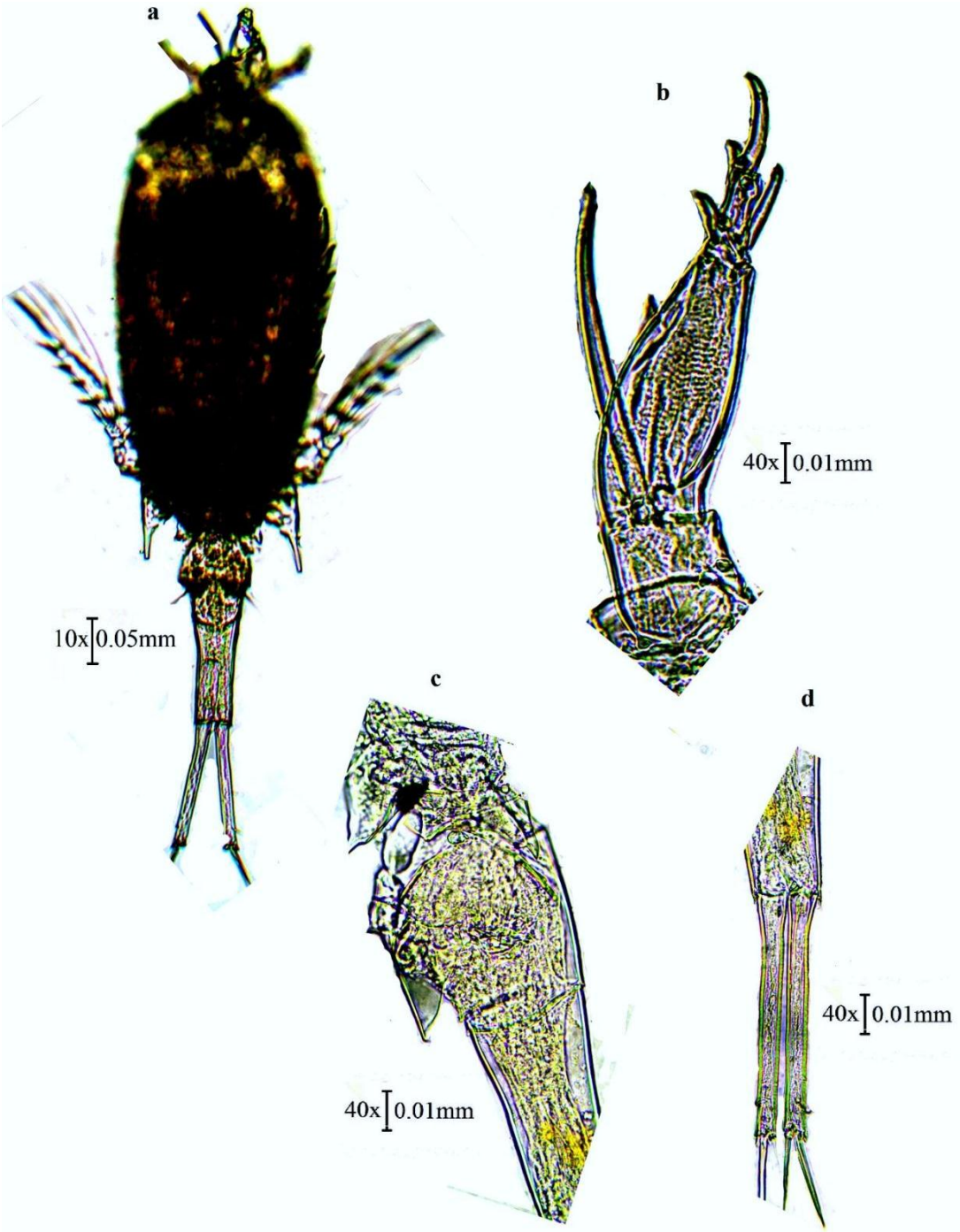


Plate.23. ***D.lubbocki*** **female.a,Habitus;b,Urosome (GS and AS);c,A2; d, Urosome (CR).**

Farranula gibbula Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.24,Plate 24)** Total Length 0.866-0.88mm.Ventral surface bears beak like keel. Dorsal bump present on the second PR segment. Prosome 2.04 times as long as urosome. Urosome one segmented. The mid part of GS swollen, 2.05 times as long as wide. Non divergent CR, 7 times as long as wide. Proportional lengths of urosomal somites 0.41:0.21(Fig.24a).A2 four segmented with Coxobasis and three endopodal segment. Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated and outer lateral margin ornamented with a row of denticles. 2nd endopodal segment shortest, bearing three elements of which the longer one with a lateral branch.3rd endopodal segment also bears three elements (Fig.24b)

Remarks: The genus Farranula is distinct in the characters like two segmented prosome, combined GDS and AS, uniramous P4 lacking endopod in both sexes and all these features very well matched with Giesbrecht's (1893) descriptions. Females of *F.gibbula* are characterized by the exclusive shaped GDS as well as the presence of dorsoposterior bump of the second PR segment. This species have been previously reported by many authors in which descriptions were inaccurate. But Wi and Soh (2013) from Korean waters gave a meticulous descriptions on this species. The present study specimens were similar to the Korean specimen in the presence of above said distinguished characters which itself confirms the species identity. The morphometry of the Lakshadweep specimens were also consistent with that of Korean specimens. Because of the similar appearance in males of different species and lack of specific criteria for identification, its very difficult to differentiate males. Farran (1911) opined on the difficulty in matching males to their respective females.

Distribution: Atlantic Ocean, Red Sea, Arabian Sea, Indo-Pacific, East China Sea, Japan Sea, South Pacific, North Pacific (http:// copepods. obs-banyuls.fr/en).

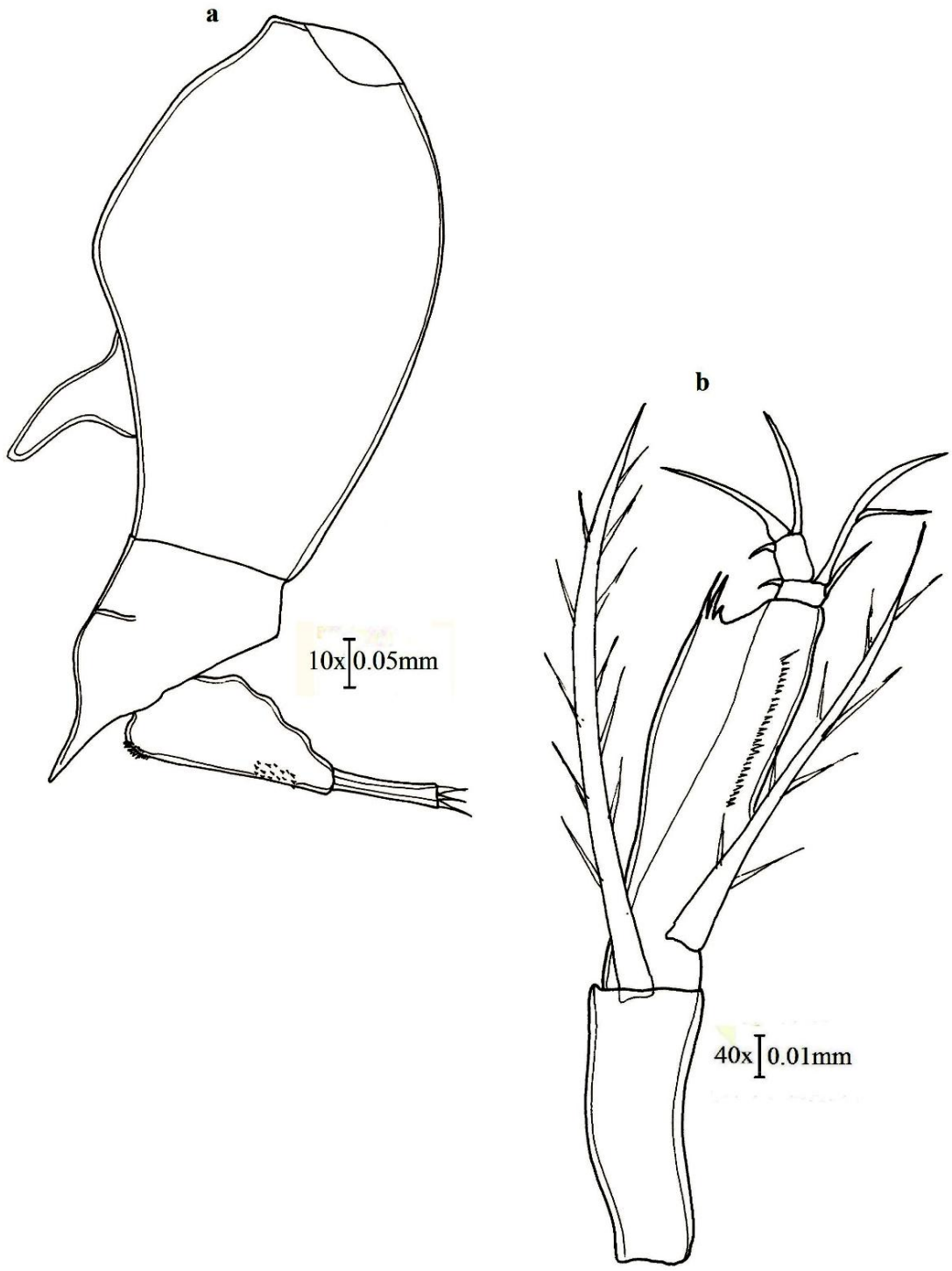


Fig.24. *F. gibbula* female.a,Habitus(lateral);b,A2.

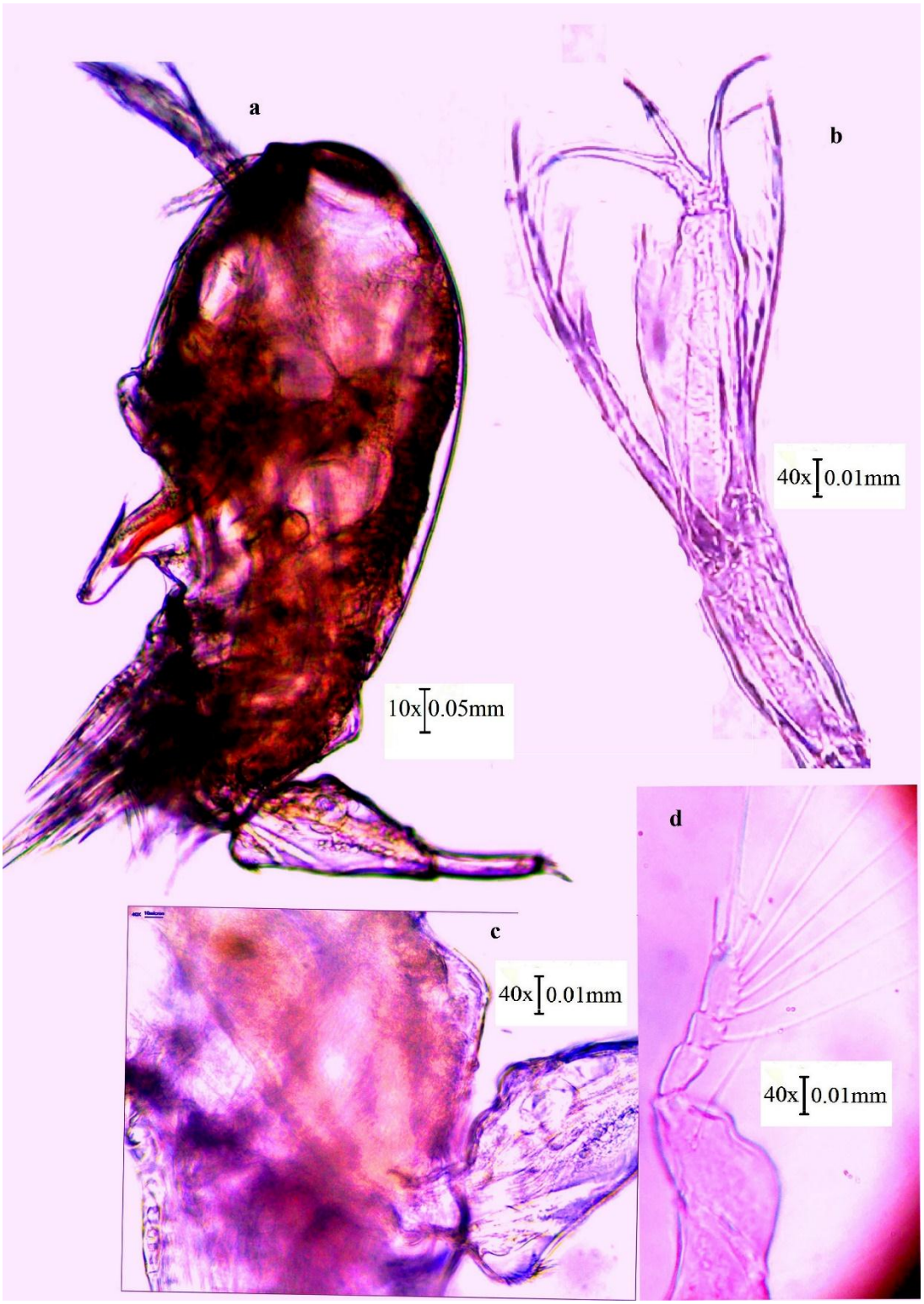


Plate.24. *F. gibbula* female.a,Habitus(lateral);b,A2; c,dorsal bump;d,P4.

Farranula concinna Dana, 1853

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.25,Plate 25).)** Total Length 0.812-82mm. Ventral surface bears beak like keel. The second PR segment without a dorsal bump.Prosome 1.76 times as long as wide. The posterolateral margin of the second PR segment projected upto the middle of GS. Prosome 2.30 times as long as urosome. Urosome one segmented. GS irregularly humpbacked, 2.14 times as long as wide, maximum width at the proximal region.CR, 2.66 times as long as wide.. Proportional lengths of GS: CR is 2.25:0.8. A2 four segmented with Coxobasis and three endopodal segments (Fig.25a).Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated and outer lateral margin ornamented with a row of denticles. 2nd endopodal segment shortest, bearing three elements of which the longer one with a lateral branch.3rd endopodal segment also bears three elements (Fig.25b).

Male **(Fig.26, Plate 26)** Total Length 0.766-0.77mm.Ventral surface bears beak like keel. Prosome two segmented. Absence of dorsal bump on the second PR segment. Prosome 1.08 times as long as urosome and 1.61 times as long as wide. Urosome one segmented. The mid part of GS swollen and the fattest part below the mid portion,2.95 times as long as wide. Non divergent CR, 9.3 times as long as wide. Proportional lengths of urosomal somites 6.5:2.8 (Fig.26a).A2 four segmented with Coxobasis and three endopodal segment. Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated and outer lateral margin ornamented with a row of denticles. 2nd endopodal segment shortest, bearing three elements of which the longer one with a lateral branch and the proximal small one serrated.3rd endopodal segment bears five elements of which longer one drawn out as a terminal claw extending upto coxobasis(Fig.26b).

Remarks: *F.concinna* is similar to *F.gibbula* but smaller in size.Another difference from *F.gibbula* is the absence of humpback in both sexes in the second prosomal somite. When PR:UR ratio of Lakshadweep specimens for females and males (2.3&1.08) when compared with Tanaka's specimens ((2.12& 1.38),were comparable.CR 9.3 times as long as broad for Lakshadweep male specimens varied

with that of Tanaka's (5).GS being slender in lateral view and 2.95 times as long as high for males were also consistent with that of Tanaka (3). This species have been previously reported by many authors in which descriptions were inaccurate. But Wi and Soh (2013) from Korean waters gave a meticulous descriptions on this species. However, the diagnostic characters which confirms the morphological identity of *F.concinna* were consistent with that of previous descriptions including the recent ones of Korean waters.

Distribution: North Atlantic, Indo-Pacific, East China Sea, South Pacific, North Pacific (http:// copepods. obs-banyuls.fr/en).

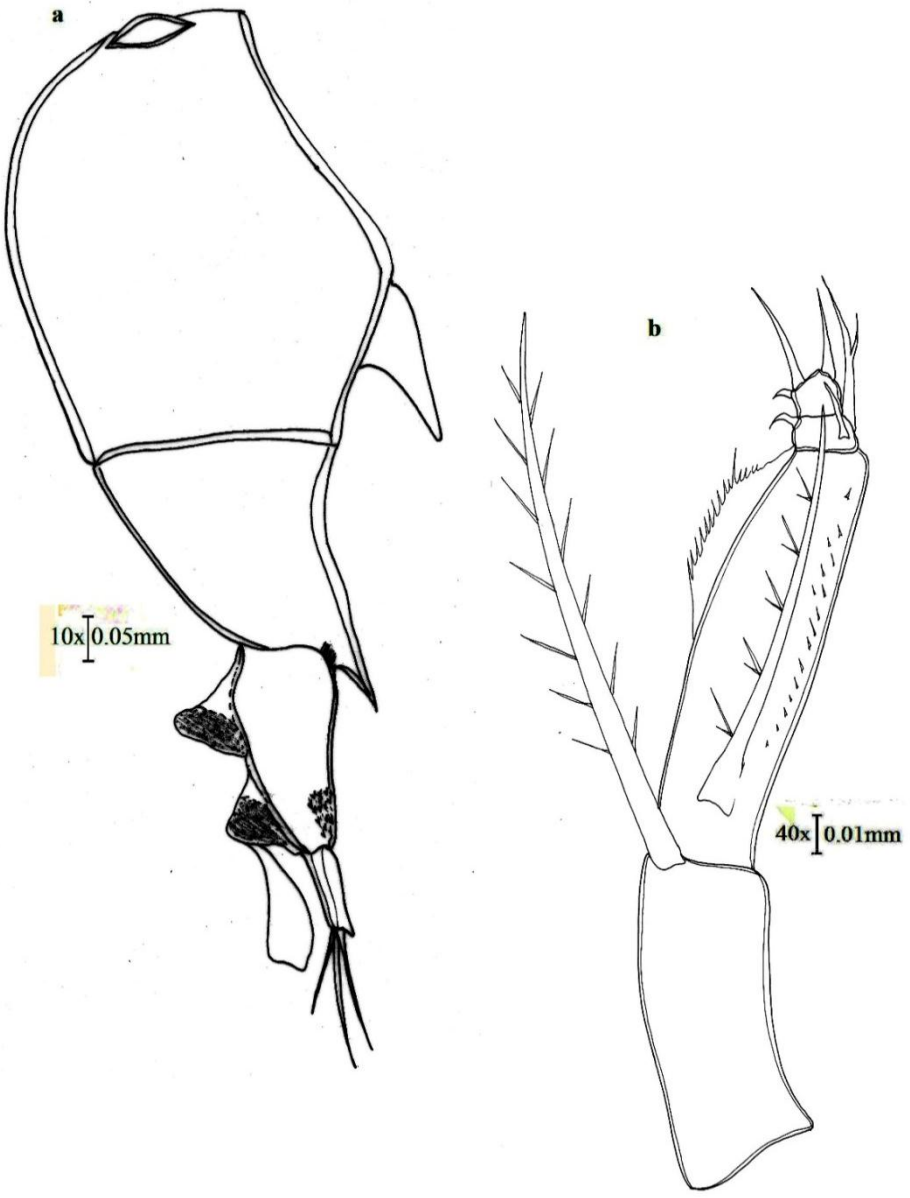


Fig.25. *F. concinna* female.a,Habitus; b,A2

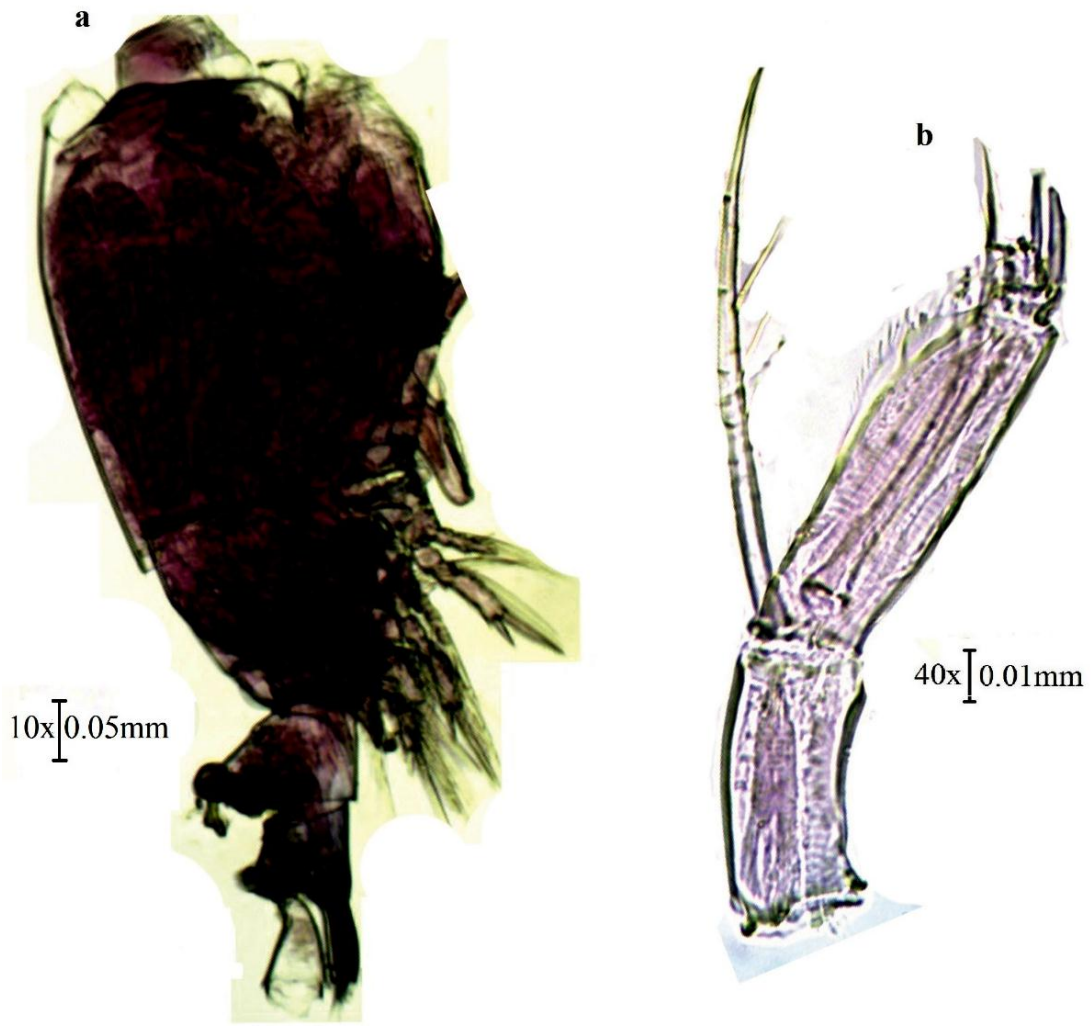


Plate.25. *F.concinna* female.a,Habitus; b,A2

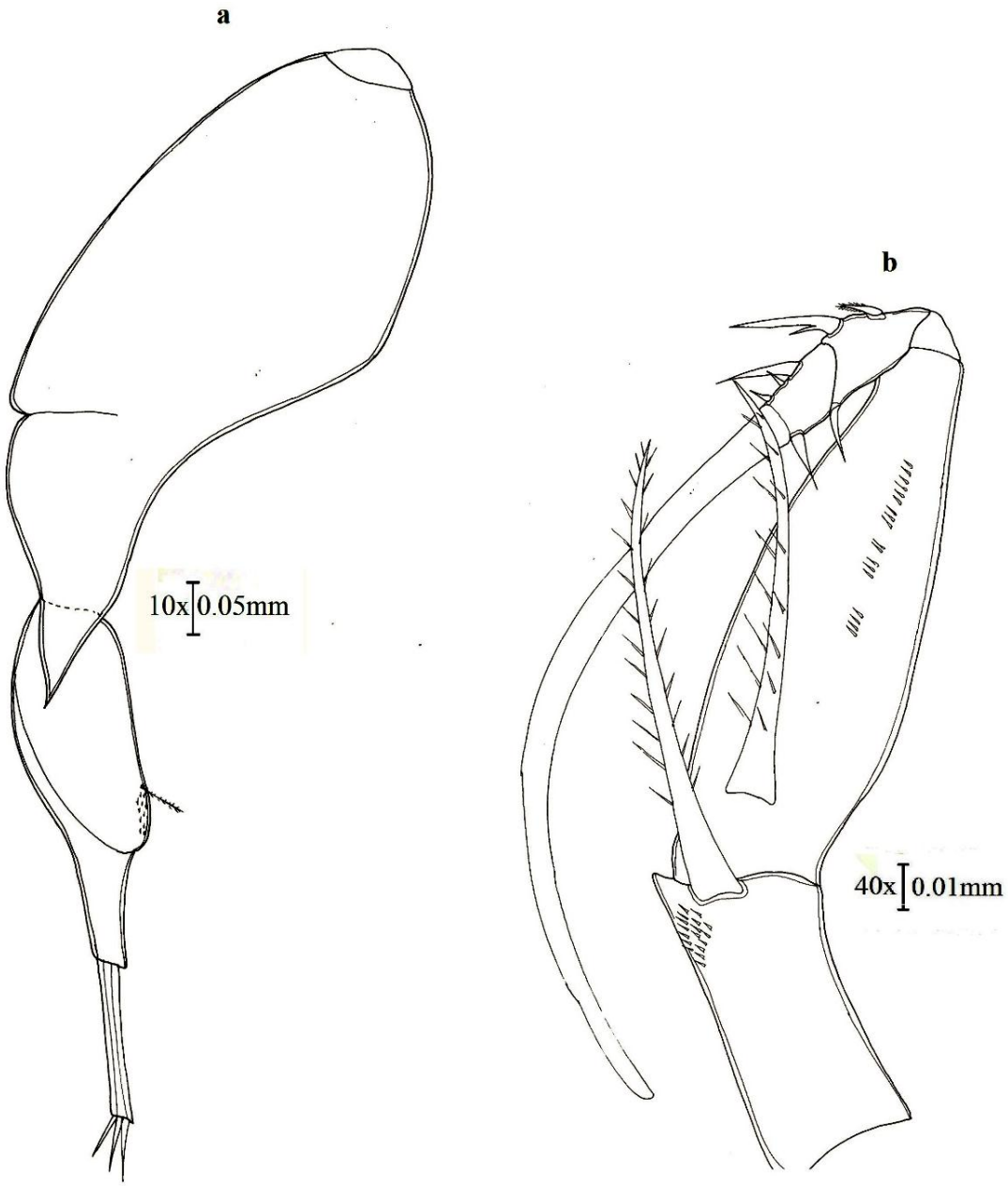


Fig.26. *F.concinna* male.a,Habitus (lateral) ; b,A2.

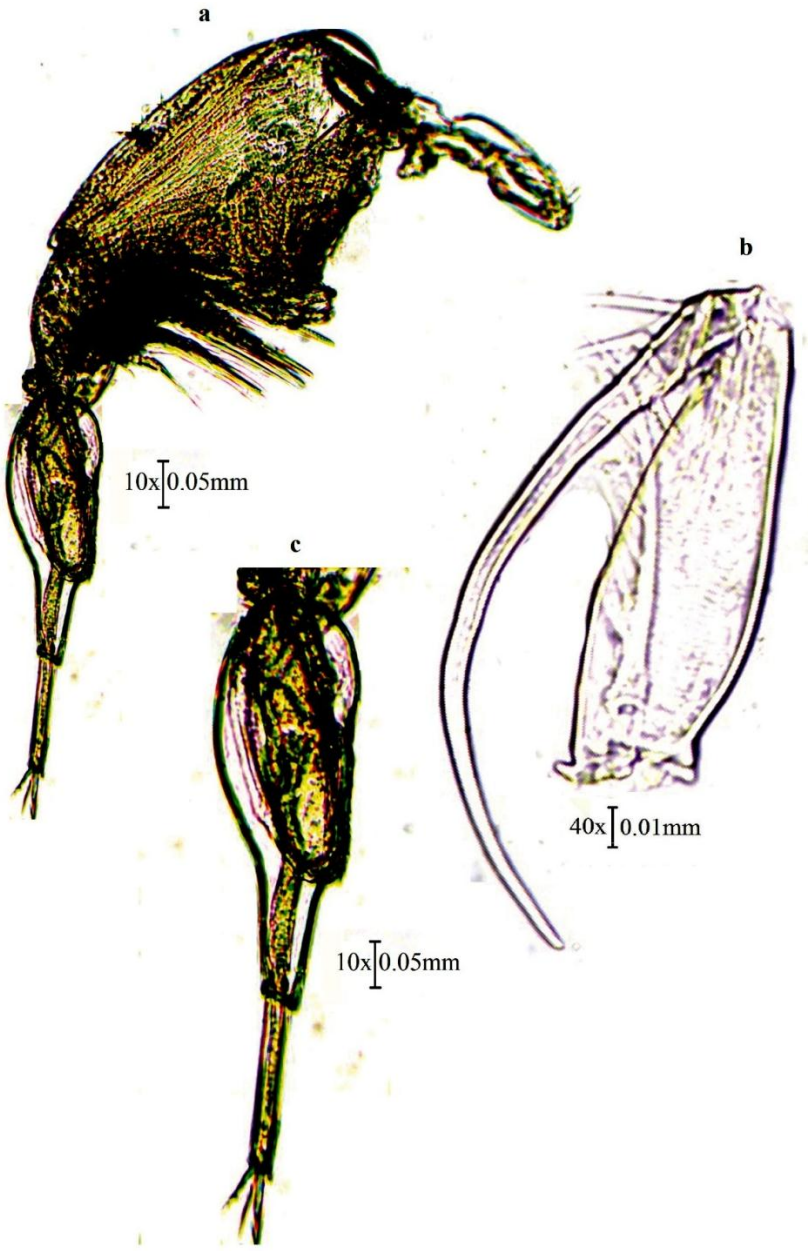


Plate.26. *F.concinna* male.a,Habitus (lateral); b,A2; c,Urosome

***Farranula gracilis* Dana, 1849**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.27,Plate 27)** Total Length 0.997-1mm.PR two segmented with no mid dorsal hump on the second PR segment as in *F.gibbula*; more than twice (2.4) times as long as wide; 2.29 times as long as urosome; ventral surface bears beak like keel. Lateral view section appears more or less humpbacked. The postero-lateral margin

of the second PR segment projected up to the middle of GS. Urosome one segmented, 2.83 times longer than wide.GS and AS combined. UR 3.09 times as long as CR.CR approximately 4.7 times longer than wide. Proportional lengths of GS: CR is 2.4:1.1.GS slender as long as wide, maximum width at the proximal region. A2 bears one plumose setae each on the basopodal and endopodal margin (Fig.27a). A2 four segmented with Coxobasis and three endopodal segments Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated.2nd endopodal segment shortest, bearing two elements of which the longer one with a lateral branch.3rd endopodal segment bears two elements (Fig.27b).

Male **(Fig.28,Plate 28)**Total Length 0.90-0.92 mm.PR two segmented with no mid dorsal hump on the second PR segment as in *F.gibbula*; more than twice (2.5) times as long as wide; 1.61 times as long as urosome.The postero-lateral margin of the second PR segment projected up to the middle of GS. Urosome one segmented, 3.03 times longer than wide.GS and AS combined. UR 3.38 times as long as CR.CR 2.88 times longer than wide. Proportional lengths of GS:CR is 3.1:1.3.GS slender 2.13 times as long as wide, maximum width at the proximal region(Fig.28b).A2 four segmented with coxobasis and three endopodal segment. Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate.2nd endopodal segment shortest, bearing three elements of which the longer one.3rd endopodal segment bears three elements of which longer one drawn out as a terminal claw extending upto Coxobasis (Fig.28b).

Remarks: After Björnberg (1963)this species when in large numbers is a good indicator of very saline (above 35.5)and warm waters (above 21°C).According to Crevigon the length ratio of abdomen to caudal rami of *F.gracilis* female is 68:32 and 71:29. Specimens of *F.gracilis* is characterized by the absence of bump on second prosomal segment in females;one segmented urosome which is more than twice (female) and thrice (male) as long as broad; slender GS in males, shape and length width ratio of CR in both sexes. The combination of general morphological features such as shape of GS, narrow PR, presence of ventral hook in females; projection of posterolateral margin of the second thoracic segment: width length ratio of the UR more than twice in females and length width ratio more than thrice in males were consistent with the description of *F.gracilis* female by Cravigon (1964). However, characters were also comparable, from the illustrations given by

Wi and Soh (2013) of Korean waters in the length ratio of the PR:UR (2.7) slightly greater than those of Lakshadweep specimen (1.61); proportional lengths of GS:CR greater (2.5) as compared to Lakshadweep specimens (2.38) and absence of dorsal bump in both specimens.

Distribution: Madagascar, Indian and Pacific Ocean (http:// copepods. obs-banyuls.fr/en).

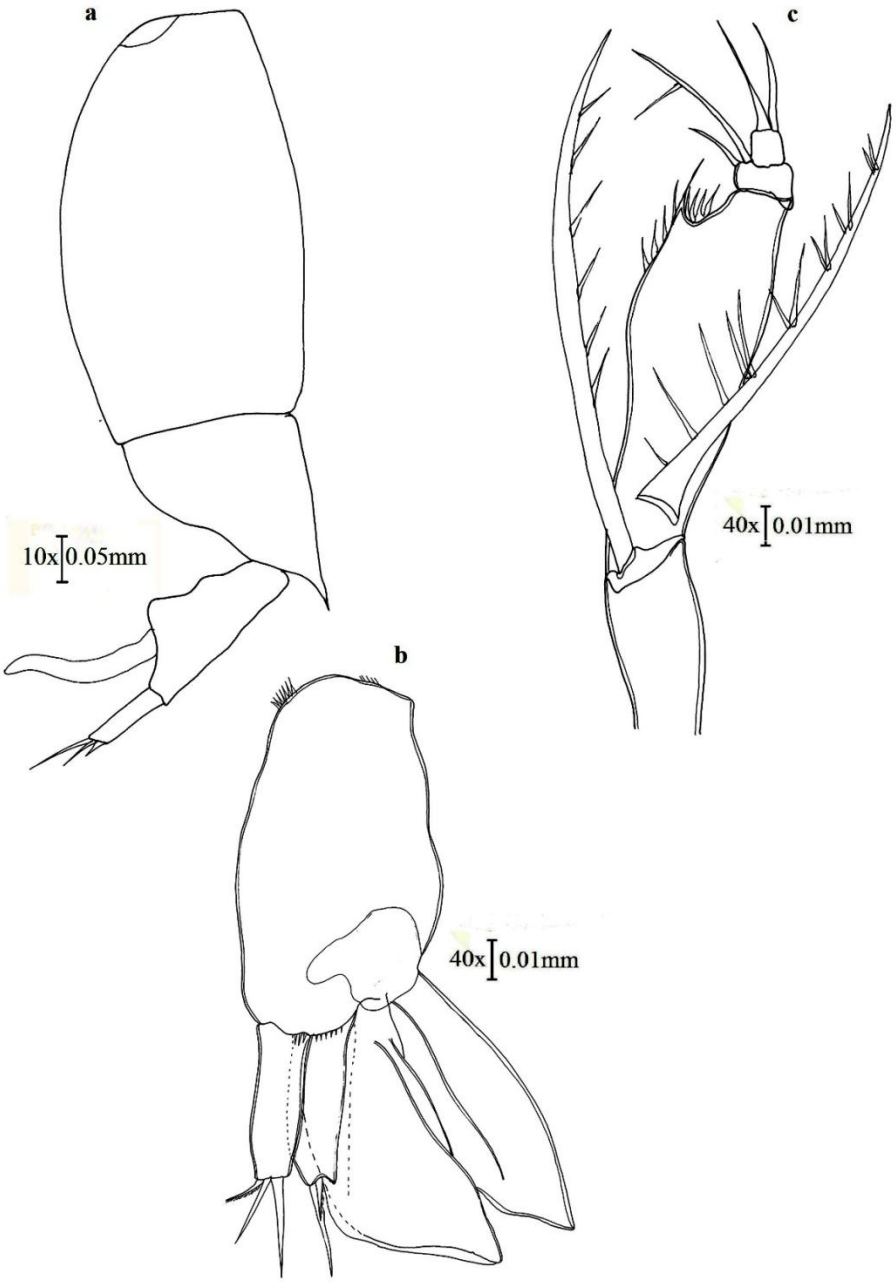


Fig.27. *F.gracilis* female.a,Habitus (lateral);b,Urosome;c,A2.

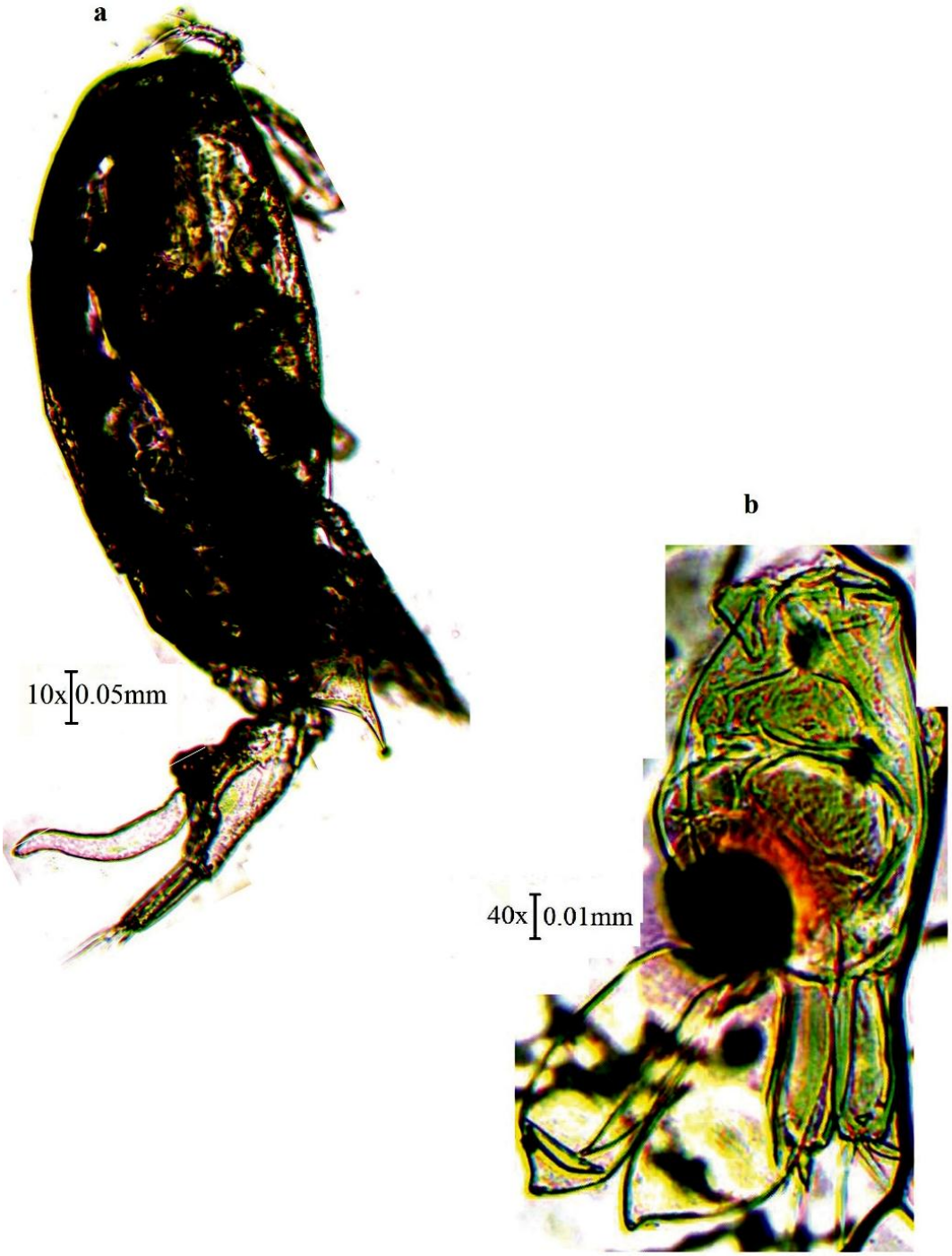


Plate.27. *F.gracilis* female.a,Habitus (lateral);b,Urosome.

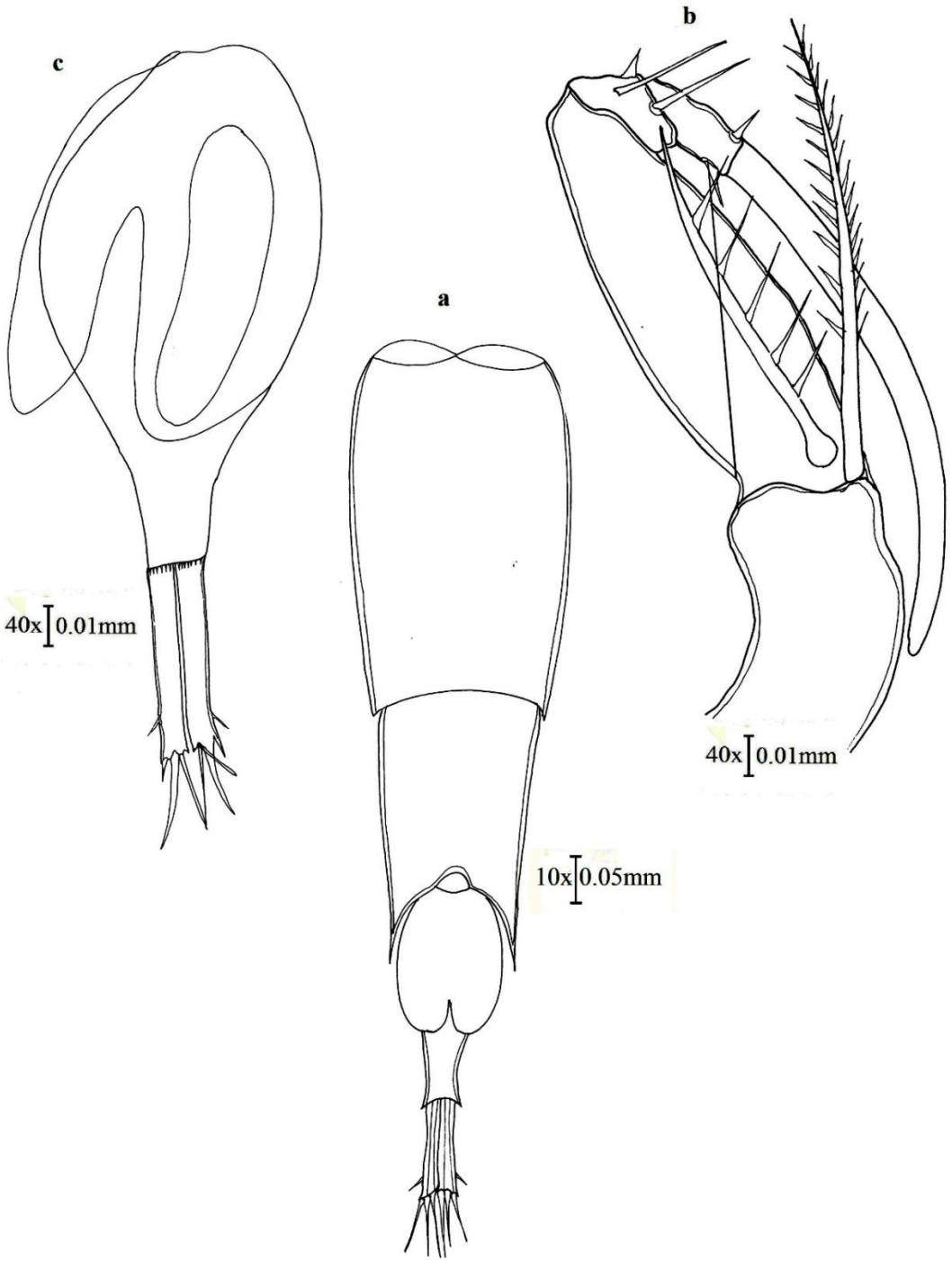


Fig.28. *F. gracilis* male. a,Habitus (dorsal);b,A2;c, Urosome.

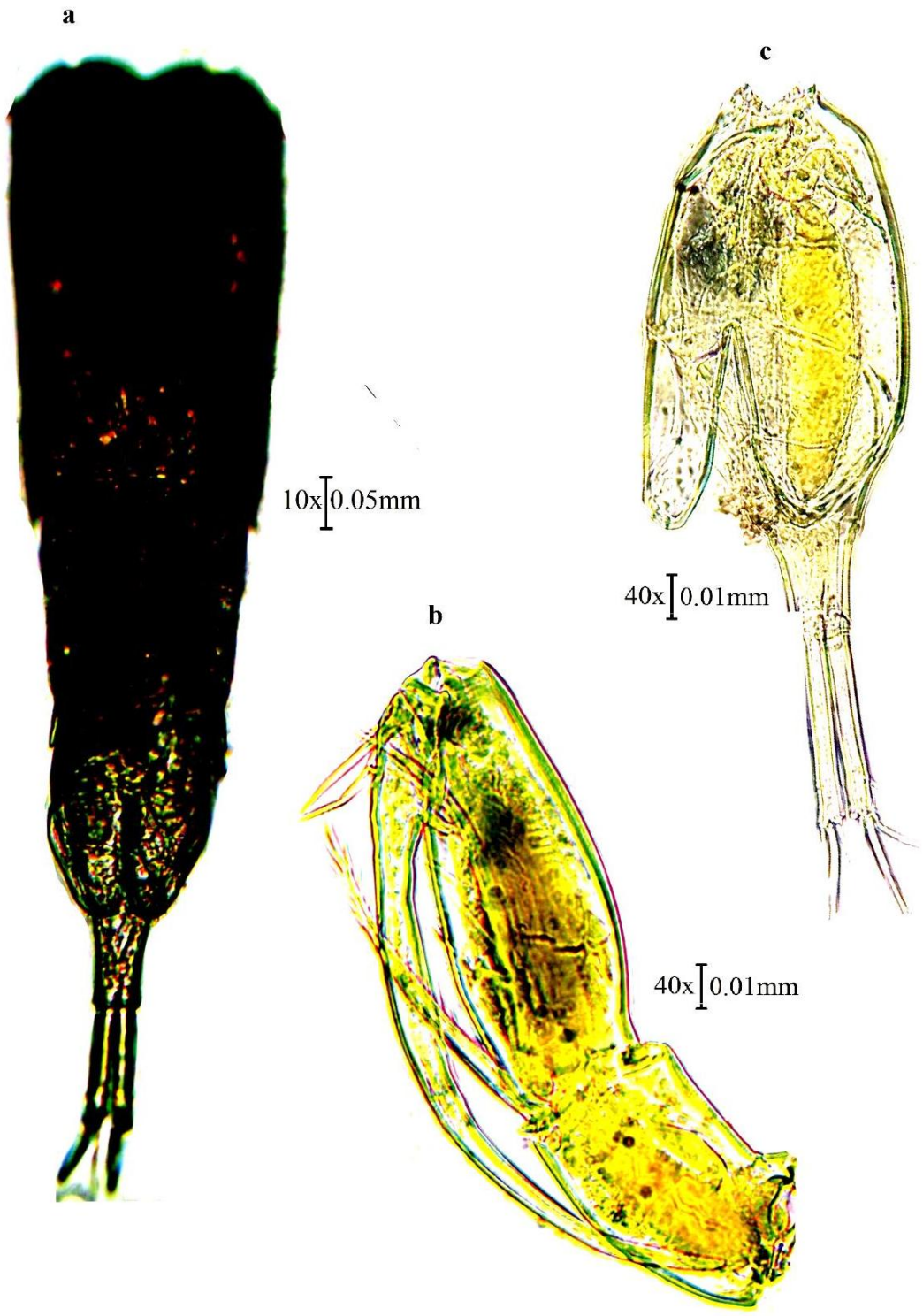


Plate.28. *F. gracilis* male. a,Habitus (dorsal);b,A2;c, Urosome.

Farranula rostrata Claus, 1863

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female (Fig.29,Plate.29) Total Length 0.710-0.75mm. Ventral surface bears beak like keel. Two segmented prosome, 2.08 times longer than wide. Cuticular lenses present. The second PR segment without a dorsal bump. The postero-lateral margin of the second PR segment projected upto the middle of GS. Prosome 1.97 times as long as urosome. Urosome one segmented, 5.59 times as long as wide. Length ratio of GS :CR 1.39, GS slender 2.48 times as long as wide, maximum width at the proximal region.CR, thrice as long as wide, slightly divergent at the distal end.A2 four segmented with Coxobasis and three endopodal segments Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated. Second endopodal segment shortest, bearing three elements of which the longer one with a lateral branch.3rd endopodal segment bears three elements (Fig.29a).

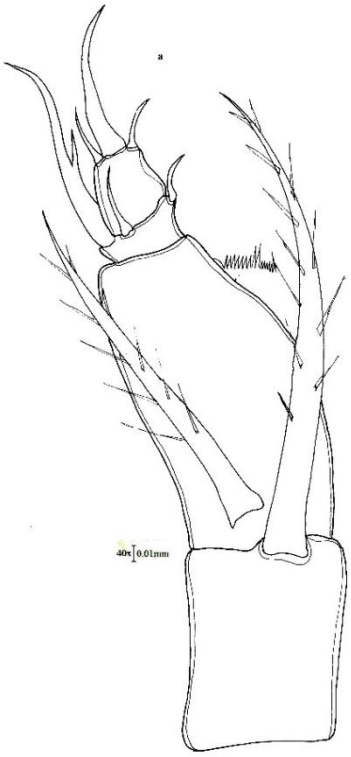


Fig.29a. *Farranula rostrata* female

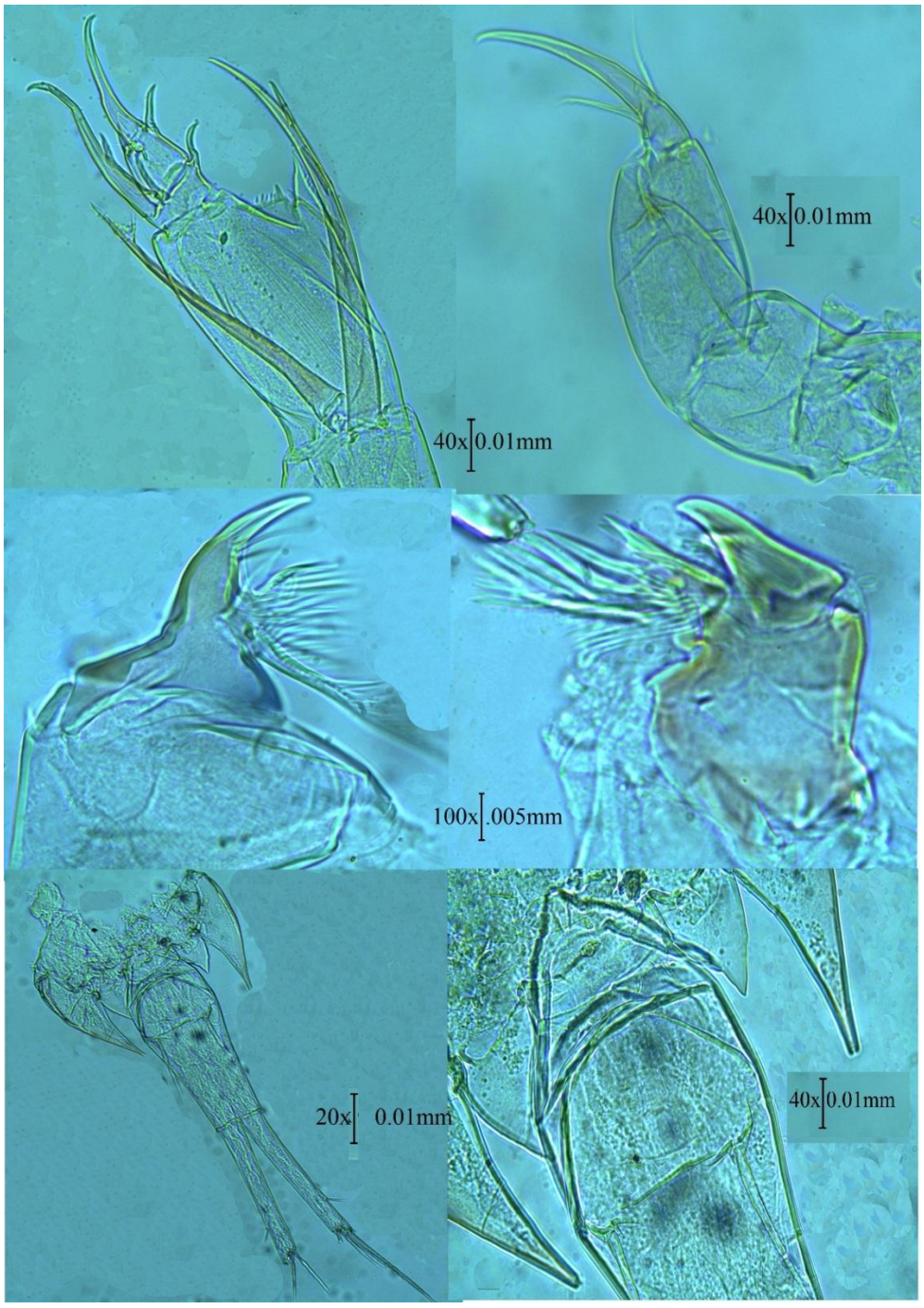


Plate29. *Farranula rostrata* female

Remarks: *F.rostrata* was characterized by the ornamentation of A1 and GS shape. This species is considered to be a good indicator of surface saline waters of temperatures between 16 & 18°C.When compared with previous literatures, length width ratio of prosome of Lakshadweep specimens were found to be comparable with Dahl (1912) and Itoh (1997) (2.08 vs 2.4 & 2.2) respectively. Length width

ratio of GDS also were consistent with Giesbrecht (1892),Dahl (1912) and Itoh (1997)(2.1,3 & 2.8) respectively but with slight variations in which present ratio being higher (3.21)**.**

Distribution: tropical Atlantic and the Mediterranean Sea, Indian Ocean, Pacific concern SE Australia, New Zealand, Indo-Pacific (http:// copepods. obs-banyuls.fr/en).

Farranula curta Farran,1911

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Agatti, Bangaram, Minicoy (Refer Table 3.1 and 3.2).

Female **(Fig.30, Plate 30)** Total Length 0.89-0.908 mm. Ventral surface bears beak like keel. The second PR segment without a dorsal bump. The posterolateral margin of the second PR segment projected upto the middle of GS. Proportional lengths of GS: CR is 1.6:1.Prosome 1.75 times as long as urosome and 1.78 times as long as wide. Urosome one segmented. GS slender 2.66 times as long as wide.CR 2.85 times as long as wide (Fig.30a).A2 four segmented with Coxobasis and three endopodal segments Bipinnate coxobasal setae at inner distal margin, slightly longer than endopodal setae which is also bipinnate. Inner distal margin of the first endopodal segment roughly serrated.2nd endopodal segment shortest, bearing two elements of which the longer one with a lateral branch.3rd endopodal segment bears two elements (Fig.30b).

Remarks: The genus Farranula is distinct in the characters like 2 segmented prosome, combined GDS and AS, uniramous P4 lacking endopod in both sexes and all these features very well matched with Giesbrecht's (1893) descriptions. Females of *F.curta* is characterized by the absence of bump on second prosomal segment, slender GS and the shape of CR. The combination of general morphological features such as shape of GS, narrow PR, presence of ventral hook; projection of posterolateral margin of the second thoracic segment; length width ratio of the GS (2.66 vs.2.5) is consistent with the description of *F.curta* female by Tanaka (1957).However characters were also comparable, from the illustrations given by Wi and Soh (2013) of Korean waters in: length ratio of the PR: UR (including CR)(2.7) slightly greater than those of Lakshadweep specimen

(1.75);proportional lengths of GS: CR greater (2.5) as compared to Lakshadweep specimens (1.16); absence of dorsal bump in both specimens.

Distribution: Tropical Atlantic and the Mediterranean Sea, Indian Ocean, Pacific concern SE Australia, New Zealand, Indo-Pacific (http:// copepods. obs-banyuls.fr/en).

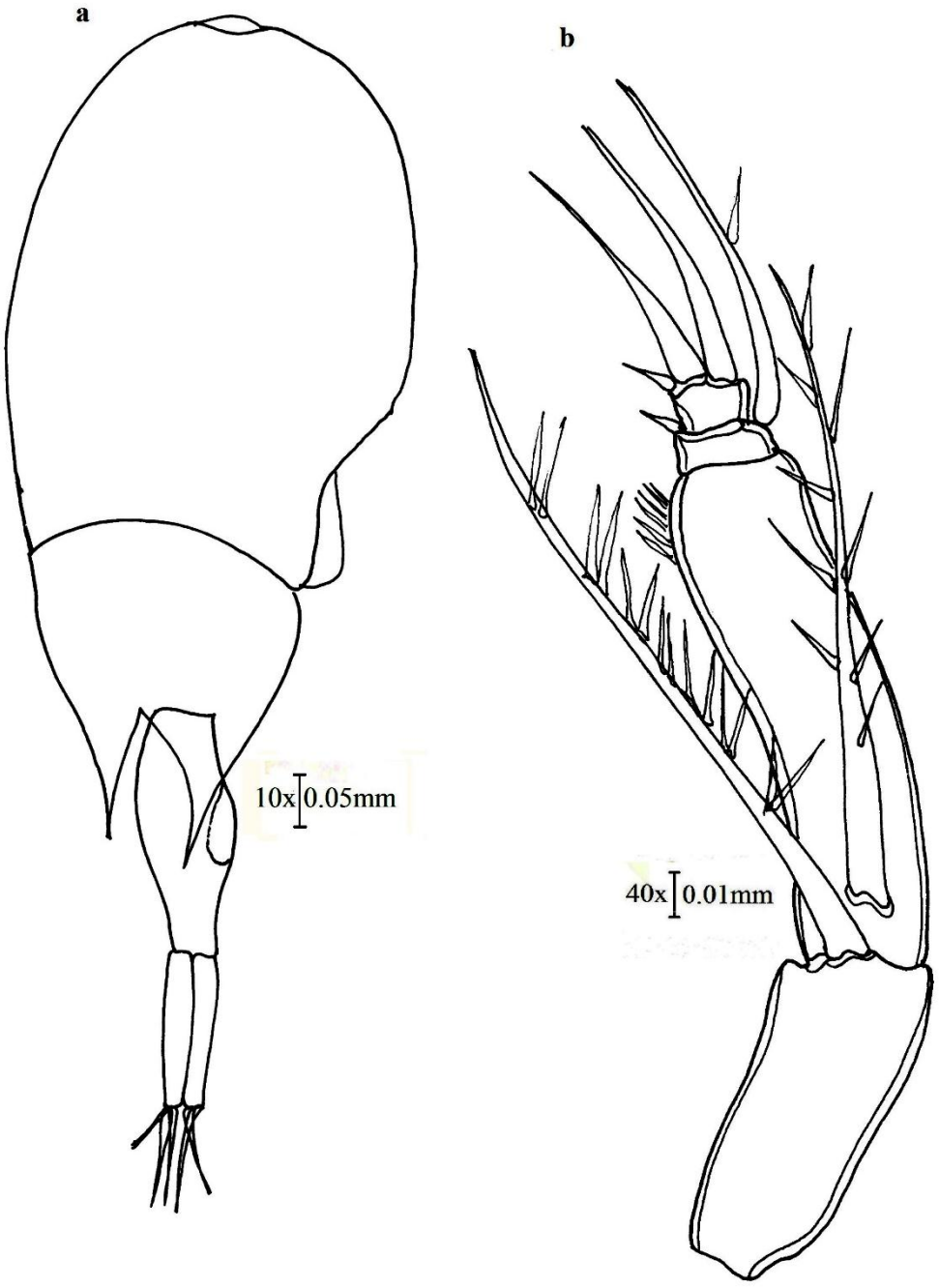


Fig.30. *F.curta* female.a,Habtus (lateral);b,A2

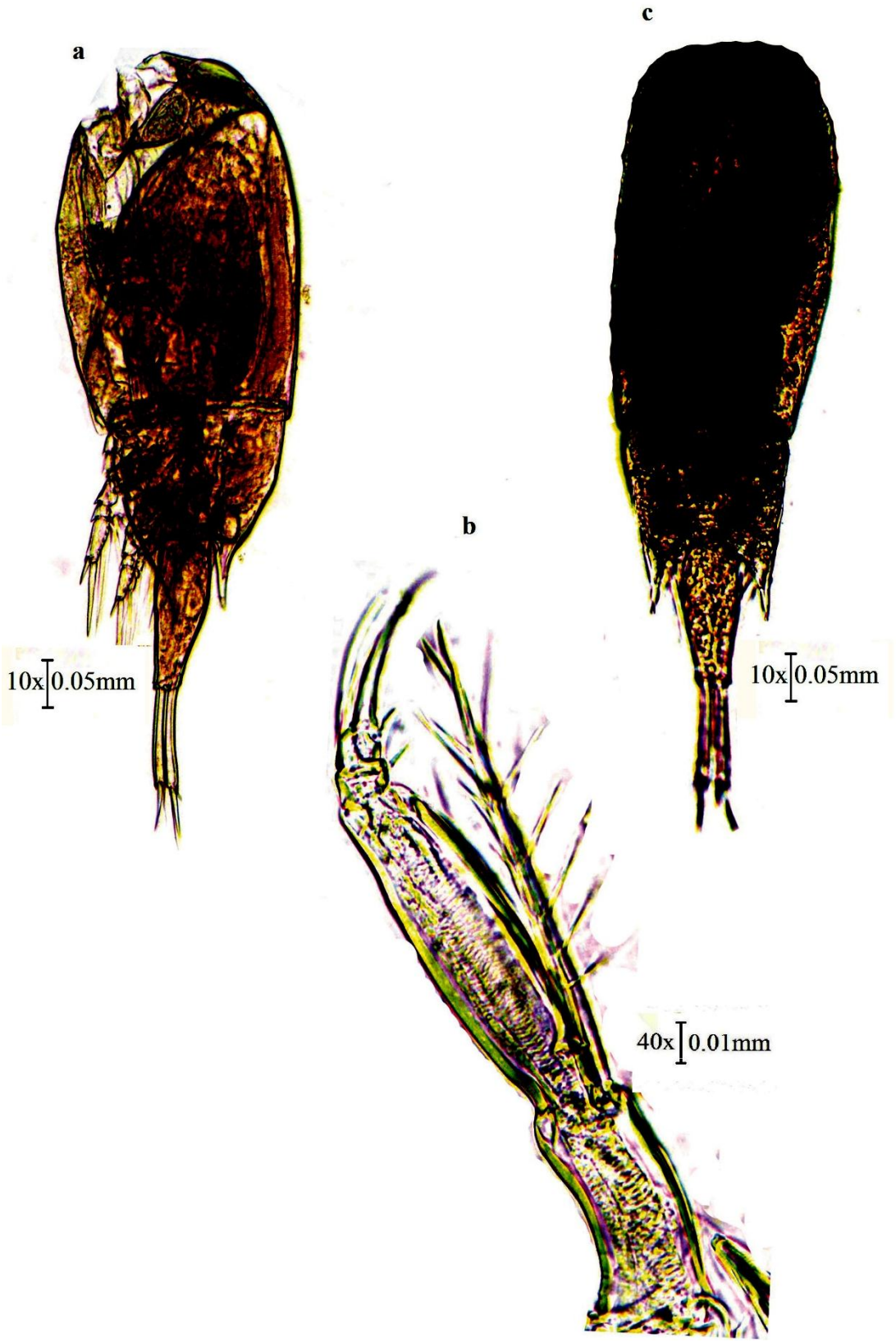


Plate 30. *F.curta* female.a,c,Habtus (Dorsal and lateral);b,A2.

Oncaea clevei Früchtl, 1923

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.31,Plate 31)** Total length 1-1.25mm. Prosome 2.08 times as long as wide and 1.5 times longer than urosome (Fig.31a). A1 six segmented (Plate.31e).Urosome five segmented, 3.84 times as long as wide. GS 2.72 times as long as wide.CR 1.25 times as long as wide. AS 1.43 times longer than CR. Proportional lengths of the urosomal somites starting with 5th thoracic segment (+CR) is 0.3:2.4:0.35:0.35:0.35:1.25.Sickle shaped sclerotization posterior to genital apertures (Fig.31b).

Male **(Fig.32,Plate 32)** Total length 0.55-0.56mm. Shorter than female. Prosome 2.29 times as long as wide and 2.05 times longer than urosome (Fig.32a).A1 four segmented. Urosome six segmented, 2.14 times as long as wide. GS 1.48 times as long as wide; longer than AS and CR combined. AS 0.66 times wider than long.CR 1.09 times as long as wide (Fig.32b).

Remarks: Primarily, agreeing with the opinion of Bottger-Schnack (2001) that this species is very similar to *O.paraclevie* and can be distinguished from each other mostly by the location of genital apertures and the pattern of sclerotization. The present female specimens slightly differ in size from those described earlier by Tanaka (1960);Hi & Soh (2009);Bottger Schnack (2001); Al-Yamani (2011) and is the maximum size ever reported. However male specimen size comes in range within the previously reported sizes. *O.clevie* male species are shorter than females as the pattern of GS itself is its distinguishing character. A comparison of Lakshadweep specimen with that of Bottger-schnack(2001) revealed some of the distinctive aspects being similar which included 1) Length width proportion of AS in female (1.43 vs 1.4) and wider than long in males; 2) CR length width proportion lower in Lakshadweep in both sexes (1.25&1.09 vs 2.3 & 1.8); 3)PR:UR ratio almost similar in both Red sea and Lakshadweep specimen in both sexes respectively (♀ 2.1 & ♂2.2 vs ♀1.5 &♂ 2.29).Features were consistent with those of North western Arabian specimens and Lakshadweep specimens along with slight variations. These include 1) PR:UR ratio slightly varied in both North west Arabian

Sea and Lakshadweep specimen in both sexes respectively (♀1.8 &♂ 1.7 vs ♀1.5 & ♂2.29); 2) CR length width proportion comparable in females (1.25 vs 1.1).

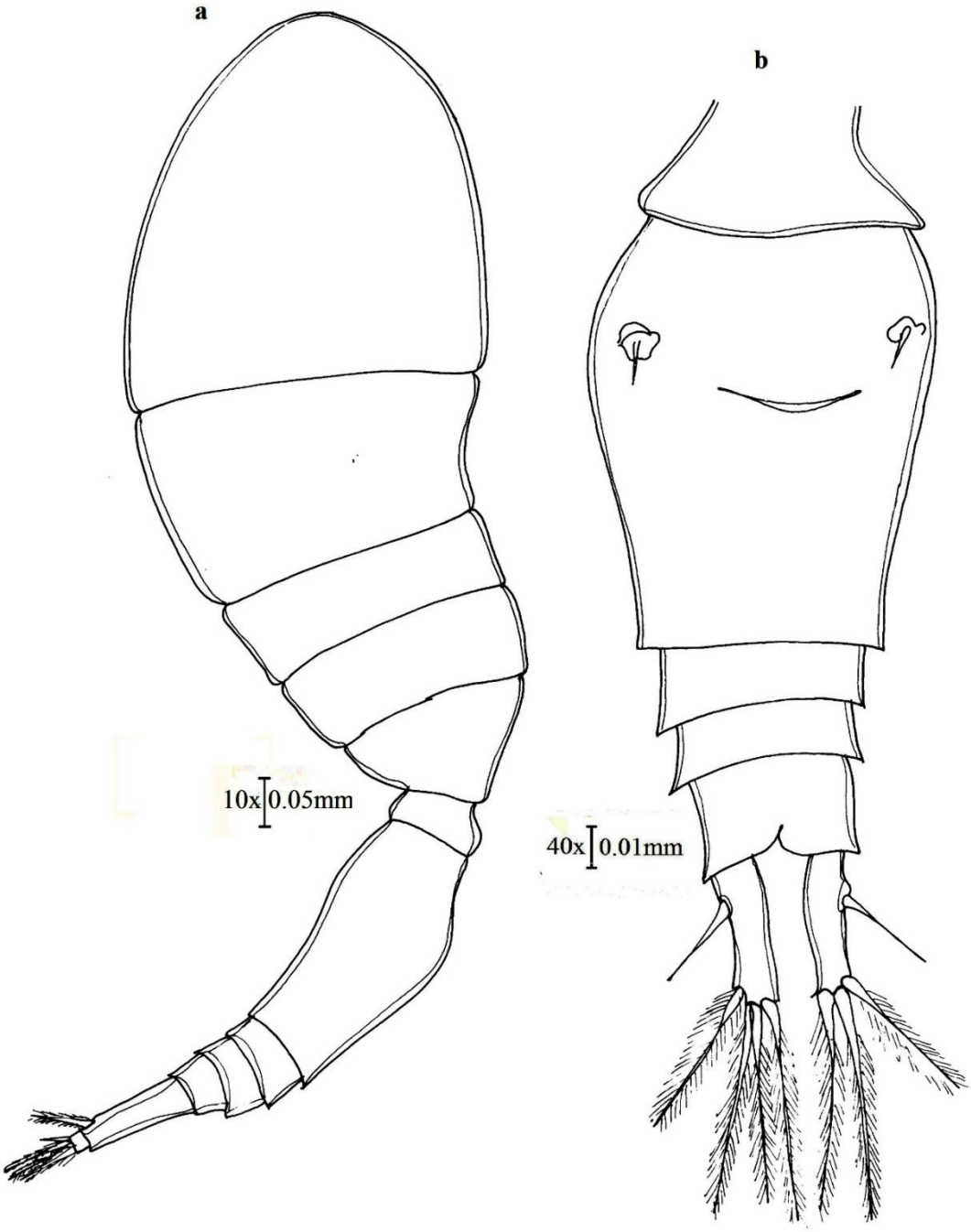


Fig.31.*O.clevei* female. a, Habitus (lateral);b,Urosome.

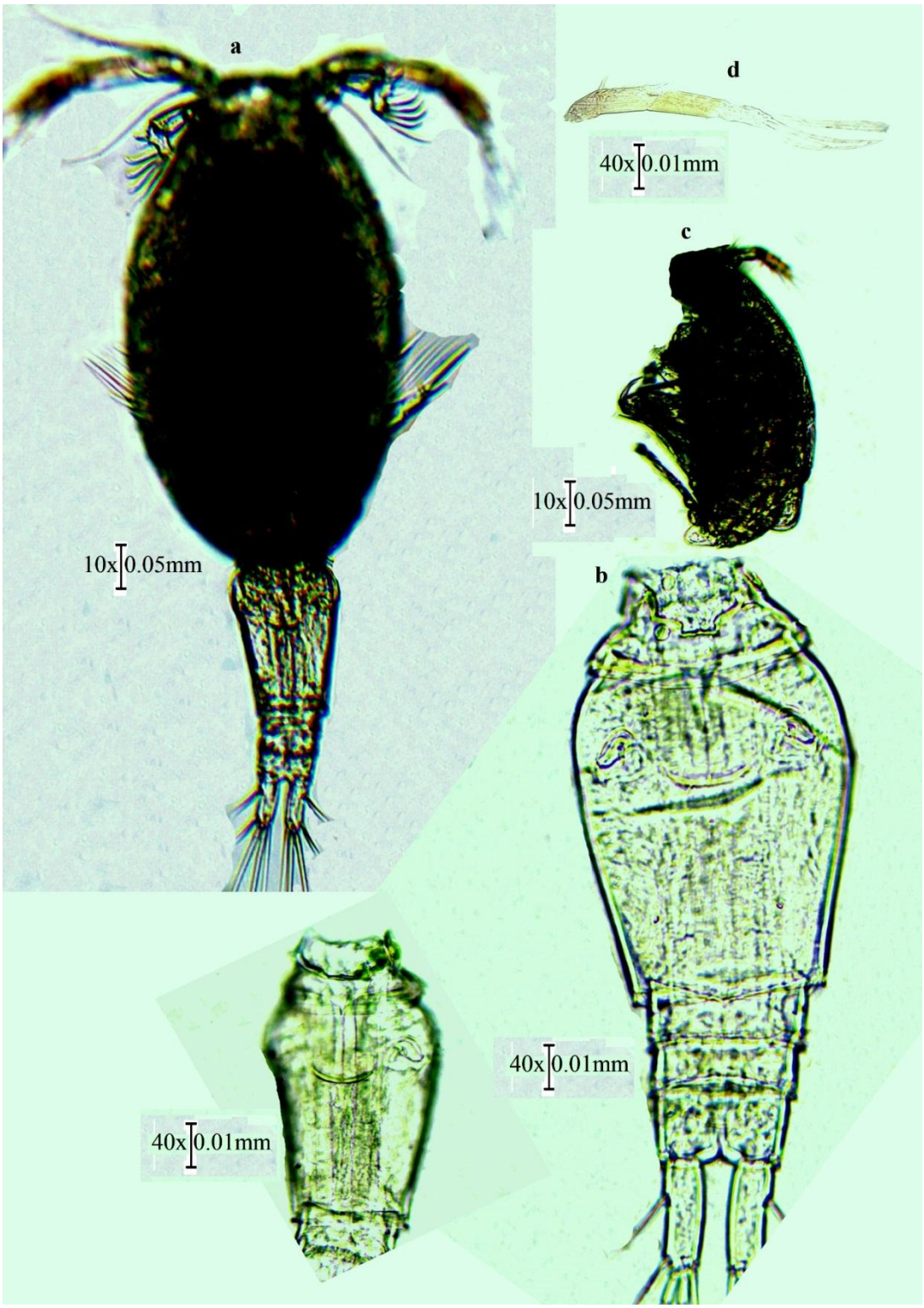


Plate.31. *O.clevei* female. a, Habitus (lateral); b, Urosome;c, sclerotization; d,Prosome (lateral).

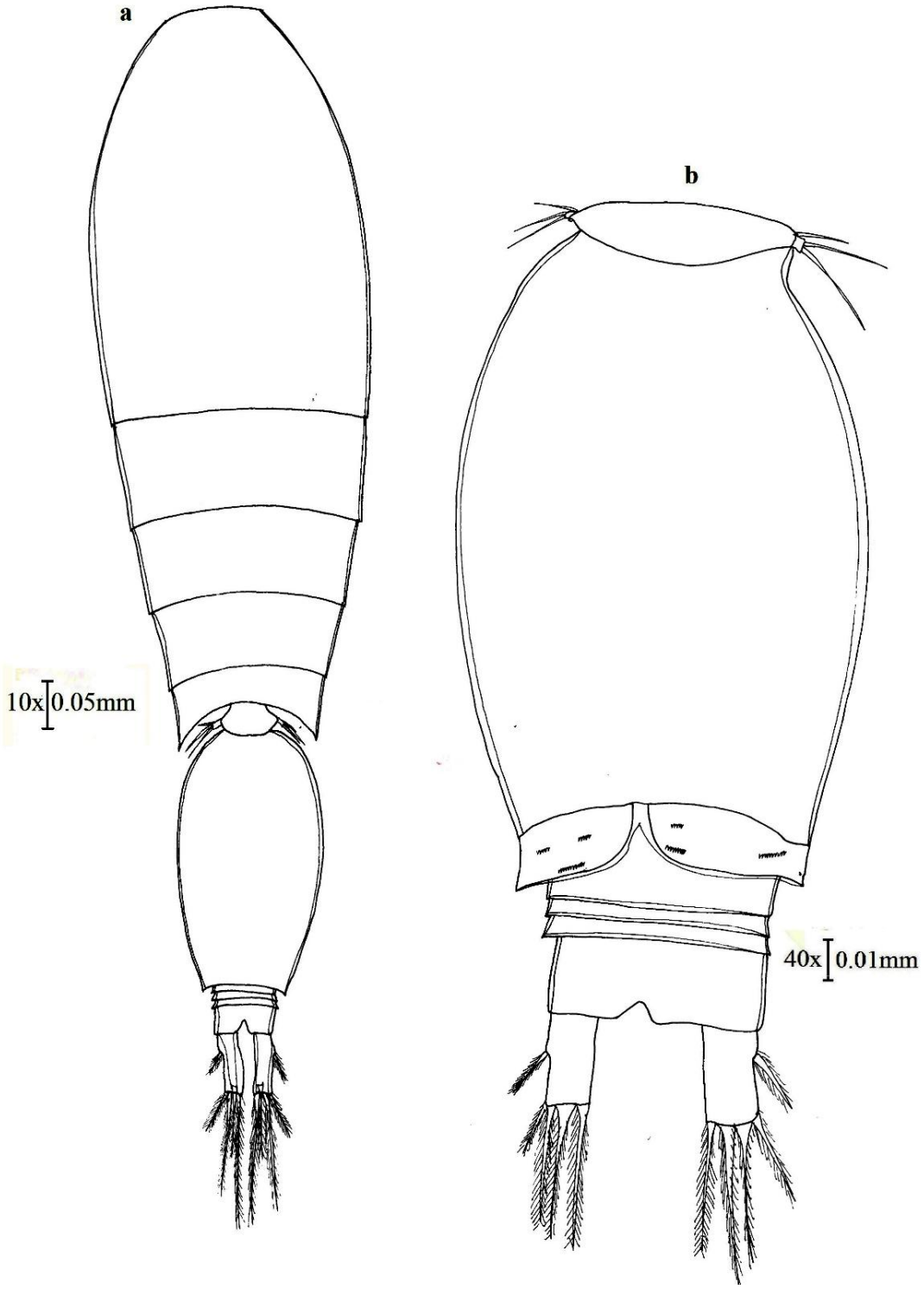


Fig.32. *O.clevei* male. a, Habitus (lateral);b,Urosome.

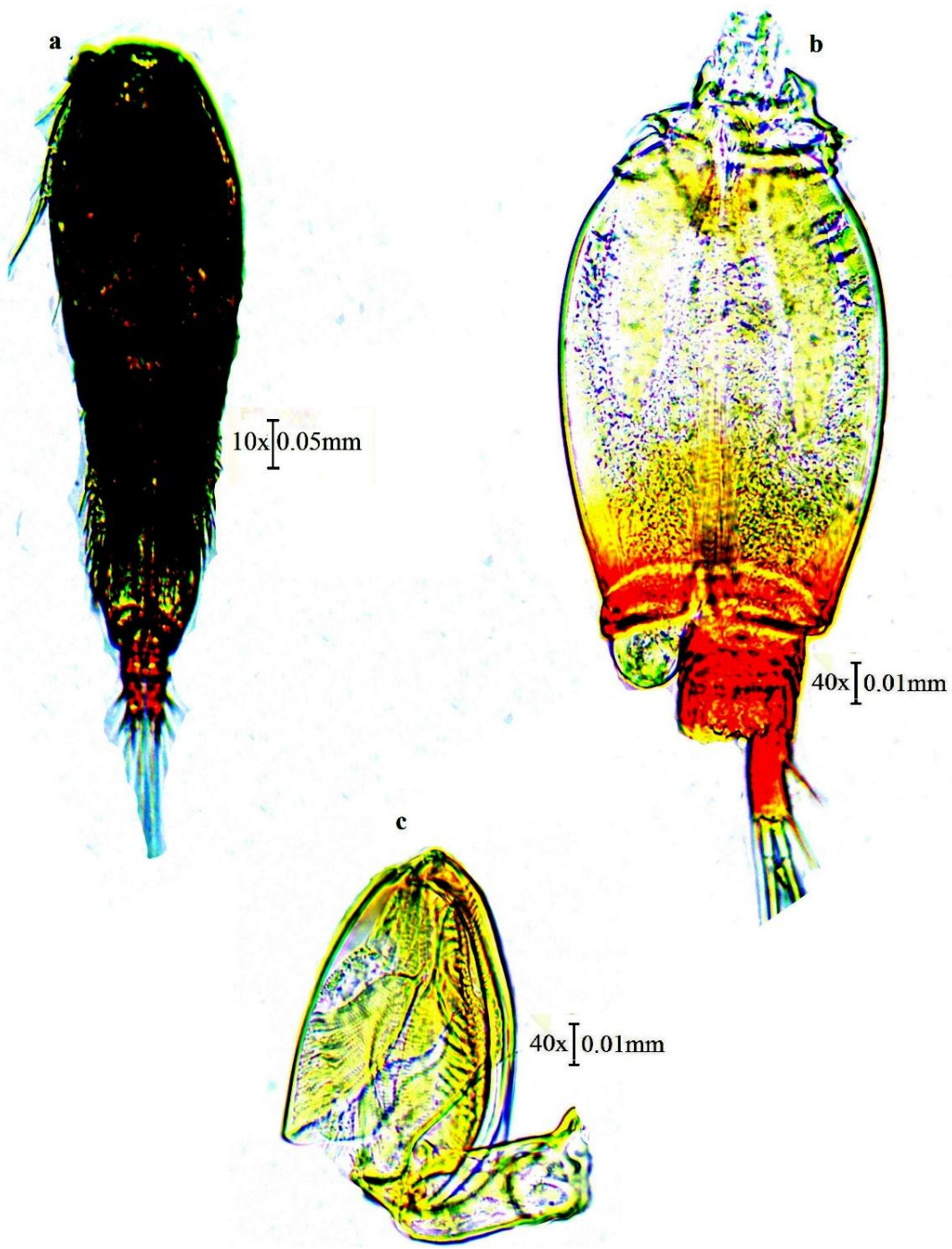


Plate.32.*Oncaea clevei* male. a, Habitus (lateral);b,Urosome;c,Maxilliped.

Distribution: Mediterranean Sea,N-S Red Sea, Gulf of Oman, G. of Aden, Arabian Gulf (Kuwait),Madagascar,SW Indian, Straits of Malacca, Malaysia (Sarawak: Bintulu coast China Seas ,S Korea, Japan, Pacific (W equatorial), Australia (http:// copepods. obs-banyuls.fr/en).

Oncaea media Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Male **(Fig.33,Plate 33)** Total length 0.911-0.95mm.Prosome thrice as long as wide and2.92 times longer than rest of the urosome. The last segment of the prosome bears lateral lappets which are large, rounded with a sharp projection directed outwards (Fig.33a).A1 four segmented (Plate.33e).Urosome six segmented, twice as long as wide.GS 1.31 times as long as wide; longer than AS and CR combined.AS 1.17 times as long as wide.CR 2.94 times as long as wide (Fig.33b,c). The first segment of maxilliped bears numerous spinous structures ventrally. Terminal claw 1.30 times longer than the preceding segment (Plate.33f).

Remarks: Only male specimens obtained from the sample. The characteristic features of *O.media* include its 1)body length; 2) Four segmented A1 and six segmented urosome conforming the sex as male; 3) Length width proportion of the prosome (3.09); 4) Length width ratio of CR (2.94) and that of GDS to rest of the urosome (excluding CR) being 2.92 were consistent with the previous descriptions of *O.media* male which in turn confirmed the taxonomic identity of the species. *O.media* was first observed by Giesbrecht (1891).This species is often confused with *O.scottodicarloi* and *O.waldemari*. Heron&Bradford-Grieve (1995) have opined that the drawings of urosome of *O.media* female by Giesbrecht are actually of *O.scottodicarloi* and therefore it is being advised to omit that figure. The present specimen has been compared with those described by Tanaka (1960),Heron & Bradford(1995), Razouls (1974), Wi& Soh (2009), Bottger-Schnack (2001).All the diagnostic features which includes the length width proportion of the body segments were scrutinized and taxonomic identity was confirmed. Length width ratio of GS with the rest of urosome(-CR) were also approximately similar (2.92:1) with that given by Conway et.al (2003).Prosome 2.2 times as long as urosome as proposed by Giesbrecht (1891) varies slightly with that of present specimen (1.54). Variations were also noticed with that of Tanaka (1960) in the length width ratio of CR being slightly lower (2.6) than that of the Lakshadweep specimen (2.94).

Distribution: Epipelagic-mesopelagic. Inshore, coastal and oceanic, Gulf of Carpentaria, Great Barrier Reef, the North West Cape, New South Wales and south east including Tasmania, Pacific, Indian and Atlantic Oceans (http:// copepods. obs-banyuls.fr/en).

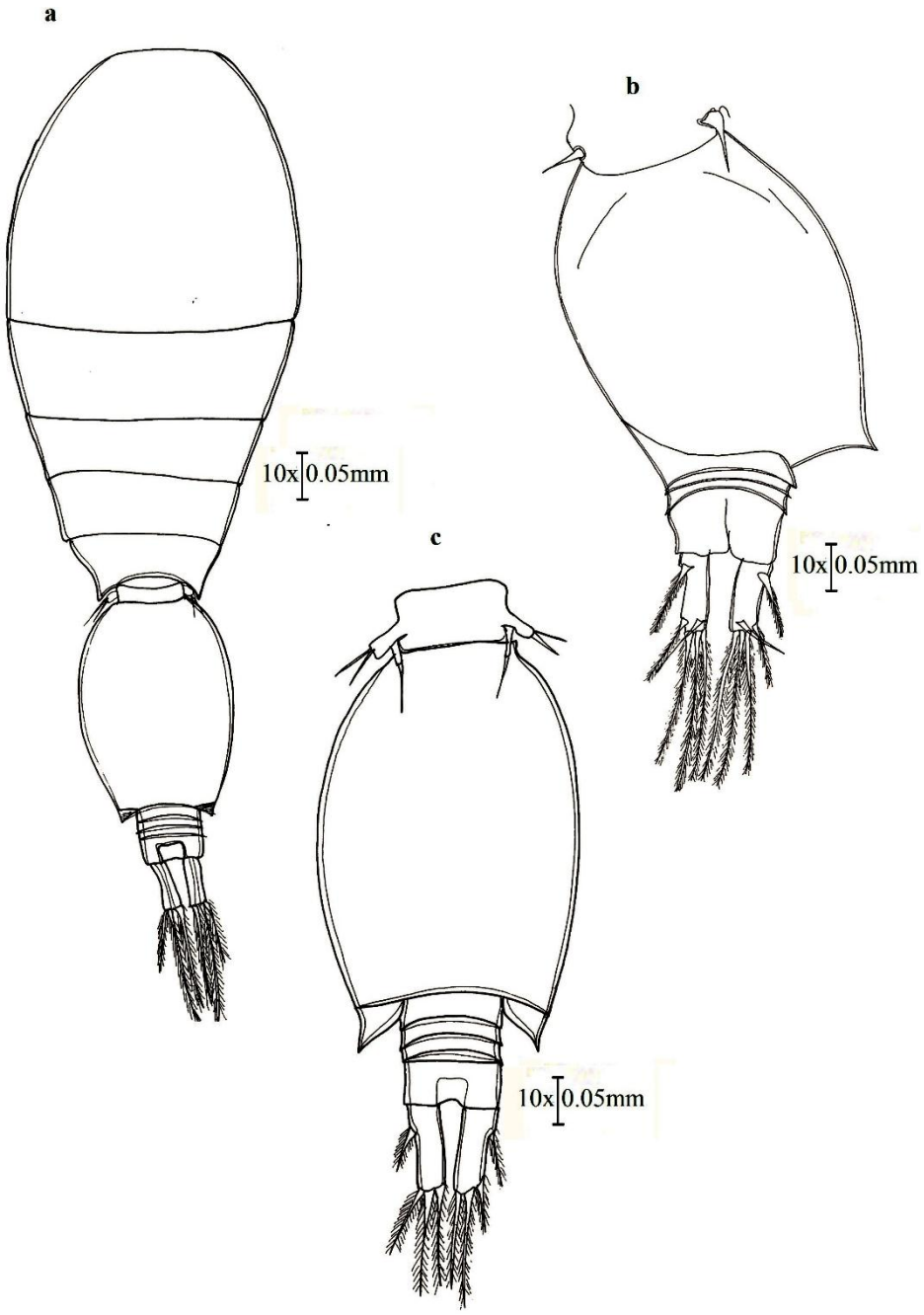


Fig.33. *O.media* male.a,Habitus; b,Urosome (lateral);c,Urosome (dorsal)

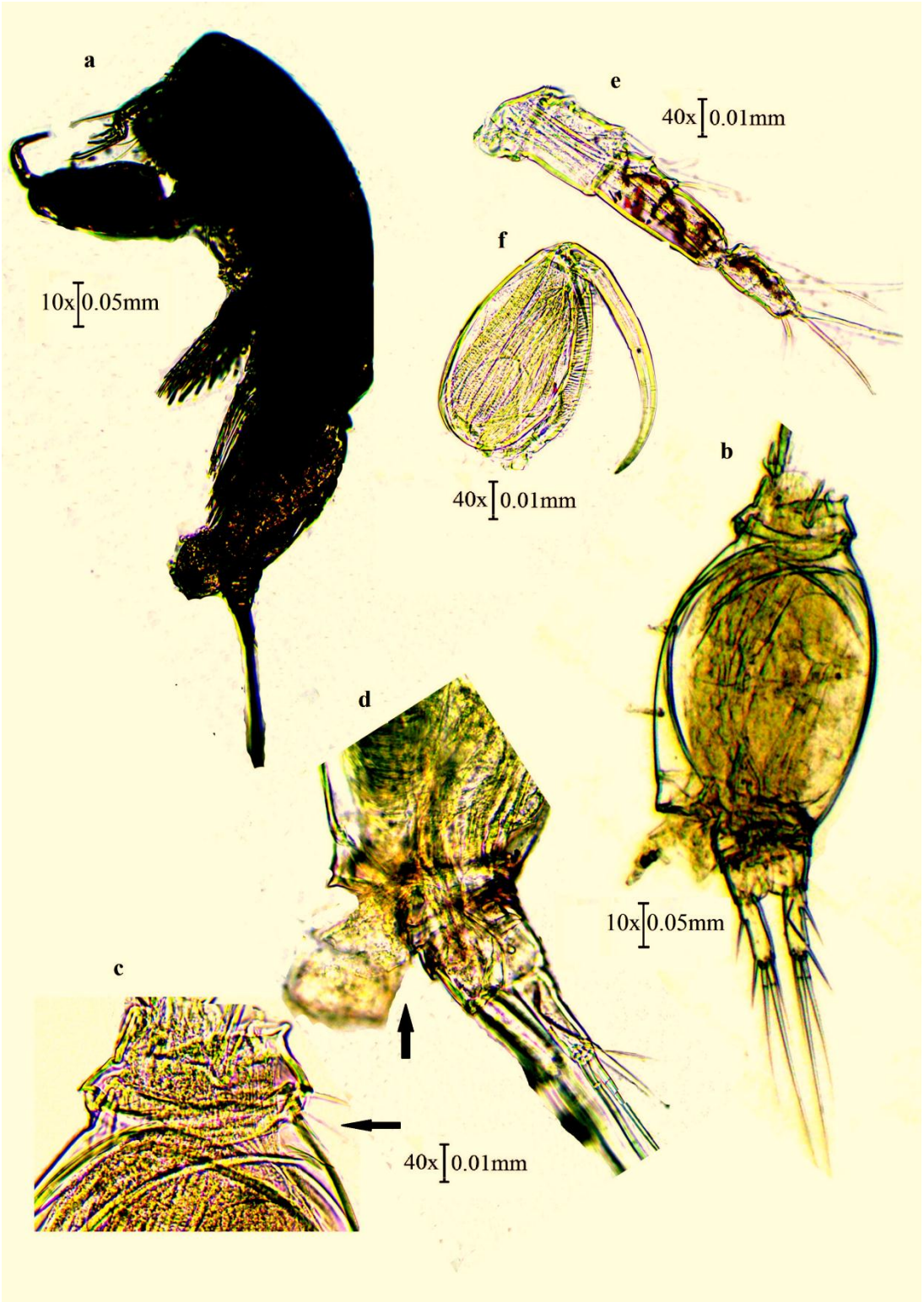


Plate.33. *O.media* male.a,Habitus; b,Urosome (lateral);d,P

Oncaea paraclevie Bottger-Schnack, 2001

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.34,Plate 34)** Total length 0.65-0.69 mm. Prosome twice as long as wide and twice longer than urosome (Fig.34a).A1 six segmented (Plate.34d). Urosome five segmented, 2.72 times as long as wide.GS 1.68 times as long as wide. Genital apertures more medially located.AS and CR as long as wide. Proportional lengths of the urosomal somites starting with 5th thoracic segment (+CR) is 0.3:1.85:0.2:0.2:0.2:0.5 (Fig.34b)

Remarks: This species is considered to be very similar to *O.clevie* with only difference in the GS more elongated form, more medial location of genital apertures and the pattern of sclerotization. During the present study, males could not be encountered. Bottger and Schnack (2001) recorded female sex of this species where male was unknown. When the body proportions were put side by side, features were almost comparable even though slightly varied. Those characteristics like 1) Length width proportion of PR more with Lakshadweep specimen than Bottger specimen (1.2 vs 1.74); 2) Shape of GS as oval elongate was corresponding; 3) Length ratio of GS to rest of urosomal somites combined less and length width ratio of GS almost similar to that of Bottger specimen (1.9 vs 1.54and 1.6 vs 1.68); 4) AS as long as wide; 5)Double curved sclerotization being same were consistent with the Bottger specimen that substantiate its taxonomy.

Distribution: Red Sea, North Arabian Sea, Straits of Malacca, Western Australia (http:// copepods. obs-banyuls.fr/en).

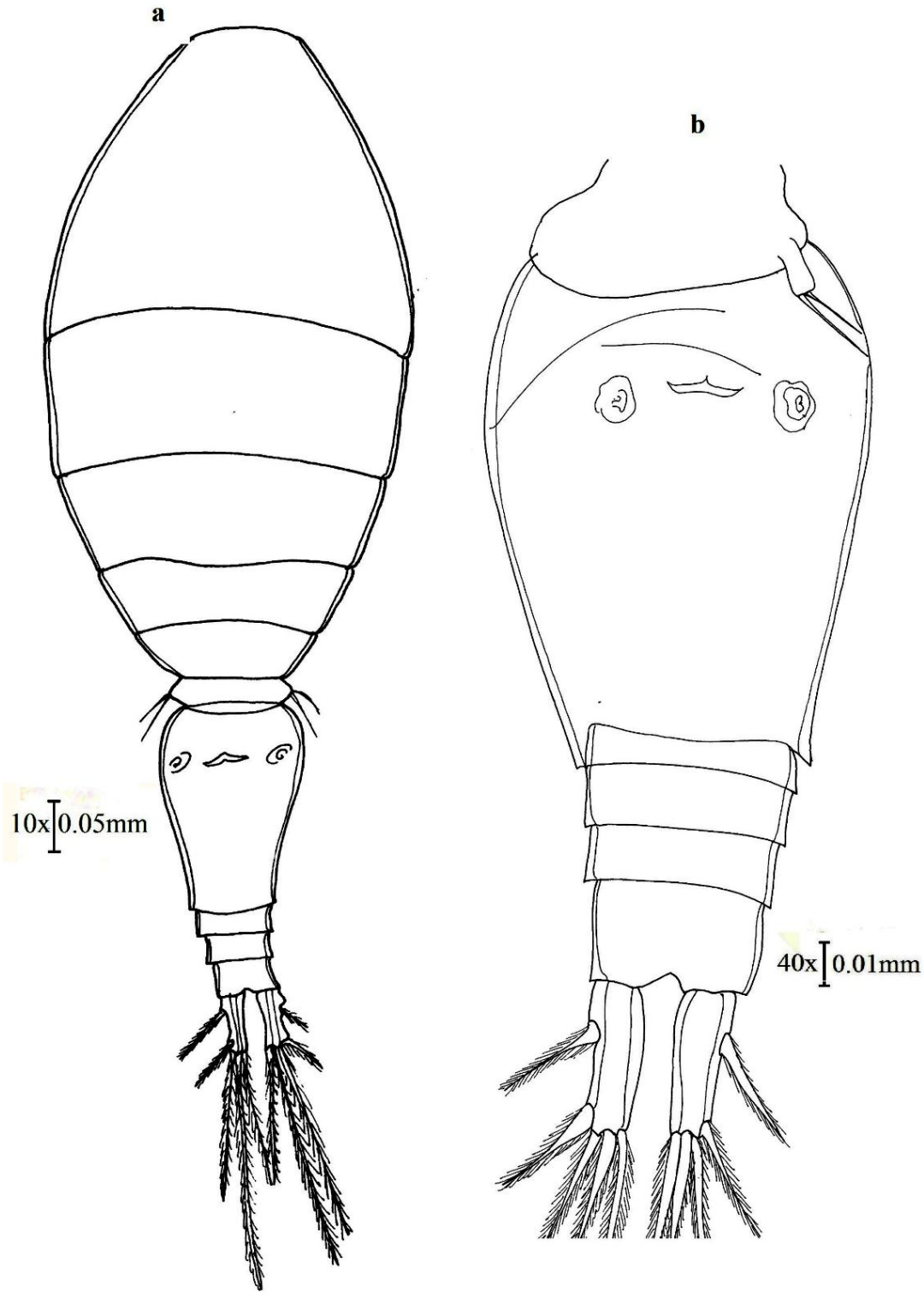


Fig.34. *O.paraclevie* female. a,Habitus; b,Urosome.

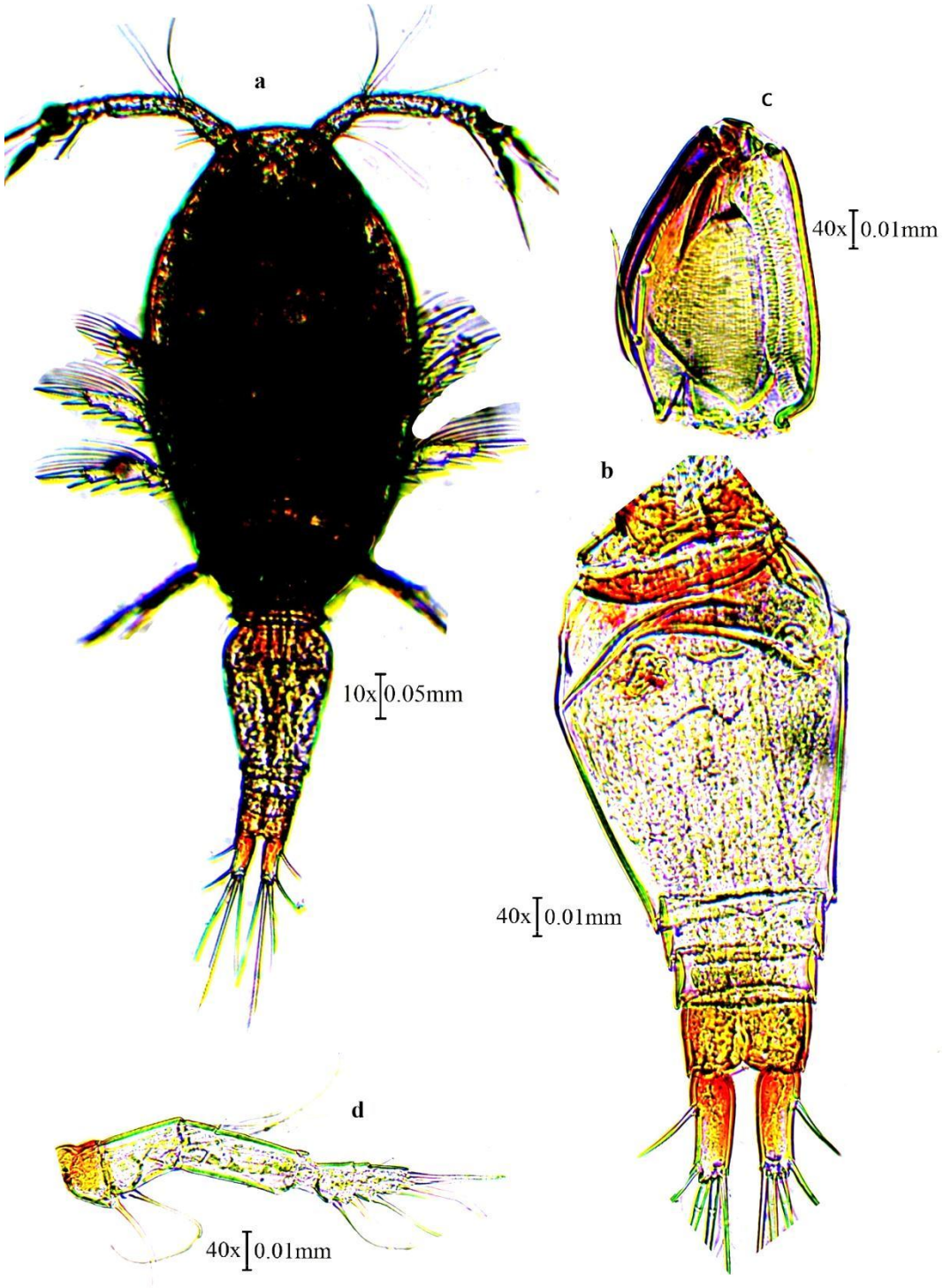


Fig.34 *O.paraclevie* female. a, Habitus; b, Urosome; c, Maxilliped; d, A1.

Onceaea venusta Philippi,1843

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.35,Plate 35.)** Total length 1.27-1.38mm.Prosome 1.72 times as long as wide and 1.81 times longer urosome (Fig.35a). A1 six segmented(Plate.35d).Urosome five segmented, 2.04 times as long as wide.GS 1.56 times as long as wide. CR 1.25 times as long as wide. Proportional lengths of the urosomal somites starting with 5th thoracic segment (+CR) is 0.9:7.6:0.3:0.3:1.2:2 (Fig.35b).

Remarks: Sewell (1947) identified two forms (subspecies) of *O.venusta* ie. *O.venusta typica* (0.75-1.23mm) and *O.venusta venella* (0.70-0.92mm).When compared with these two specimens in body length, Lakshadweep specimens were more comparable to *O.venusta typica* but slightly higher in length (1.27-1.38mm).Though with slight differences, the length proportions of many diagnostic features were comparable with Sargasso specimens such as length ratio of PR:UR (1.43 vs 1.81); length width ratio of PR being lower in Lakshadweep specimen (2.03 vs 1.72); length width ratio of CR being lower (3.83:1.25). Tanaka (1960) also identified two forms of specimens (large and small).When compared the above mentioned features of Tanaka with Lakshadweep specimens, the latter were found to be slightly higher but comparable. That included PR: UR(1.32:1.81); PR (length:width) being same (1.7vs 1.72) and CR (length:width) being lower (4 vs 1.25). When Bottger-Schnack (2001)opined on the aberrant spine numbers on P1 endopod terminal segment of his specimen, the same was not exhibited by present study *O.venusta* female species.Besides, the description on four segmented A1 and armature formula by Boxshall (1977) too agreed with Lakshadweep specimens. As suggested by Heron(2002) it's rare to find either sex of the species where the urosome is not flexed at a 45° angle to the prosome, and the two postgenital segments and the anal segment telescoped .Thus, the taxonomic identity of a unisex collection of *O.venusta* female specimens were confirmed.

Distribution: Indian Ocean, SE Australia, New Zealand,Peru,Chile,Australia, East Korea, Cheju Island, China Seas, Malaysia (Sarawak: Bintulu coast), Mediterranean Sea ,Black Sea, Red Sea (http:// copepods. obs-banyuls.fr/en).

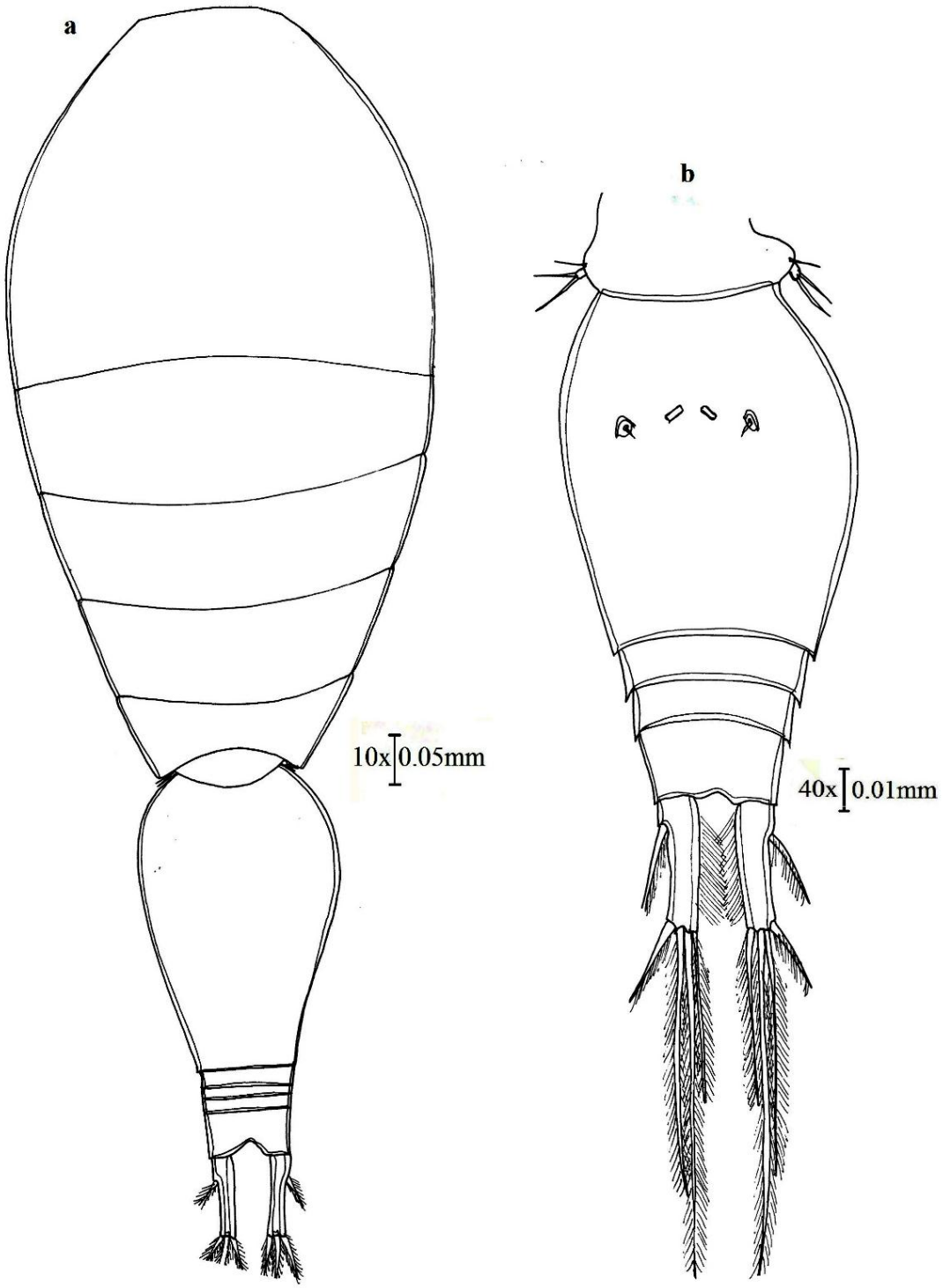


Fig.35. *O.venusta* female. a, Habitus; b, Urosome.

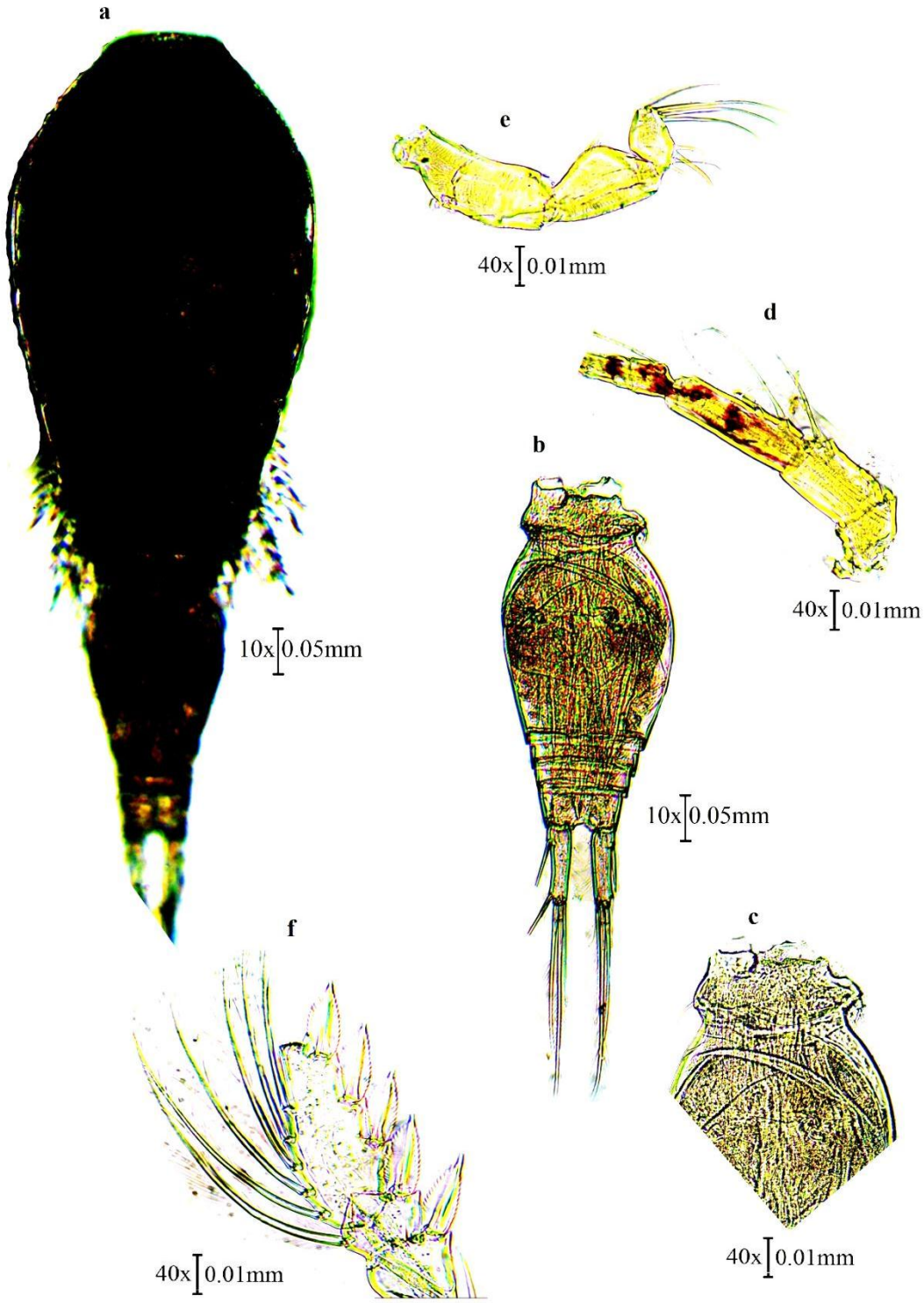


Plate.35. *O.venusta* female. a,Habitus; b, Urosome;c,P5; d,A1;e,A2.

Oncaea scottodicarloi Heron-Bradford, 1995

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Male **(Fig.36,Plate 36)** Total length 0.537-0.55mm.Prosome oval elongate. Prosome 2.23 times longer than urosome.A1 short (Fig.36a).Six segmented UR which is 2.25 times longer than wide. GS bulgy oval shaped different from that of females, 1.37 times longer than wide. Shorter CR 1.1 times wider than long. Proportional lengths of the urosomal somites starting with 5th thoracic segment (+CR) is 0.6:4.4:0.3:0.2:0.3:1.3:1(Fig.36b).

Remarks : *O.scottodicarloi* was first recorded from the Gulf of Naples by Heron and Bradford (1995). This species is closely related to *O.media ,O.waldermari & O.curta.* The distinguishing characters like 1) CR of the male shorter than that of female; 2) Difference in shape and segmentation of UR in both sexes 3) males generally smaller in size than females;4) form and type of sclerotization between genital apertures in females. When compared with the original description, specimens from the Red sea had different morphological characters like length width ratio of CR being smaller, smaller size in females, antennule with minute element on the sixth segment. The present specimens from Lakshadweep sea were consistent with the preceding descriptions with the body size of male shorter than female, UR segmentation and shape in both sexes, CR length in male being smaller than female.

Distribution: Mediterannean sea ,Red Sea, Australia, New Zealand,Japan, Ariake Bay, Tokyo Bay, Kuroshio & Oyashio regions, E.Korea, Panama Basin(http:// copepods. obs-banyuls.fr/en).

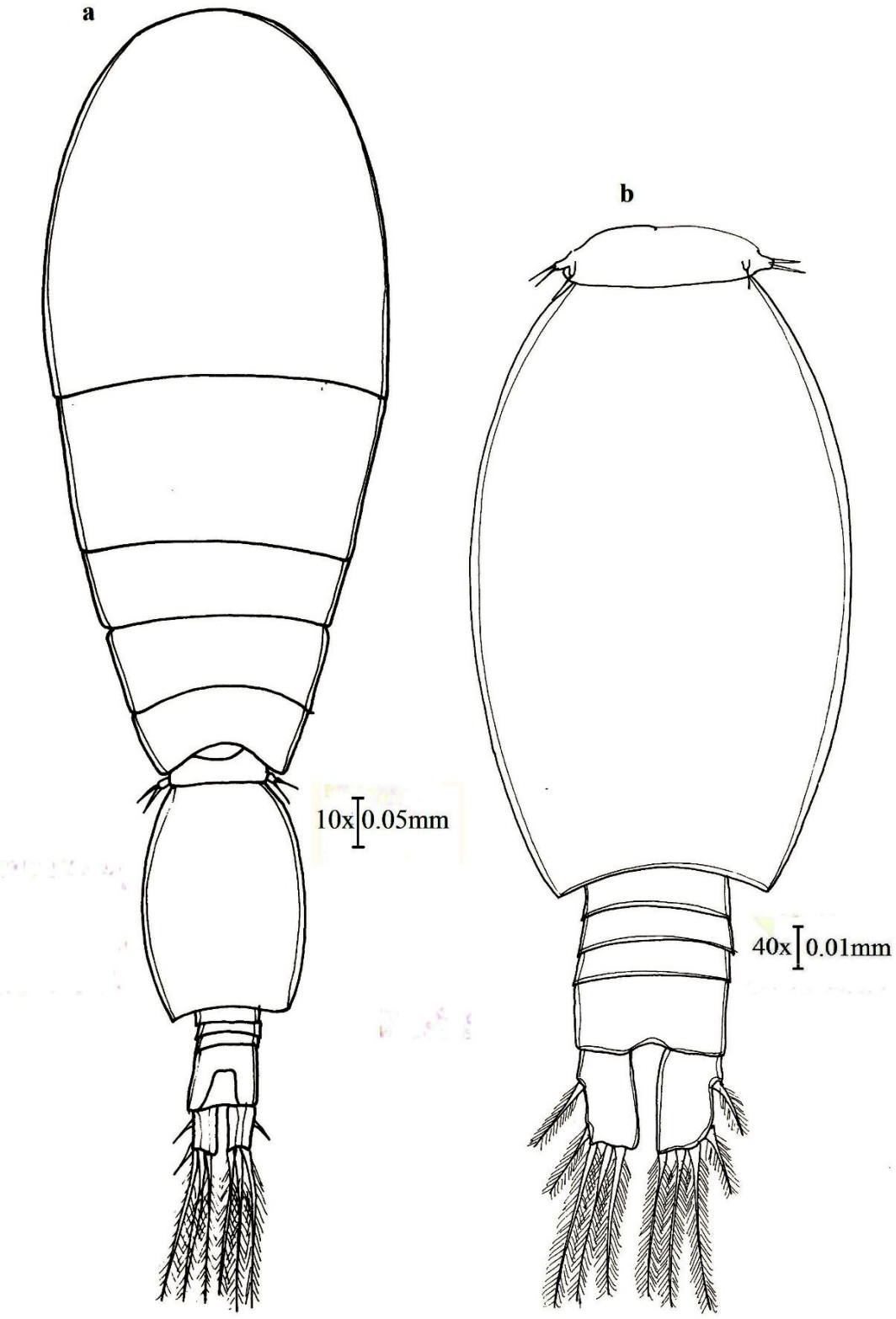


Fig.36. *O.scottodicarloi* male.a,Habitus;b,Urosome.

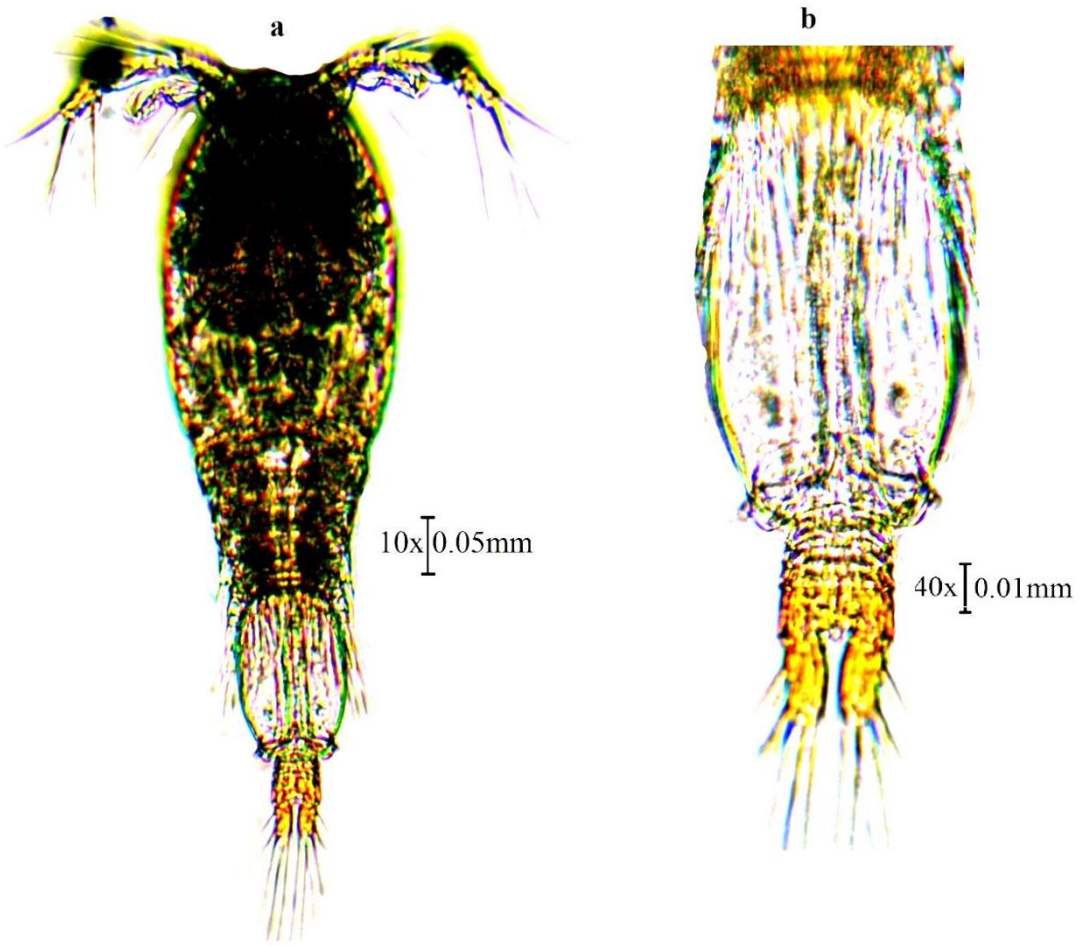


Plate 36. *O.scottodicarloi* male. a, Habitus; b, Urosome.

Oncaea mediterranea Claus 1866

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Male **(Fig.37,Plate 37)** Total length 0.93-0.95mm.Prosome 1.45 times longer than urosome and 1.83 times as long as wide (Fig.37a). Urosome six segmented, 2.16 times as long as wide.GS oval shaped ,1.75 times as long as wide .AS 1.11 times as long as wide.CR 1.21 times as long as wide. Length proportion of GDS: AS is 1.68 and GDS: CR is 3.11.Three segmented P1-P4. Proportional segments of the GS: AS: CR 23.27:73.41:54.46.Distal corner of GS has lateral projections (Fig.37b).

Remarks: From the samples we could get only the male specimens of this species. Males of *O.mediterranea* can be identified by 1)Total body length 2)length proportions of the urosomal somites 3) Distal corner of GS has lateral projections.

All these characters of the Lakshadweep specimens agreed with those of previous literatures.

Distribution: Mediterannean sea ,Barents sea, Red Sea, Black sea, South Korea, China seas, Indian, South west Pacific (http:// copepods. obs-banyuls.fr/en).

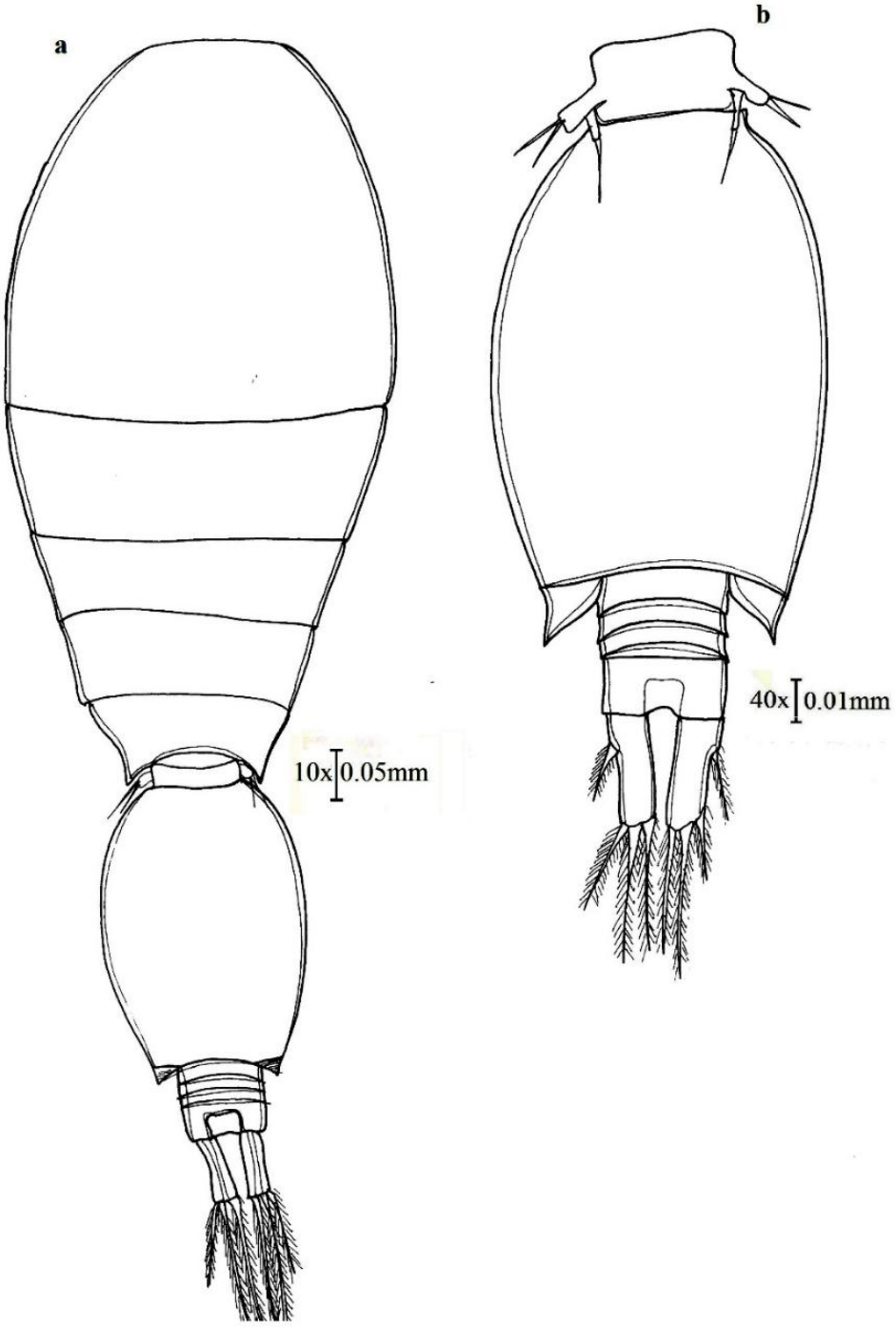


Fig.37. *O.mediterranea* male.a, Habitus; b, Urosome.

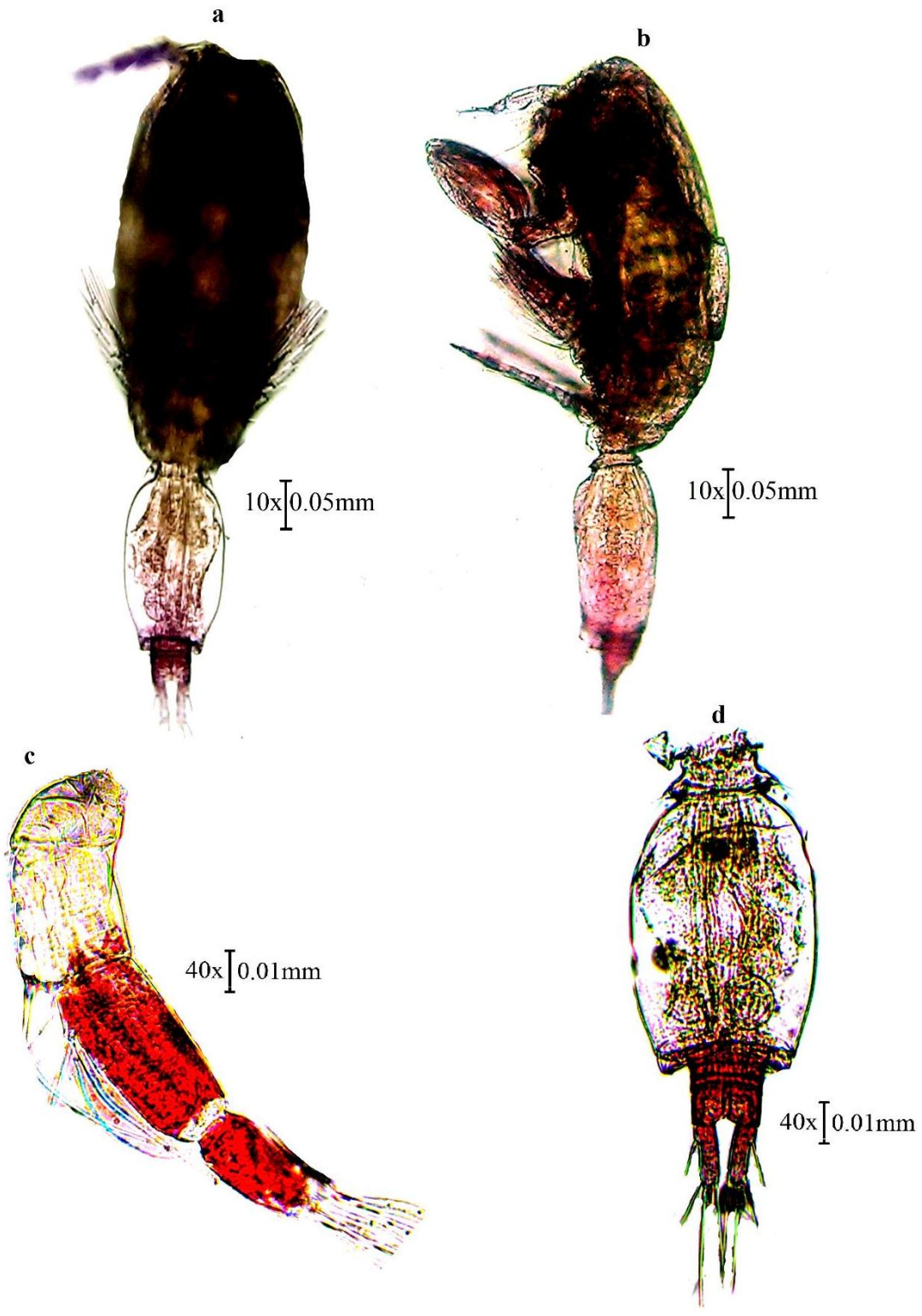


Plate.37. *O.mediterranea* male.a, Habitus; b, Urosome; c, Habitus (lateral);d,A1.

Oncaea macilenta Heron,1977

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy and Agatti (Refer Table 3.1 and 3.2).

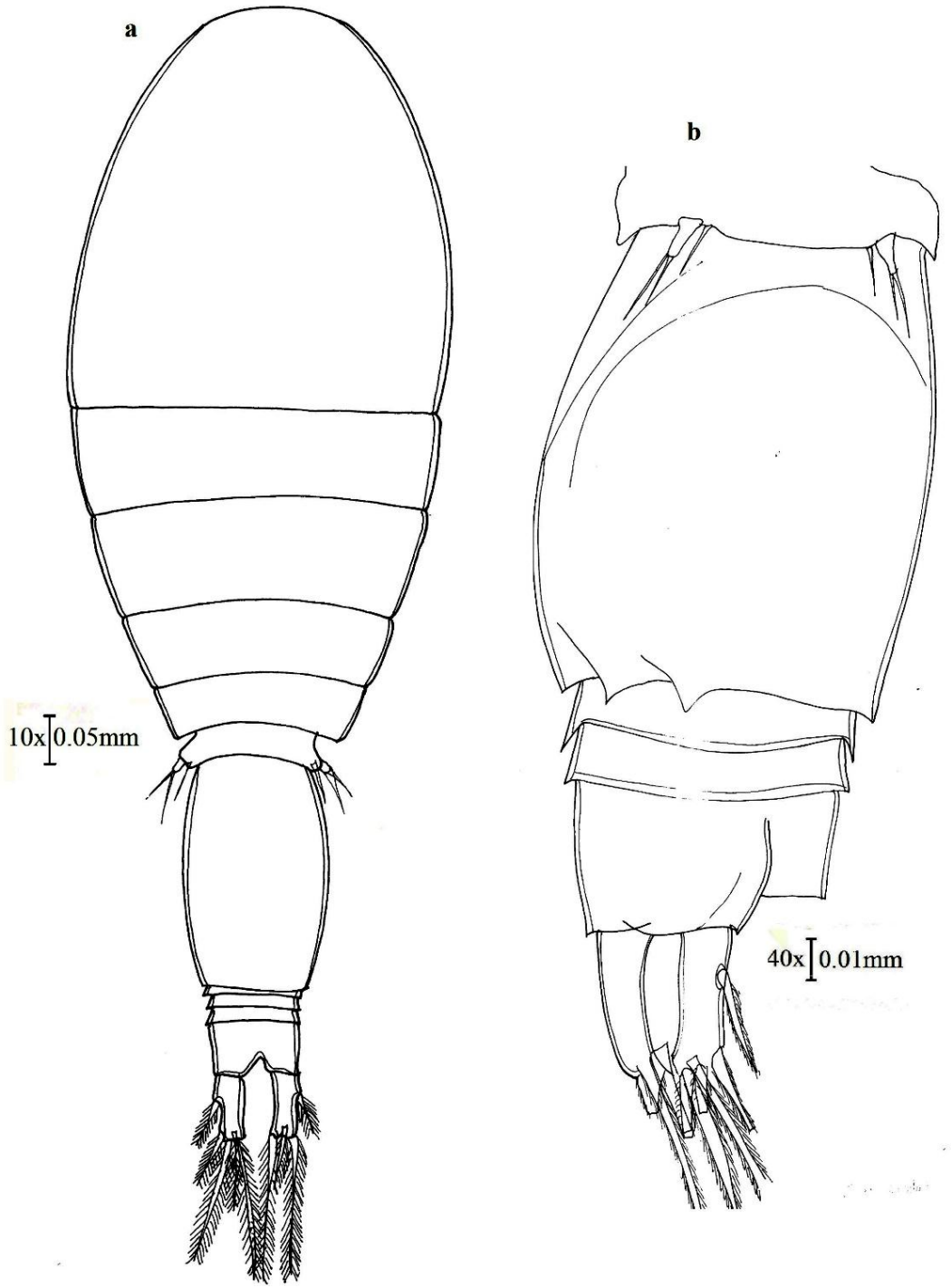


Fig.38.*O. macilenta* female. a, Habitus; b, Urosome.

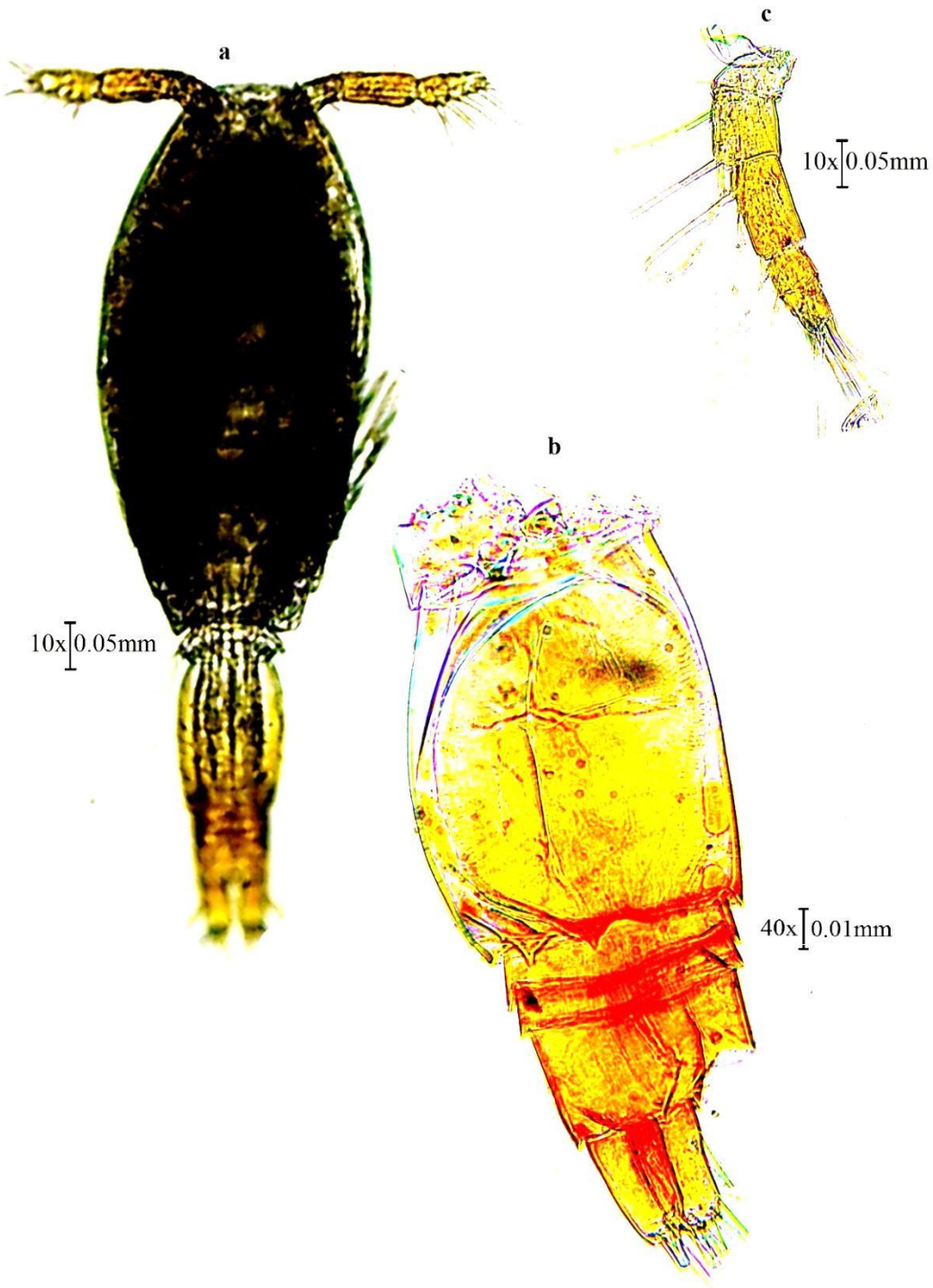


Plate.38*. O. macilenta* female. a, Habitus; b, Urosome.

Female **(Fig.38, Plate 38)**Total length 0.75-0.8mm.Prosome 1.94 times longer than urosome and 1.97 times as long as wide (Fig.38a).A1 six segmented (Plate.38c).Urosome five segmented,2.65 times as long as wide.GS 1.62 times as long as wide with lateral flaps protruding.AS as long as wide.CR 1.23 times wider

than long. Length proportion of GS: AS slightly wider than long. GDS:CR is 3.61. Proportional segments of the GS:AS:CR is 4.7:1.8:1.3.Distal corner of GS has lateral projections (Fig.38b).

Remarks: Heron (1977) reported this species first and that too only female specimens from North east and South west Pacific. Later Heron and Frost (2000)again reported this species from Washington. This can be considered as the first report in Lakshadweep Sea, part of Indian Ocean

Distribution: North East pacific, South West Pacific,Washington inland (http:// copepods. obs-banyuls.fr/en).

Oncaea curta Sars, 1916

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.39,Plate39)** Total length 0.67-0.68mm. Pyriform shaped body. Prosome 1.89 times longer than urosome and 1.97 times as long as wide. Urosome five segmented,2.51 times as long as wide.GS bulgy oval shaped,1.45 times as long as wide.AS 1.33 times as long as wide.CR 1.27 times as long as wide. Length proportion of GS:AS:CR is 4.5:2:1.4.Length proportion of GS:AS is 2.25 and GS:CR is 3.21 (Fig.39a).

Remarks: From the samples collected,we could get only female specimens of this species which was numerically abundant. The size of the obtained specimens was comparable with those of the previous workers. As reviewed by Bottger-Schnack (2010),the original pictures by Sars(1916) is considered as valid and original descriptions of *O.curta*. The distinctive features like 1) PR 1.47 times longer than wide 2) Proportional length of GS:AS being smaller (2.25) with that of CR (3.21) 3) Five segmented urosome 4) CR as long as wide were consistent with the studies by Sars(1916) and Bottger-Schnack (2010) which in turn confirmed the taxonomic identity.

Distribution: Caribbean, Adriatic Sea, Indian Ocean, Pacific Ocean, Black Sea, Rodrigues, Madagascar(http:// copepods. obs-banyuls.fr/en).

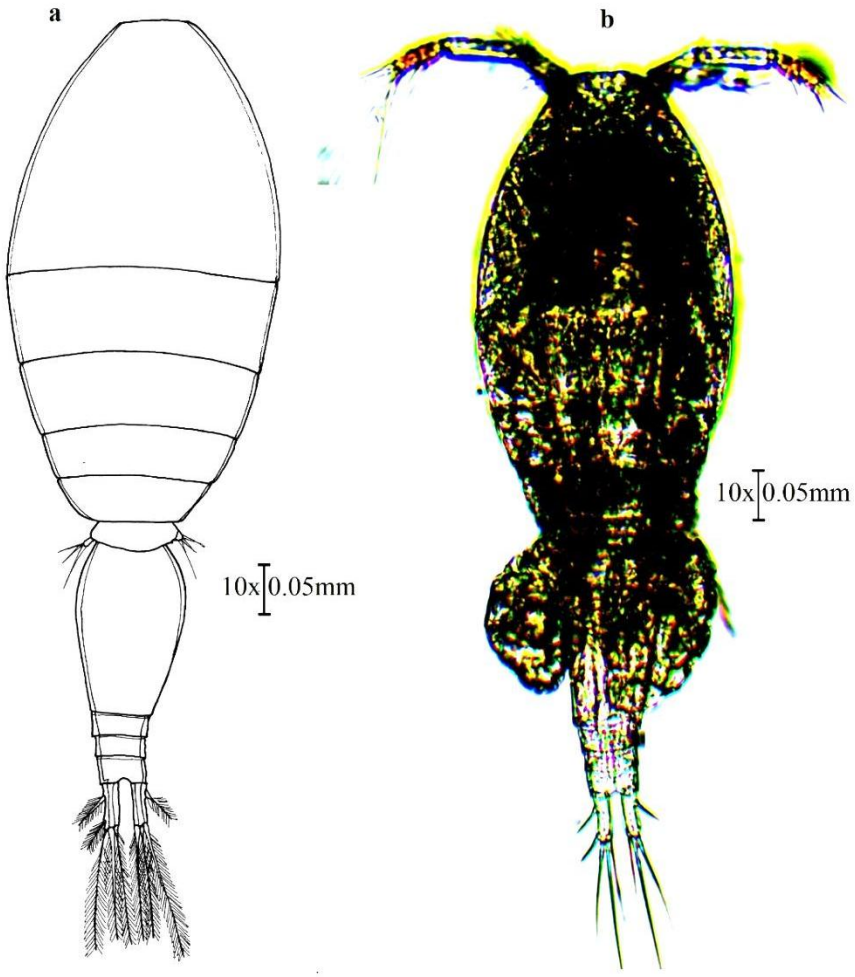


Fig.39 and Plate .39.*O.curta* female. a, Habitus.

Oithona brevicornis Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti(Refer Table 3.1 and 3.2).

Female (Fig.40,Plate 40) Total length 0.65-0.8mm. Prosome elongate ellipsoid,2.14 times as long as wide and 1.93 times as long as urosome. Anterior rounded cephalosome laterally produced into a sharp rostrum (Fig.40a).Urosome five segmented, 3.1times as long as wide. GS 1.53 times as long as wide and swollen laterally at the proximal margin.CR 2.5 times wider than long. Proportional lengths of the GS:AS:CR is 3:3.3:1 (Fig.40b).

Remarks: This species is closely allied to *O.aruensis* and *O. wellershausi*. The Lakshadweep specimens agree with Temnykh and Nishida (2012) from Black sea in the morphological characters like 1) Anterior part of prosome rounded in dorsal

view; 2) Rostrum pointed ventrally; 3) total body length. However a large degree of comparability existed with Rosendorn (1917) in the PR:UR ratio being 1.16 vs 1.93 for Lakshadweep. But comparing with Ferrari (1981) PR:UR ratio was high with 1.3 for former and 1.93 for latter.

Distribution: Adriatic Sea, Red Sea, Gulf of Oman, Arabian Sea, Arabian Gulf, India (Saurashtra coast, Kerala,Madras, Gulf of Mannar, Palk Bay, Chilka Lake, Calcutta Salt Lakes, Bay of Bengal, Malaysia (Kurau River),China Seas Korea Japan Sea, Japan (http:// copepods. obs-banyuls.fr/en).

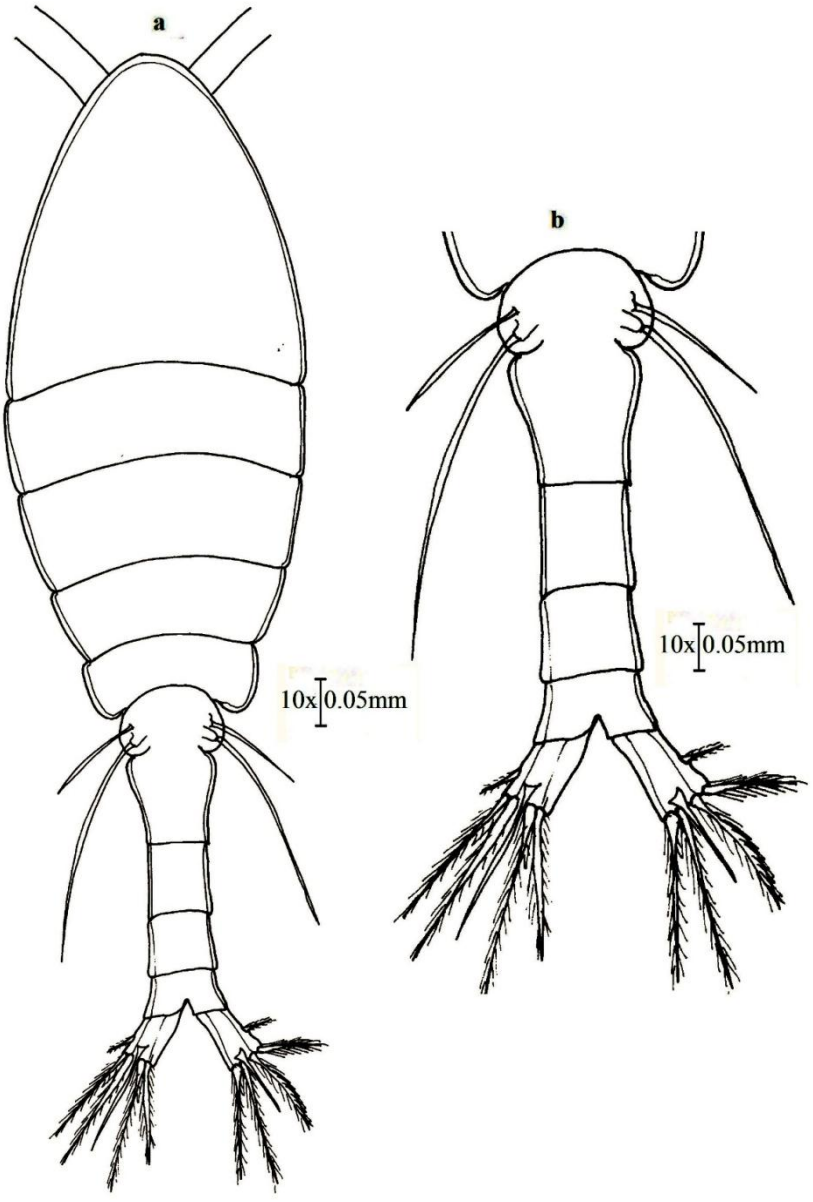


Fig.40. *O.brevicornis* female. a, Habitus; b, Urosome.

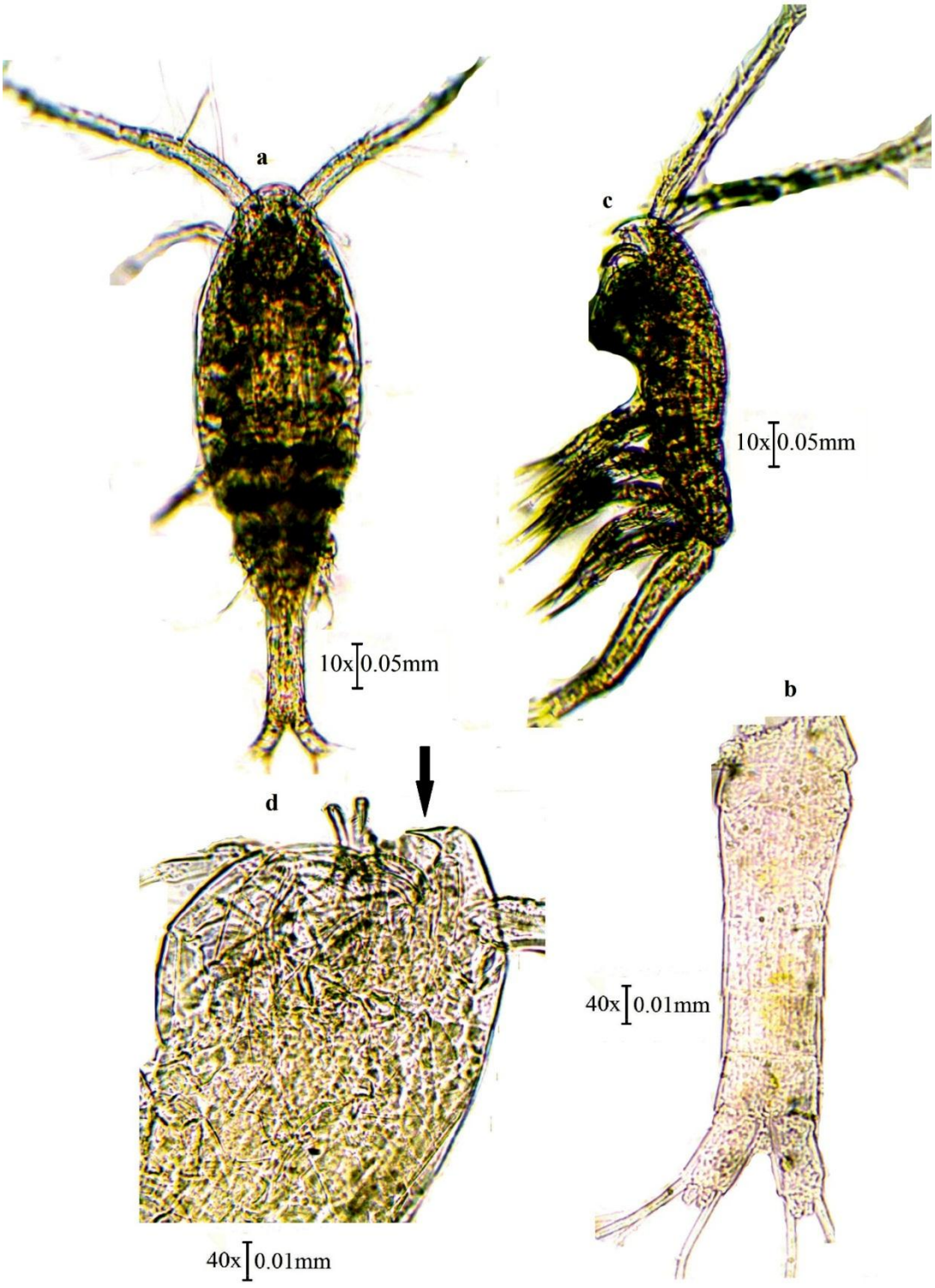


Plate.40. *O.brevicornis* female. a, Habitus; b, Urosome;c,Habitus(lateral);d,rostrum.

Oithona plumifera Baird, 1843

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.41,Plate 41)**Total length 1.11-1.2mm. Prosome oval and fusiform with plumes present; five segmented 2.44 times as long as wide and almost as long as urosome. Anterior rounded cephalosome with distinctively pointed rostrum that is visible dorsally (Fig.41a).A1 long and reaches the AS (Plate.41c).Urosome five segmented,6.12 times as long as wide.GS being the longer segment; 2.66 times as long as wide and swollen laterally at the proximal margin. Ventral side ornamented with tuft of hairs.CR slightly shorter than AS. CR 2.8 times longer than wide being shorter than AS; wide at base. Proportional lengths of GS:AS:CR is 4:3:2.8 (Fig.41b).

Remarks: Only female specimens were encountered during the present study.As the name indicated, plumose setae, one of the distinguishing character of this species, aroused from even from the swimming legs of the Lakshadweep specimen. However, in Sewell's case, there appeared specimens in whom setae aroused from the swimmimg legs or anterior 2 legs or totally absent. He also mentioned on the probability of plumose termination as a variable character.When compared with the specimens of Tanaka (1960); Shmelva (1965); Nishida (1977,1985); Chen& Zang (1974); Roserdorn (1917);Shuvlov (1980);Giesbrecht (1892);Conway et.al (2003);Al Yamani (2011),the present specimen totally agreed with the characters like 1) pointed rostrum on anterior of cephalosome; 2) GS being more than twice as long as wide; 3) laterally swollen GS with ventral side bearing tuft of hairs; 4) CR shorter than AS; 5)length width proportion of CR; 5) presence of plumose setae arising from the swimming legs; 6) length ratio of PR:UR being same. All these concluded on the correct taxonomic identity of *O.plumifera* female specimens.

Distribution: Widely distributed in Pacific, Atlantic and Indian Ocean and also in the Red Sea and Mediterranean Sea (http:// copepods. obs-banyuls.fr/en).

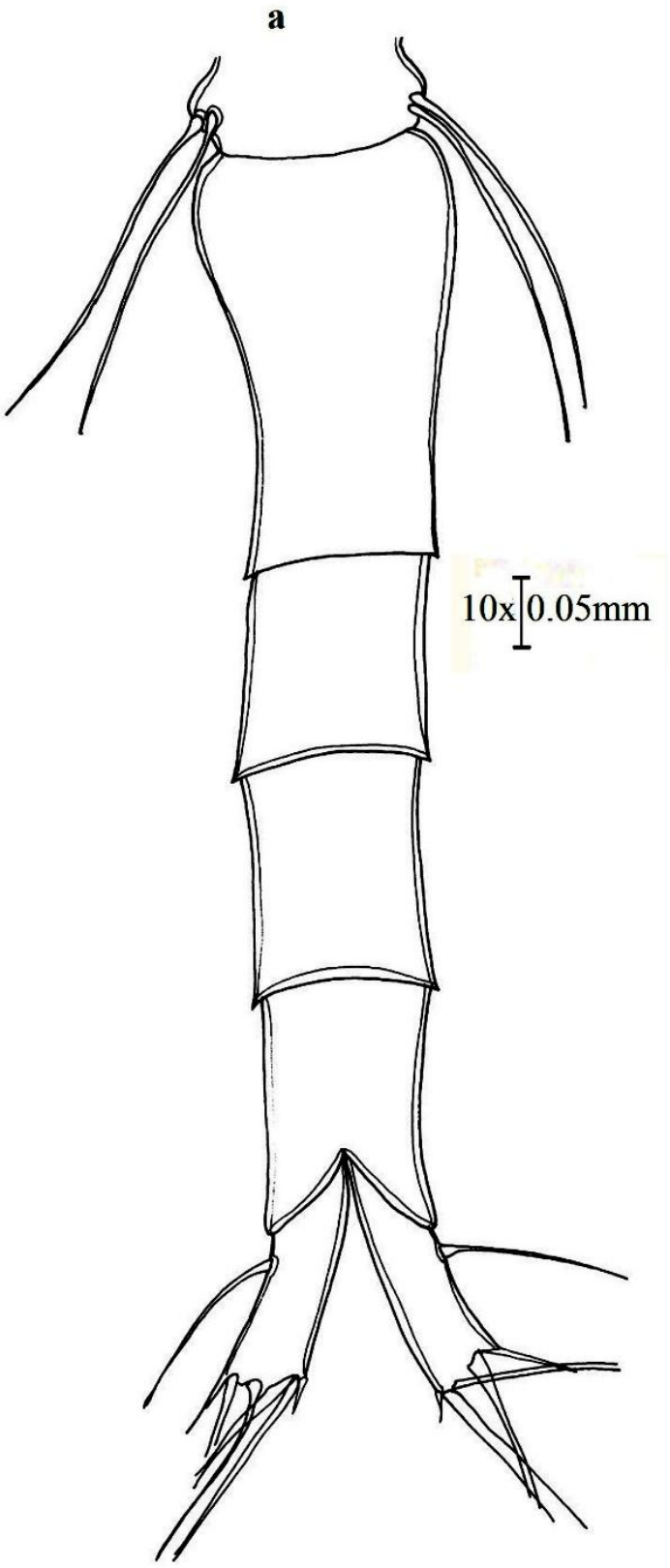


Fig.41. *O.plumifera* female. a, Urosome.

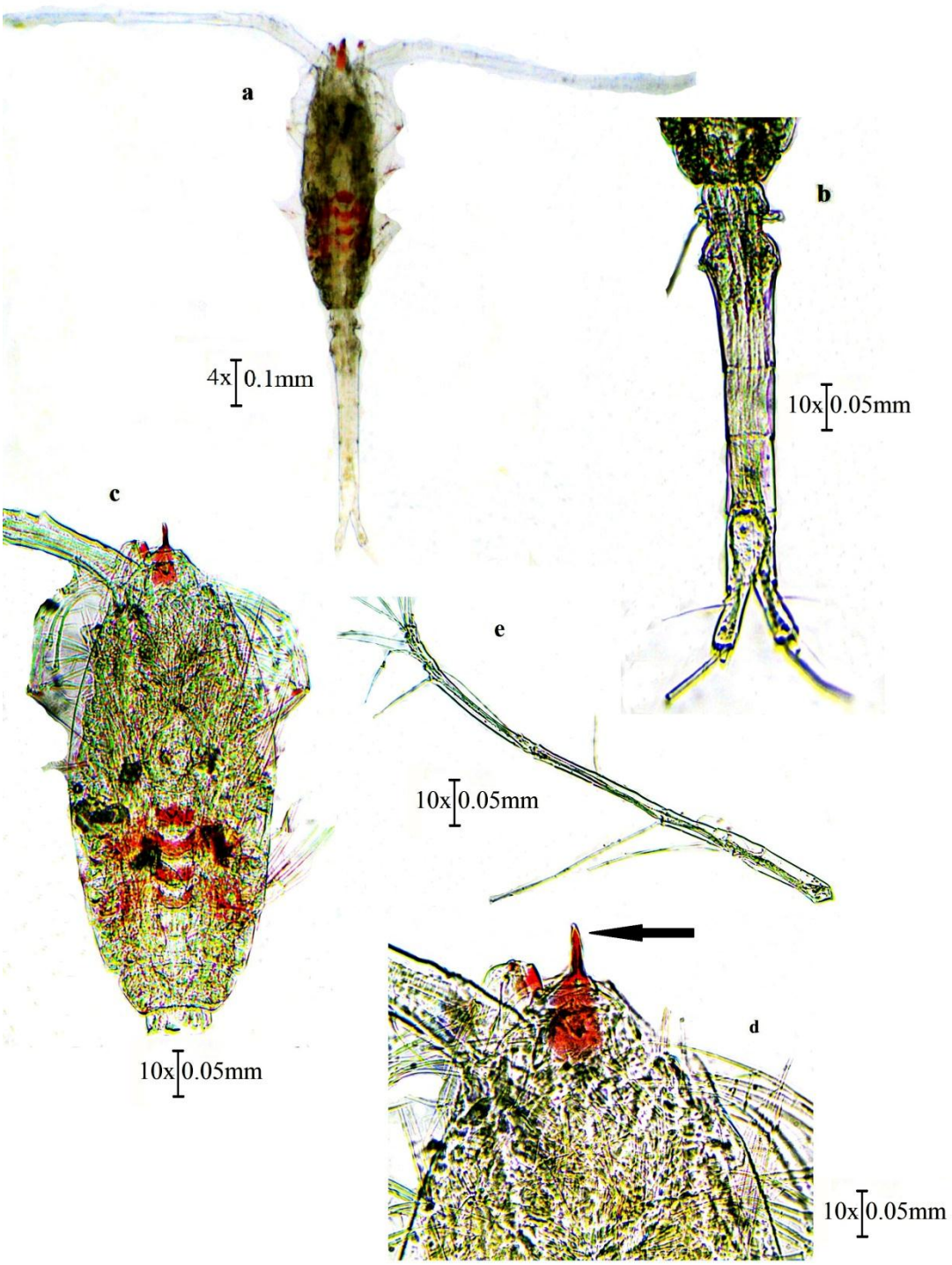


Plate.41. *O.plumifera* female. a,Habitus; b,Urosome;c,A1;d,Prosome;e,Rostrum.

Oithona simplex Farran, 1913

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram(Refer Table 3.1 and 3.2).

Female **(Fig.42,Plate 42)**Total length 0.37-0.4mm. Prosome oval five segmented;1.43 times as wide as long and 1.58 times as long as urosome.Blunt rostrum which is not visible dorsally (Fig.42a).A1short almost as long as prosome (Plate.42a).Urosome 3.75 times longer than wide.GS 1.91 times as long as wide and swollen laterally at the proximal margin.AS 2.14 times longer than wide.CR 1.05 times longer than wide.P5 with one seta. Proportional lengths of GS:AS:CR is 4.6:3:1.8 (Fig.42b).

Remarks: *O.simplex* had already been reported from Indian Ocean by Rosendorn(1917) and Nishida(1985).This species is very much identified by its small size, ovate body.Nishida (1985) identified two forms- *O.simplex* typical and *O.simplex* long. Tanaka's female specimen showed PR:UR length ratio as 1.85,absence of rostrum and CR being twice as long as wide. All these were comparable with that of present specimens in which PR:UR length ratio being 1.58,CR 1.05 times as long as wide but rostrum being blunt.

Distribution: Sub-Antarctic,South Africa (E), Adriatic Sea, Ionian Sea, Aegean Sea, Red Sea, Gulf of Oman, Arabian Sea, Kuwait, Madagascar ,Indian Ocean, Christmas Island, Perai River estuary (Penang),Indonesia-Malaysia, Sarawak:Bintulu coast,China Seas, Australia, New Caledonia, Samoa Island, Palau Island, Pacific Ocean,Hawaii, Kaneohe Bay (http:// copepods. obs-banyuls.fr/en).

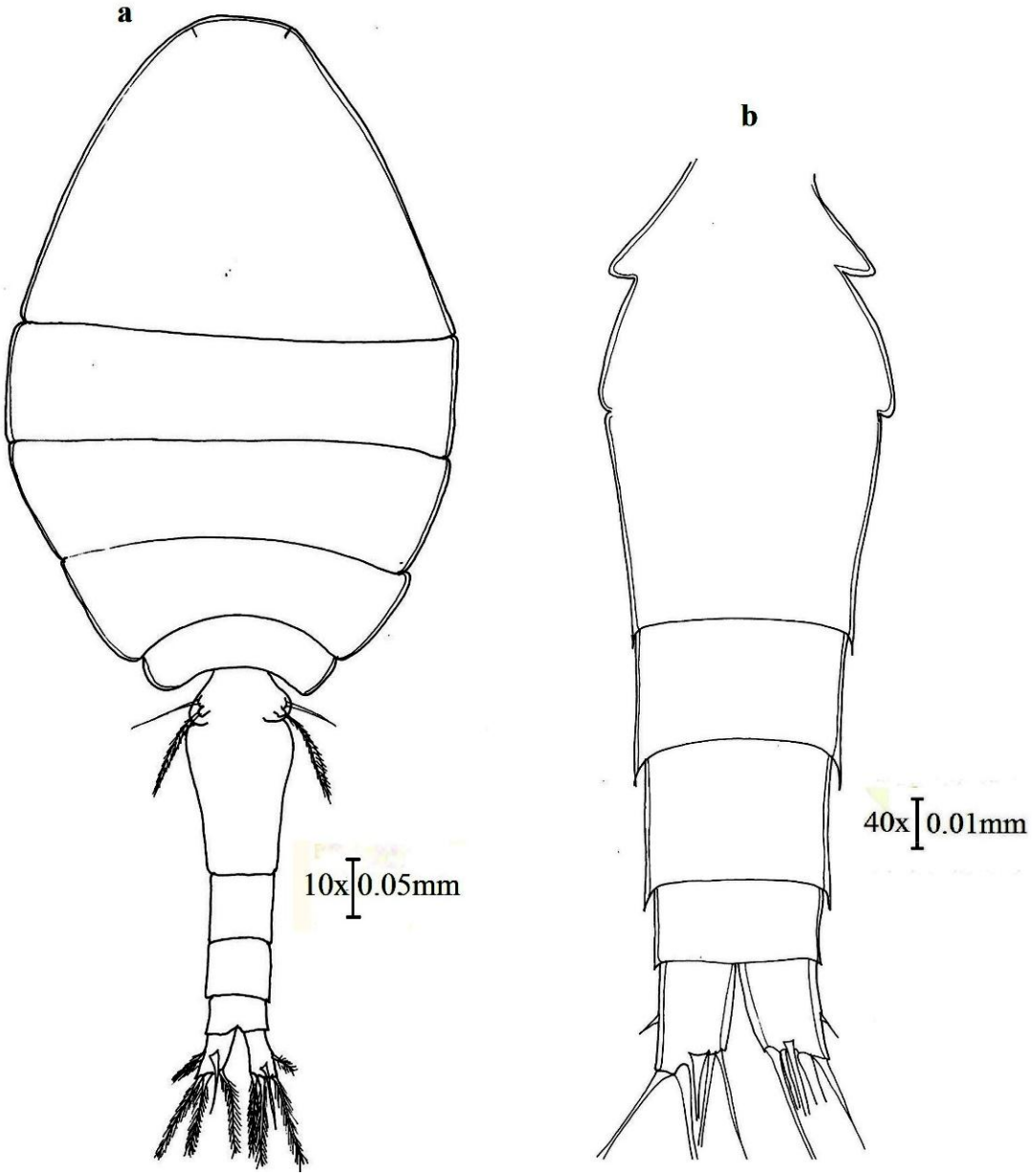


Fig.42.*O.simplex* female. a, Habitus; b, Urosome.

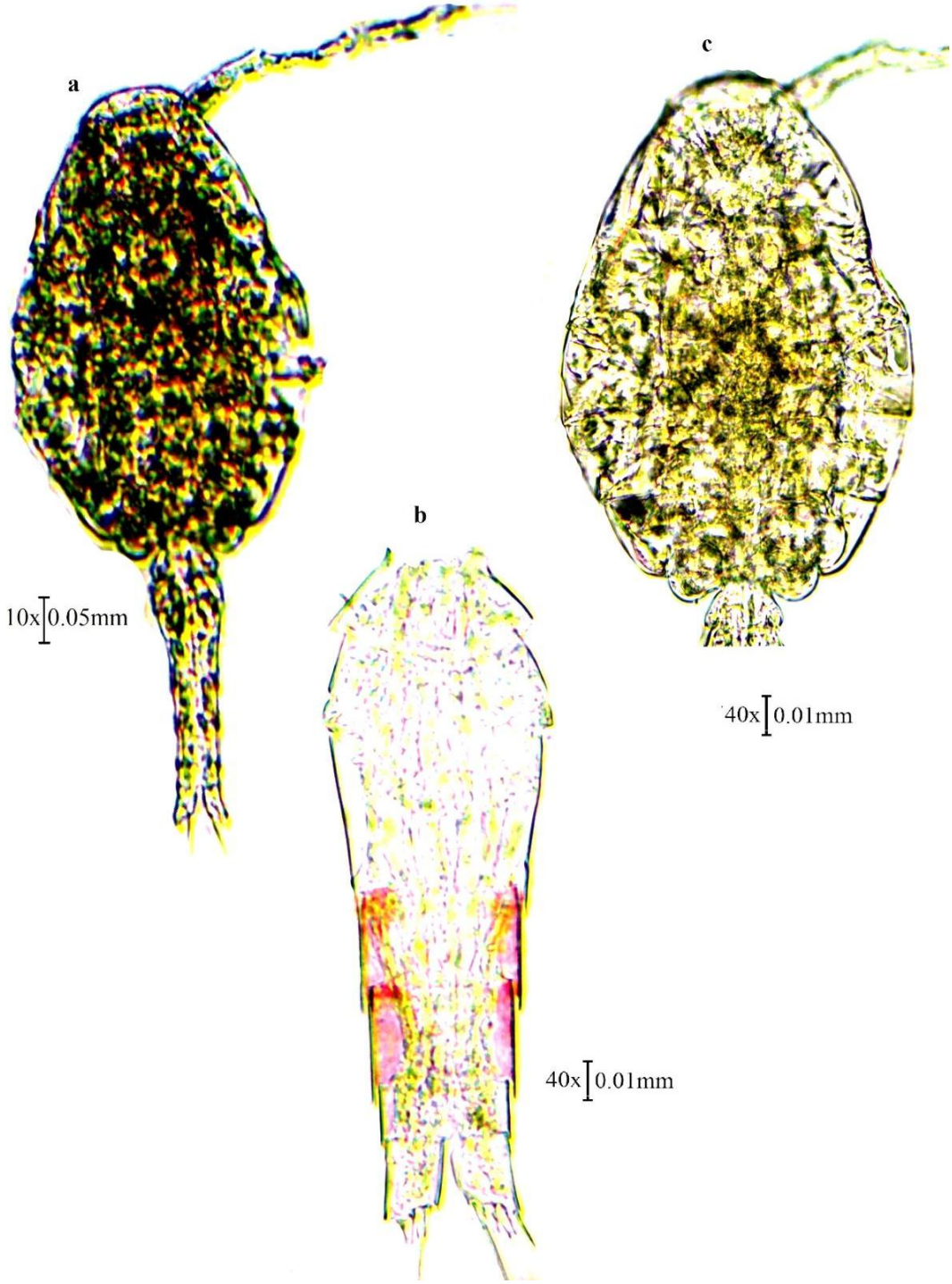


Fig.42.*O.simplex* female. a, Habitus; b, Urosome;c,Prosome.

***Oithona nana* Giesbrecht, 1892**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.43,Plate 43)**Total length 0.53-0.6mm.Prosome 1.39 times as long as urosome. Blunt rostrum which is not visible dorsally (Fig.43a).A1short. Urosome five segmented, 4.85 times as long as wide.GS 2.38 times as long as wide. AS 2.5 times as long as wide.CR 1.13 times longer than wide.P5 with one seta (Fig.43b).

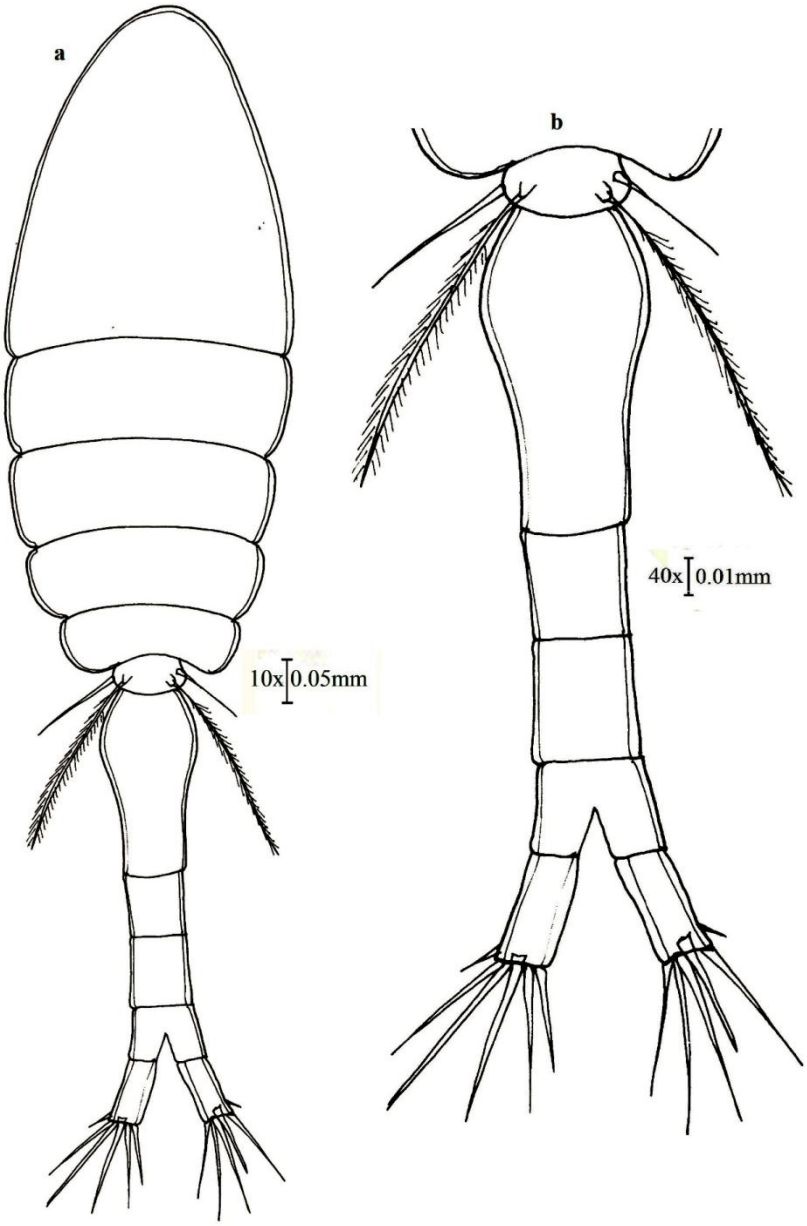


Fig.43. *O.nana* female.a,Habitus;b,Urosome.

Remarks: When compared with the specimens of Tanaka (1960); Shmelva(1965); Nishida (1977,1985);Chen & Zang(1974); Roserdorn (1917); Shuvlov (1980); Giesbrecht (1892); Conway *etal*.,2003; Al Yamani (2011), the present specimen totally agreed with the characters like 1) Blunt rostrum which is not visible

dorsally; 2)PR almost as long as UR; 3) CR 1.13 times as long as wide. Only female specimens could be obtained from the samples

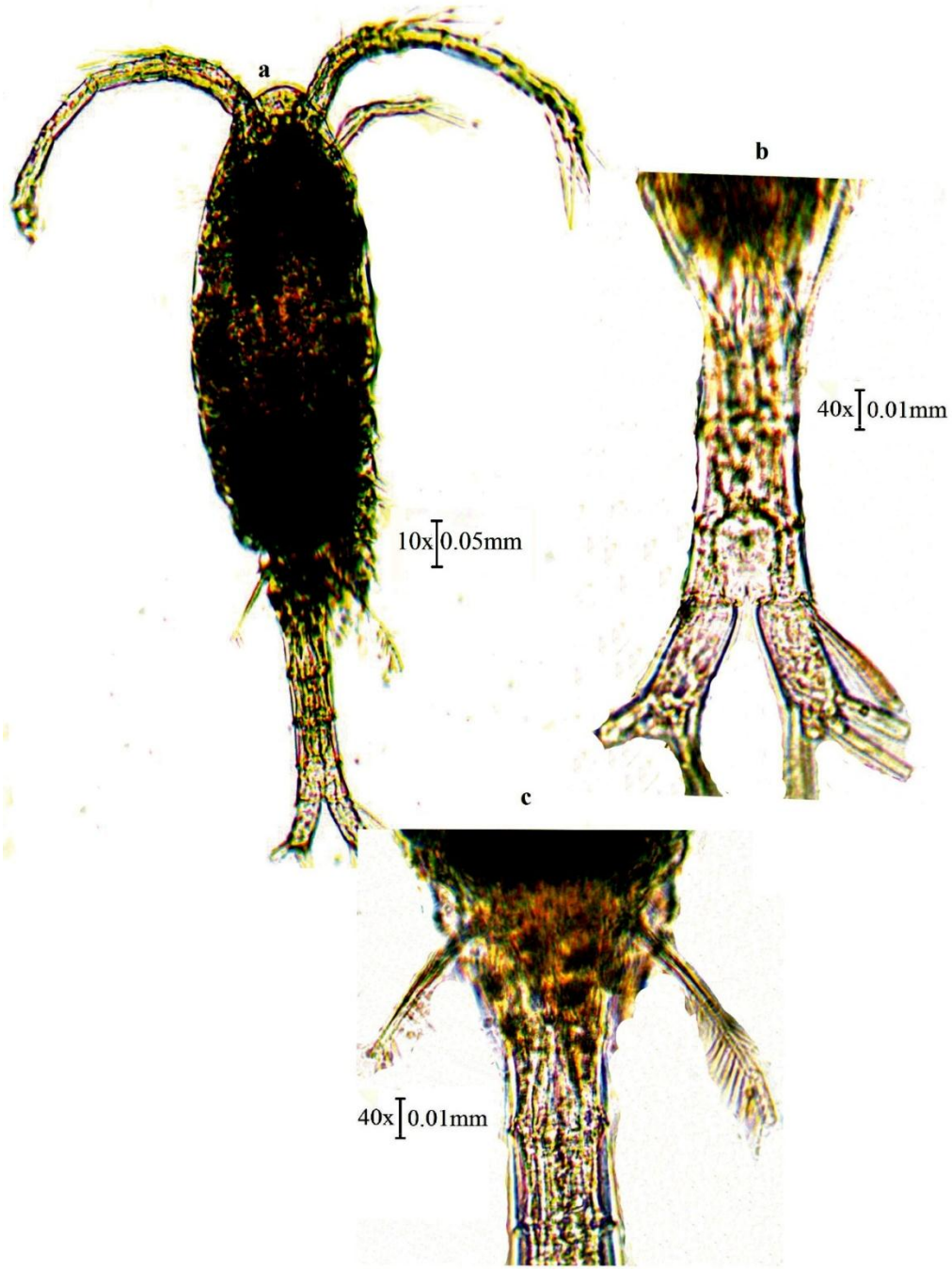


Plate.43. *O.nana* female. a, Habitus; b, Urosome;c,P6.

Distribution: Rodrigues,Madagascar, Red Sea, Gulf of Oman, Arabian Sea, Arabian Gulf, UAE coast, Kuwait, Sri Lanka, Madagascar ,Rodrigues Island,Gulf of Mannar, Indonesia-Malaysia,Viet-Nam, China Seas (http:// copepods. obs-banyuls.fr/en).

Oithona similis Claus, 1866

Material examined: The samples were sorted out from plankton samples collected from Kavaratti, Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.44, Plate 44)** Total length 0.82-1.12mm.Anteriorly narrowed prosome. Rostrum not visible dorsally.Prosome 1.12 times as long as urosome and 2.76 times as long as wide.GS thrice as long as wide. Anterior swollen GS. Divergent CR,1.72 times as long as wide(Fig.44a).

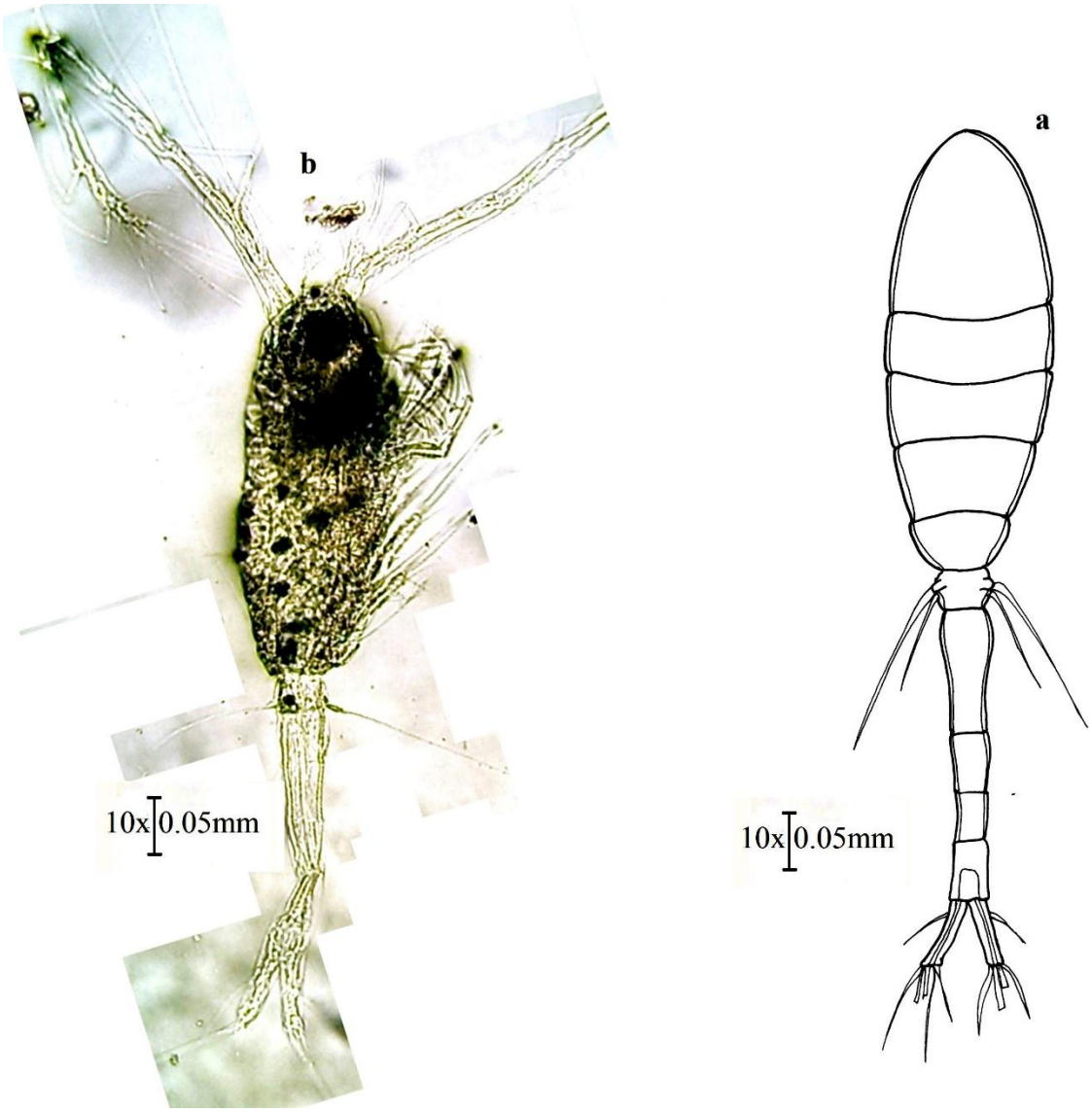


Fig.44 *and* Plate.44.*O.similis* female.Habitus

Remarks: This species is closely allied to *O.helgolandica*. The Lakshadweep specimens agree with Tanaka(1960),Giesbrecht(1892),Conway *et.al*., 2013,Cepeda *et al*., 2016 in the morphological characters like 1)Anteriorly narrowed prosome; 2)Divergent CR; 3) Prosome as long as urosome.

Distribution: Madagascar, Indian Ocean, Atlantic Ocean, Australia, Pacific Ocean (http:// copepods. obs-banyuls.fr/en).

***Dioithona rigida* female (Giesbrecht, 1896)**

Material examined: The samples were sorted out from plankton samples collected from Kavaratti (Refer Table 3.1 and 3.2).

Female **(Fig.45, Plate 45)** Total length 0.68-0.8mm.Prosome comprises cephalosome and four thoracic segments. Frontal margin arc shaped, laterally produced into single rostrum which is blunt (Fig.45a).Urosome five segmented. Genital somite longest part of urosome; anterior swollen part bears P6 represented by a genital flap armed with setae. Distal margin ornamented with spines ventrolaterally. Anal somite rectangle shaped; distal margin bears spines ventrolaterally. Caudal rami armed with six setae.A1 twelve segmented.The inner margin of proximal segment of the exopod ramus in P1-P4 bears compact dagger like setae and engorged portions of P1 basis bears a setae. P5 represented by an exopod armed with two naked setae.

Remarks: The samples collected in the present study could be identified to *genus Dioithona* on the basis of well-developed P5 with two setae. Further, identification to species *rigida* was based on several characters like twelve segmented non-geniculate antennule (A1);five segmented urosome, swollen anterior part of the genital segment which is wider than that of other urosomal segments, presence of compact dagger like setae on the inner margin of proximal segment of exopod ramus in P1-P4 and presence of spine on the engorged portion of P1. All these characters agreed very well to the previous descriptions of *D.rigida* female (Sewell, 1947; Mori, 1964; Wellershaus, 1970; Cheng & Zhang, 1974; Shuvalov, 1980; Nishida, 1985). Identification of these specimens based on morphology exposed only the characters which were similar to the morphology of female *D. rigida* described earlier. None of the characters were similar to that of a previously

described male specimen of this particular species which, in turn, endorsed a unisexual collection.

Distribution: South Africa, Arabian sea,Red sea,Gulf of Oman,Laccadive island, Maldives, Srilanka, India,Gulf of Mannar,Palk Bay, Indonasia, Bintulu Sarawak (http:// copepods. obs-banyuls.fr/en).

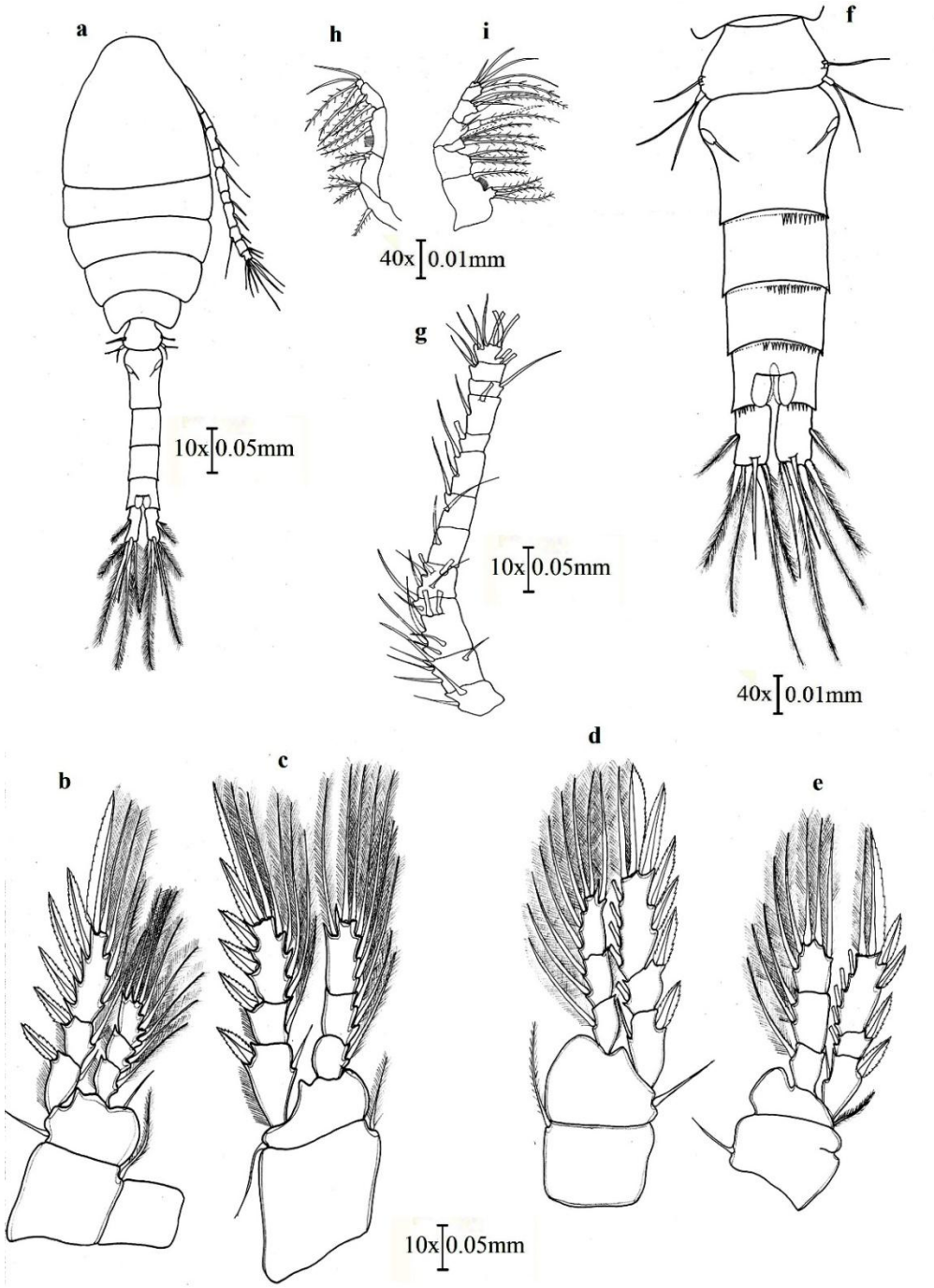


Fig.45.*D.rigida* female.a,Habitus;b-e,P1-P4;f,urosome

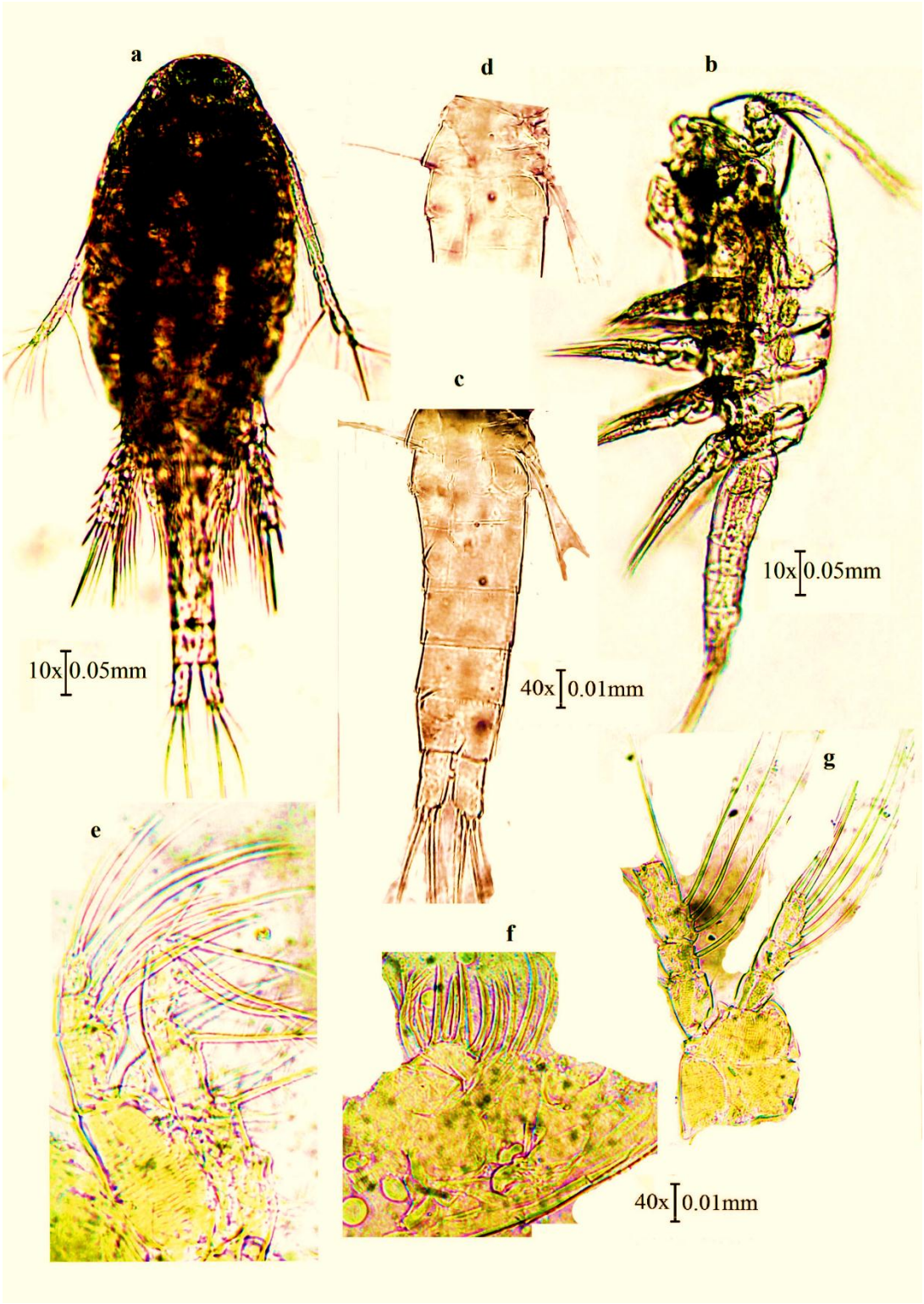


Plate.45. ***D.rigida*** **female.a, Habitus; b, Habitus (lateral) showing rostrum; c,urosome;d,P5;e, maxilla; f, maxillule; g,P4.**

Dioithona oculata Farran, 1913

Material examined: The samples were sorted out from plankton samples collected from Kalpeni, Minicoy, Agatti, Bangaram (Refer Table 3.1 and 3.2).

Female **(Fig.46,Plate 46)**Total length 0.68-0.8mm.Prosome robust oval or fusiform,five segmented; 2.11 times as long as wide and 1.52 times as long as urosome. Blunt rostrum which is not visible dorsally (Fig.46a).A1 long reaching upto 2nd metasomal segment (Plate.46d).Urosome five segmented,4.8 times longer than wide.GS 1.86 times as long as wide and swollen laterally at the proximal margin.AS 1.22 times longer than wide.P5 endopod with two seta. CR 1.6 times as long as wide. Proportional lengths GS:AS:CR is 9.7:5:8 (Fig.46b).

Remarks: This species is easily distinguished by the cephalic ganglia which forms a large bilobed mass. According to Ferrari (1980) in the female specimen, the setae of exopodal segment of P4 both modified and curved at the tip, GS armed with antero-dorsally curved spine and ventrally attached spermatophore. All these features of Caribean specimen very much agreed to that of Lakshadweep specimens too. Males were not observed during the present study. Farran considered this species to be more closely allied to *D.rigida* female which differ from *D.oculata* in the exopodal terminal spines shorter than terminal segments and comparatively larger size of the inner edge setae on the first segments of exopodites. The above said facts are strictly followed by the Lakshadweep specimens. It also agrees to Farran in the CR length width proportion being almost comparable (1.6 vs 2.5) respectively; rostrum being absent; P5 endopod with two setae. However it slightly differs in the PR:UR ratio being slightly higher (1.5 vs 1.42) and the same with that of Nishida (1977)(1.52 vs 1.45). Conversely, length of exopod 3rd segment in legs P1-P4 shorter than that of terminal spine of exopod 3rd segment; PR:UR ratio were comparable to that of Tanaka (1.52 vs 1.8).

Distribution: South Africa,Brazil, Mucuri estuary, Barbada Island, Caribbean, Colombia, Belize, Caribbean, Jamaica,Gulf of Mexico, Gulf of Oman, Arabian Gulf, Laccadive Island (lagoons), Madagascar, Rodrigues Island,Nicobar Island, Christmas Island, Straits of Malacca, China Seas (Yellow Sea, East China Sea),

Taiwan, Korea, Australia (New South Wales, Great Barrier, Coral reef, New Caledonia, Caroline Island (http:// copepods. obs-banyuls.fr/en).

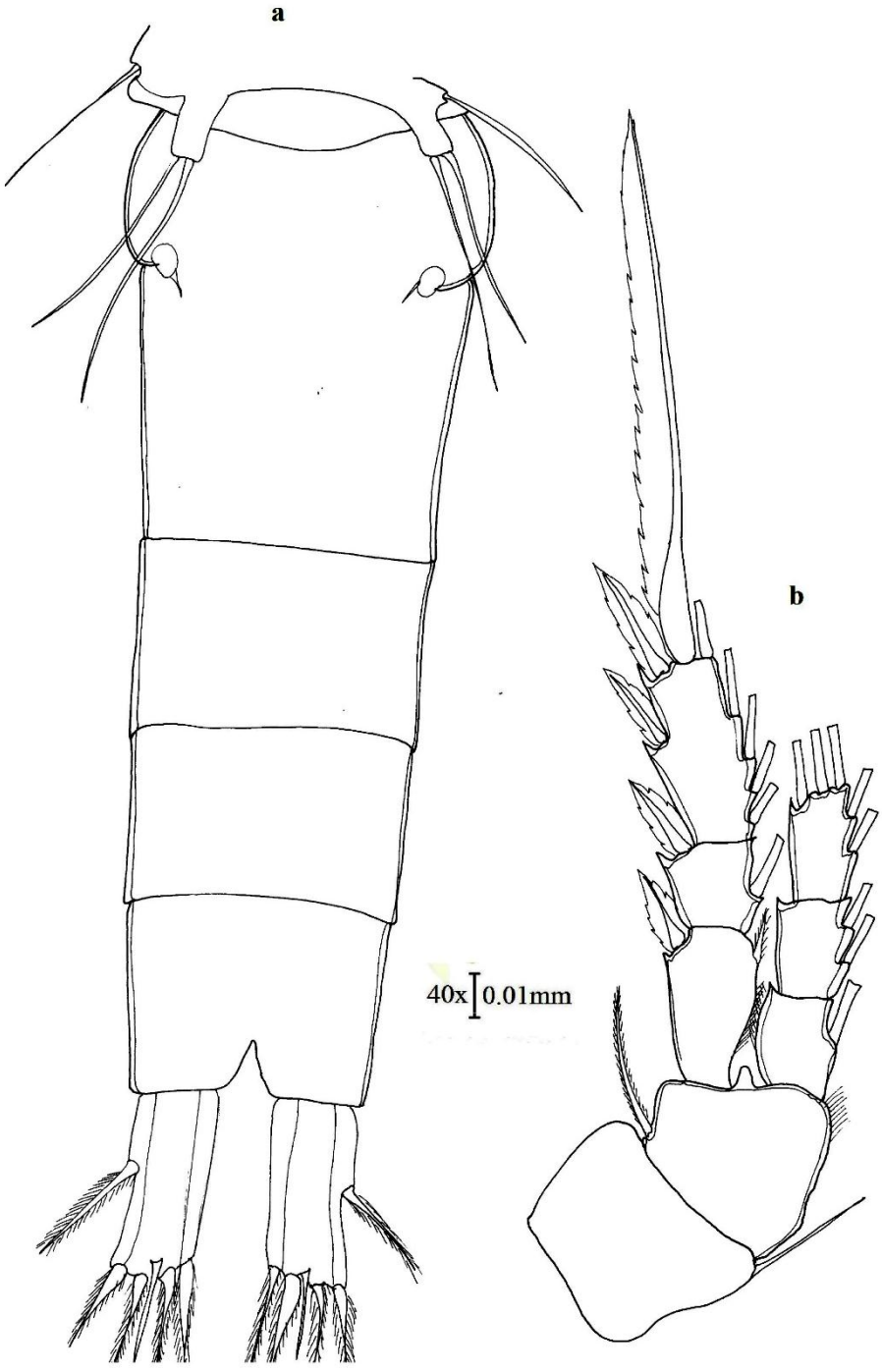


Fig.46.*D.oculata* female.b,Urosome;c,P4.

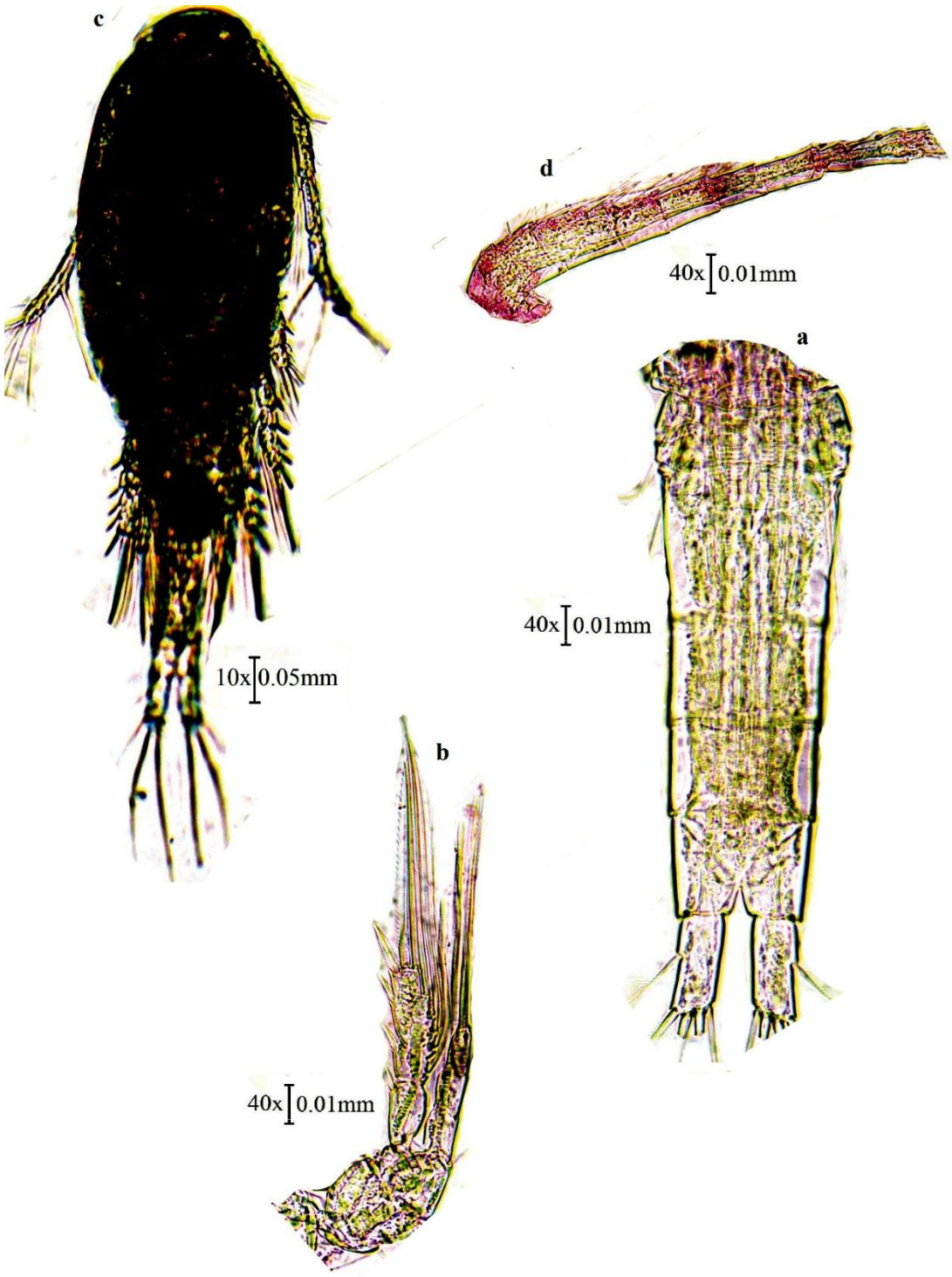


Plate.46. *D.oculata* female. a,Habitus;b,Urosome;c,P4;d,A1.

Sapphirina auronitens Claus, 1863

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

Female (Fig.47, Plate 47) Total length (+CR) 1.36-1.96mm.Cephalosome wider than long. Adjacent cuticular lenses visible dorsally. 1st metasomal segment not as wide as cephalosome, 2nd metasomal segment wider than 1st (Fig.47a).Urosome, 1.7 times long as wide, narrower than prosome, distal margin ornamented with minute spines ventrally. Caudal rami oval leaf like, 0.66 times wide as long (Fig.47c).Antennule (A1) 5 segmented (Fig. 47d).Antenna (Fig.47b) 4 segmented with coxa and basis fused and 3 endopodal segments. Coxobasis bears a short coxobasal spine at the inner distal margin. 1st endopodal segment robust,2.32 times longer than wide, bears short spine at its inner medial margin. 2nd endopodal segment, short, 0.87 times wide as long and is adorned with two curved lean spines at the inner distal corner. 3rd endopodal segment cylindrical, 3.84 times as long as wide at base, armed with 5 elements.Two slender naked spines arising from outer distal margin, 2 slender spines from inner distal margin and 1 terminal spine curved and drawn out as a claw.

Male (Fig 48,Plate 48) Total length (+CR) 1.84 -2mm.Prosome 1.50 times as long as wide; 1.80 times as long as urosome .Prosome wider than urosome(Fig.48a).Lateral flaps of the urosome possess a hook like process on its tip. Distal margin of urosome ornamented with minute spines ventrally. Antenna(Fig.48b) bears a short coxobasal spine at the inner distal margin. 1st endopodal segment robust and long; thrice as long as wide; bears a short endopodal spine medially. 2nd endopodal segment 1.73 times long as wide is short and adorned with 3 spines of unequal length at the inner distal end. 3rd endopodal segment 4.26 times as long as wide is armed with 4 elements.2 slender spines arising from outer distal corner; a thin spine from the inner distal margin and a terminal spine drawn out as a claw.A1 five segmented (Fig.48c).Caudal rami similar to that of female. (Fig.48e)

Remarks and discussion: When the morphological characters of *S.auronitens* described in the present study were evaluated, salient features in both sexes like cephalosome wider than long; dorsally visible cuticular lenses; ovate caudal rami; five segmented antennule; longer second segment of A1 than three following

segments together and presence of a hook like process on the last endopod segment of P2, the last segment of A2 more than twice longer than terminal claw in males; fully agreed to the descriptions employed by Scott(1909);Mori (1964);Crusafi& Mazza (1966);Giesbrecht (1892);Wilson (1932).

Distribution: Meditteranean Sea, Black Sea, Japan Sea, North west and Central tropic Pacific Ocean, Gulf of Thailand, Malaysia, Indonesia, Philippines, Indian Ocean (http:// copepods. obs-banyuls.fr/en).

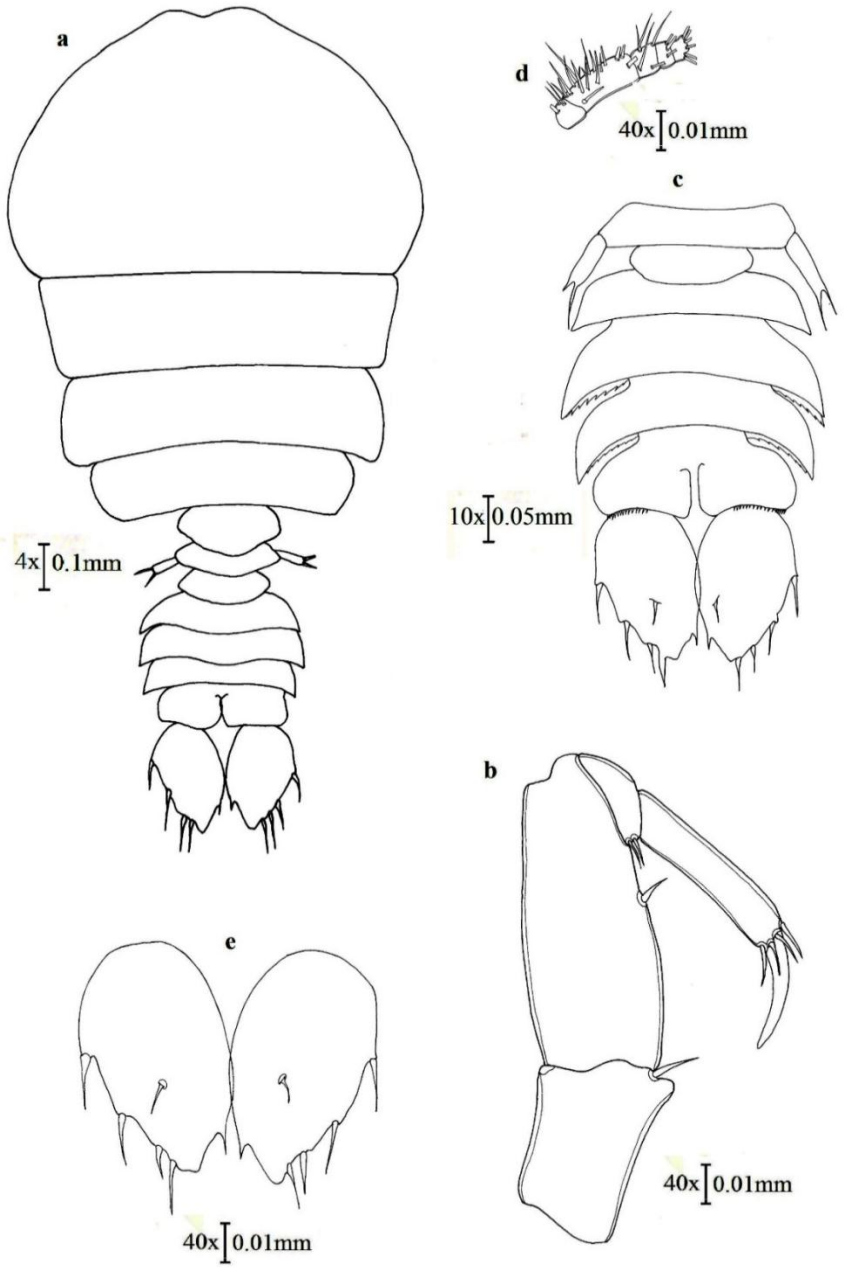


Fig.47.*S.auronitens* female.a,Habitus;b,A2;c,Urosome;d,A1;e,CR.

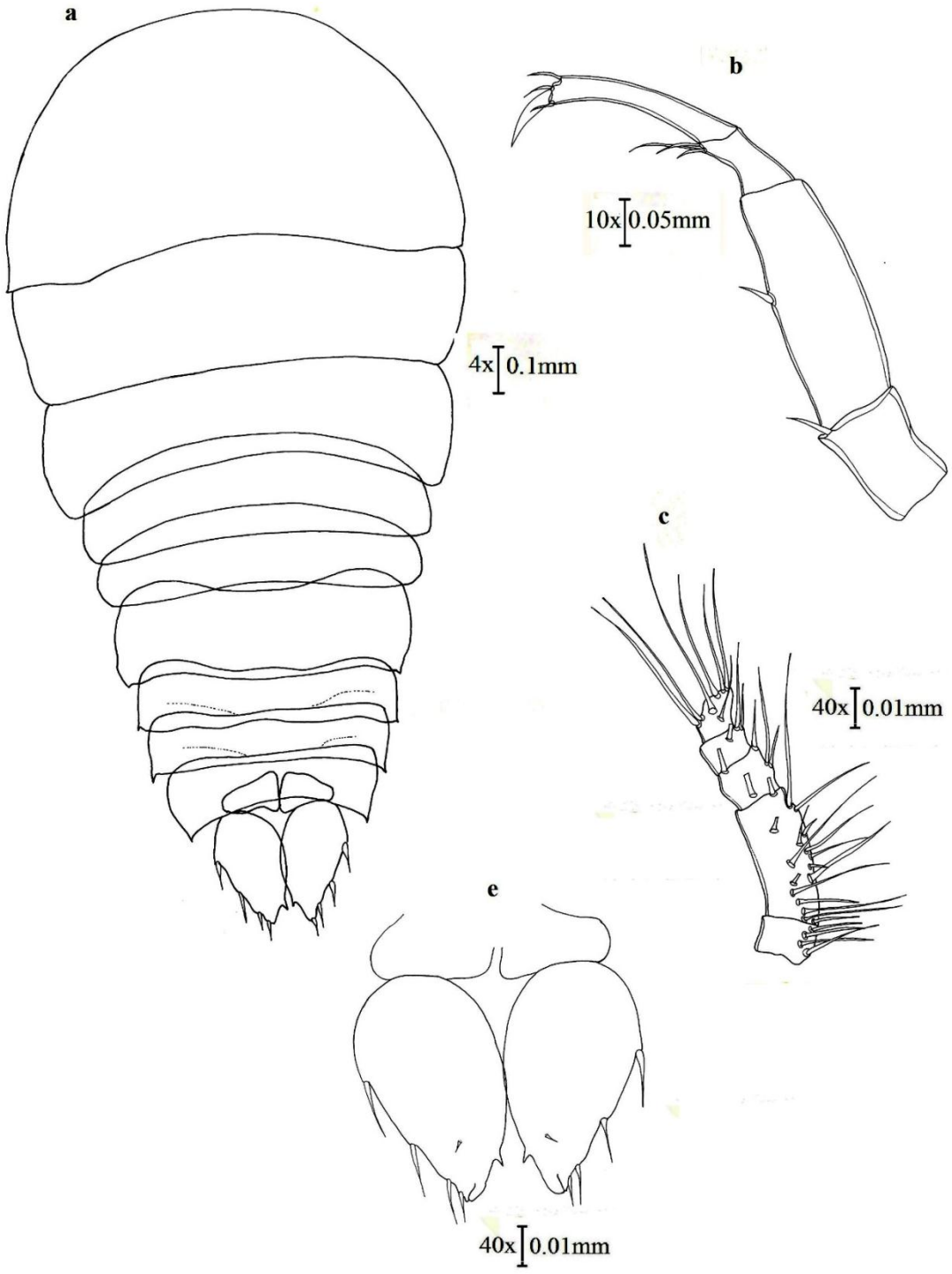


Fig.48.*S.auronitens* male. a,Habitus;b,A2; d,A1;e,CR.

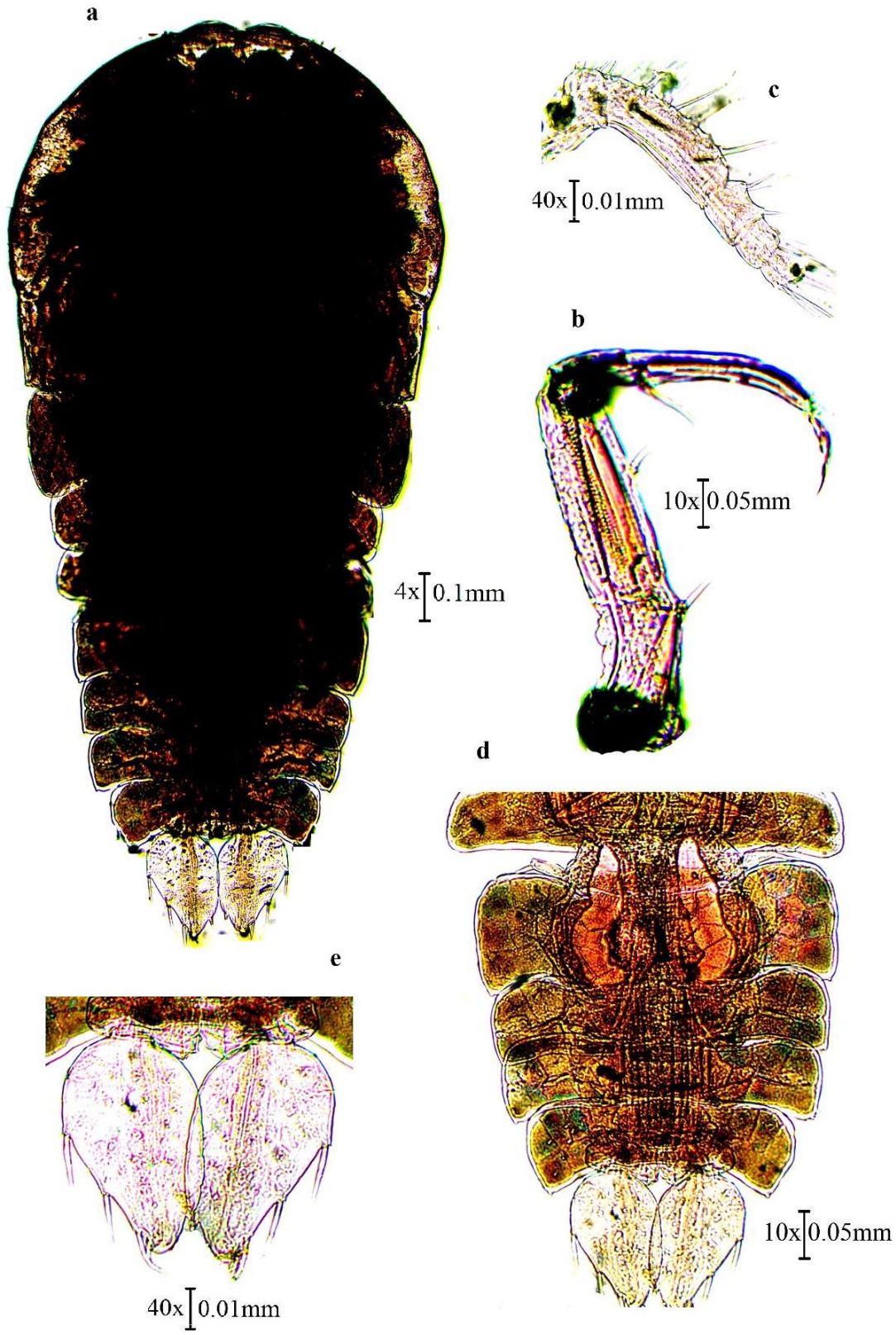


Plate.48. *S.auronitens* male.a,Habitus;b,A2;c,A1;d,Urosome;e,CR.

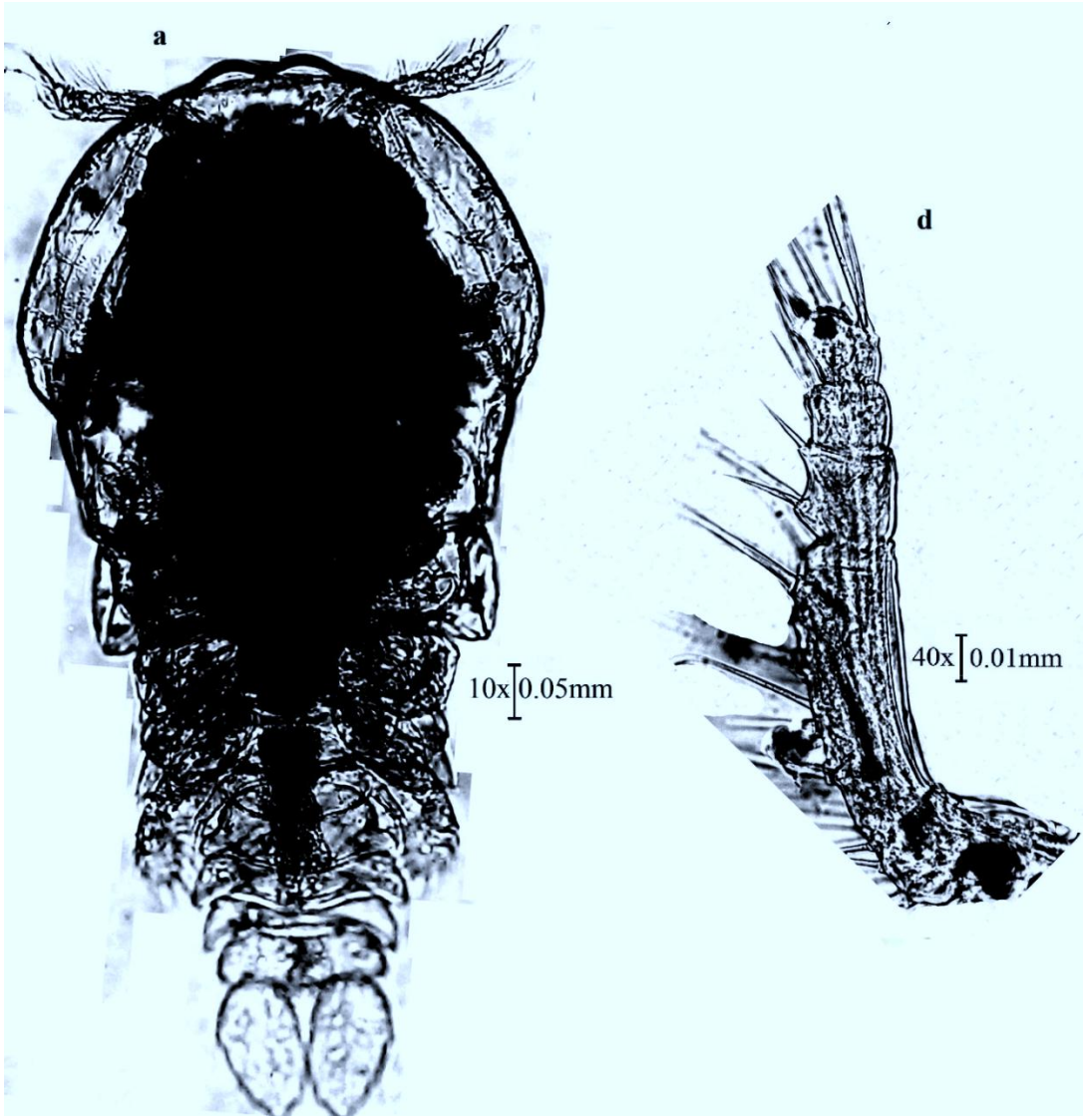


Plate.47.*S.auronitens* female. a, Habitus; d,A1.

Sapphirina metallina Dana, 1849

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

Female (Fig.49, Plate 49) Total length (+CR) 1.82-2mm .Elongated body with cuticular lenses adjacent and visible dorsally.Cephalosome 1.19 times wider than long. Cephalosome length approximately half of prosome length. Length of prosome 1.76 times long as urosome (Fig. 49a). Quadrangular shaped caudal rami, unlike other species which is as long as wide and with two long foliacious spines of

the distal margin. The posterior distal margin ornamented with numerous spines (Fig. 49d).Antenna (Fig. 49b) four segmented with coxa and basis fused and three endopodal segments. Length of coxobasis twice as long as wide bearing two uniramous spines at the inner distal margin.Endopod unequal in length;1stendopodal segment robust, moderately rectangular and longest among three. Inner proximal margin bears endopodal spine shorter than coxobasal spine. The proximal outer margin adorned with numerous small spines. 2ndendopodal segment triangular in shape bearing three unequal elements 1) 2 unequal thin spines at the inner distal margin 2) spine at the tip of the segment.3rd endopodal segment bears a terminal spine drawn out as a claw. The outer distal margin of the claw bears 2small spines. Antennule 6 segmented (Fig. 49c)

Male(Fig.50,Plate50) Total length (+CR)1.76-2.05mm.Dorsoventrally flattened and cyclindrical body with cuticular lenses adjacent and visible dorsally. Width of the prosome 1.25 times as wide as urosome (Fig.50a).Antenna (Fig. 50b) and CR (Fig. 50d). similar to that of females. Antennule (A1) 6 segmented (Fig. 50c).

Remarks: The specimens of *S.metallina* described here also exhibited full agreement to previous descriptions (Scott,1909;Mori, 1964; Crusafi&Mazza, 1966; Giesbrecht, 1892;Zheng et.al,1982) which included the presence of two spines on the first segment of antenna; quadrangular shaped caudal rami with two fallacious terminal setae; endopod of P2 ending in 3 foliaceous spines and 6 segmented antennule; in both sexes.

Distribution: Carribean Sea, Sargasso Sea, Red Sea, Meditteranean Sea, Black Sea, Japan Sea, North west and Central tropic Pacific Ocean, Central South Atlantic(http:// copepods. obs-banyuls.fr/en).

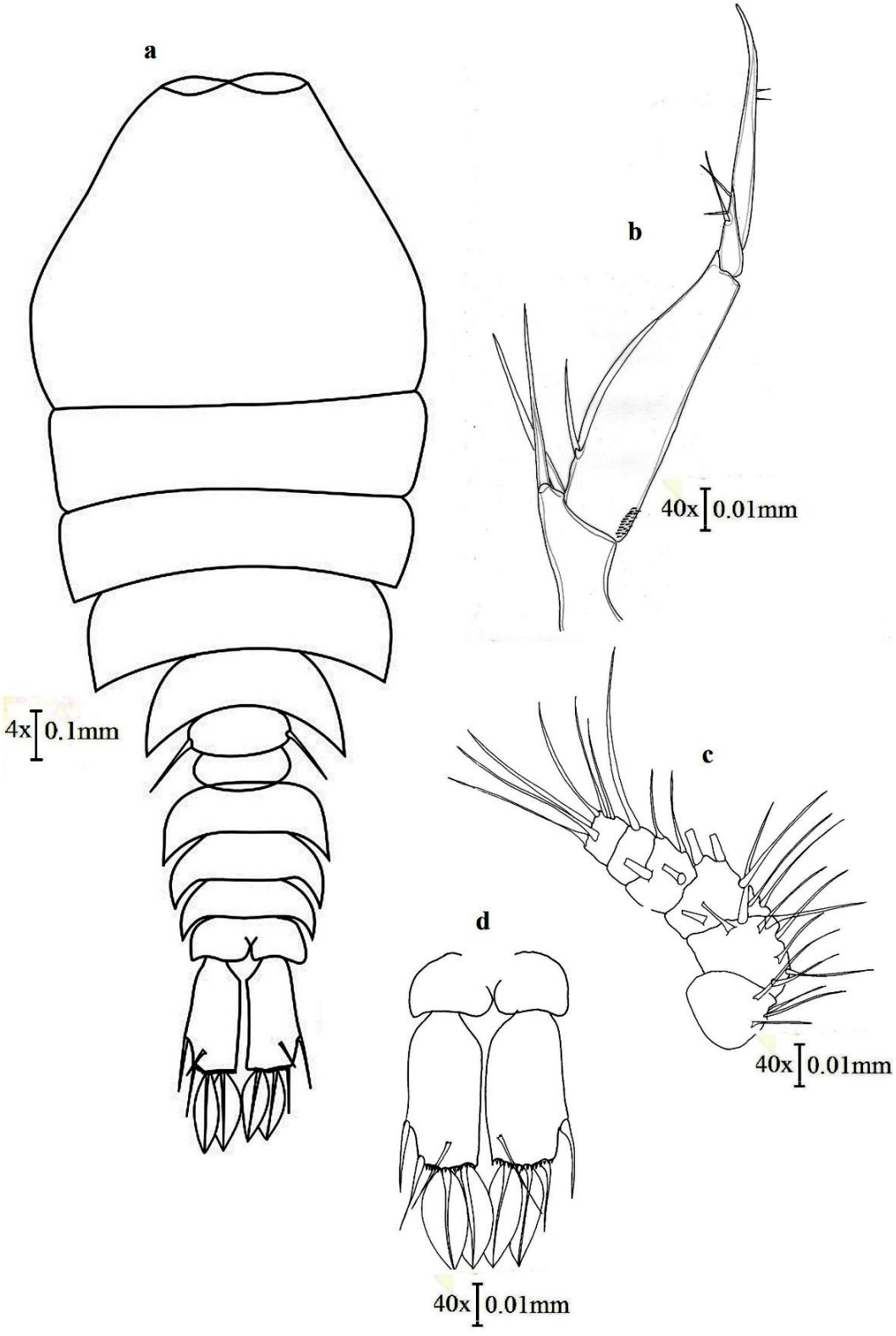


Fig.49.*S.metallina* female.a,Habitus;b,A2;c,A1;d,CR.

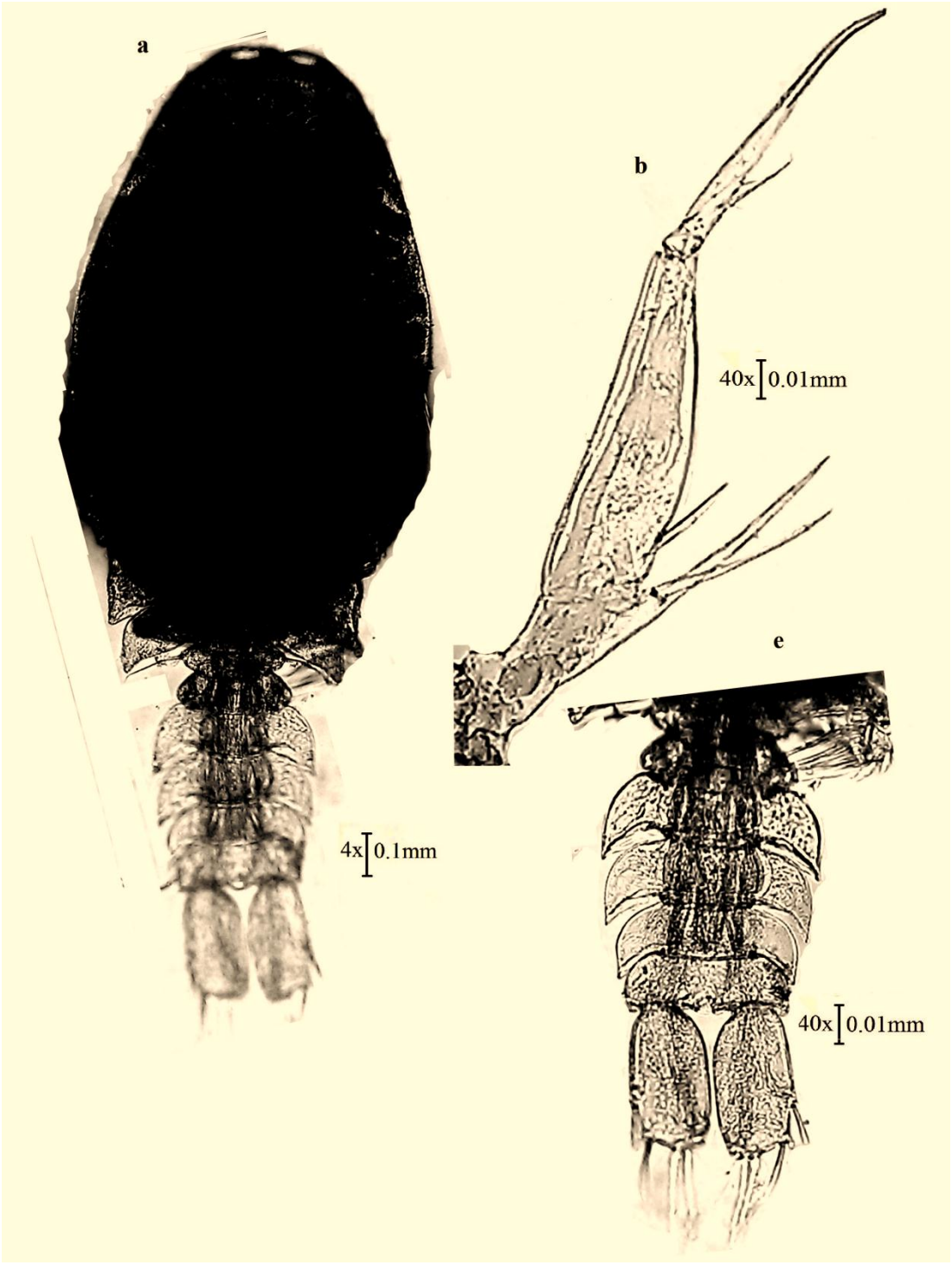


Plate 49. *S.metallina* female.a,Habitus;b,A2;e,Urosome.

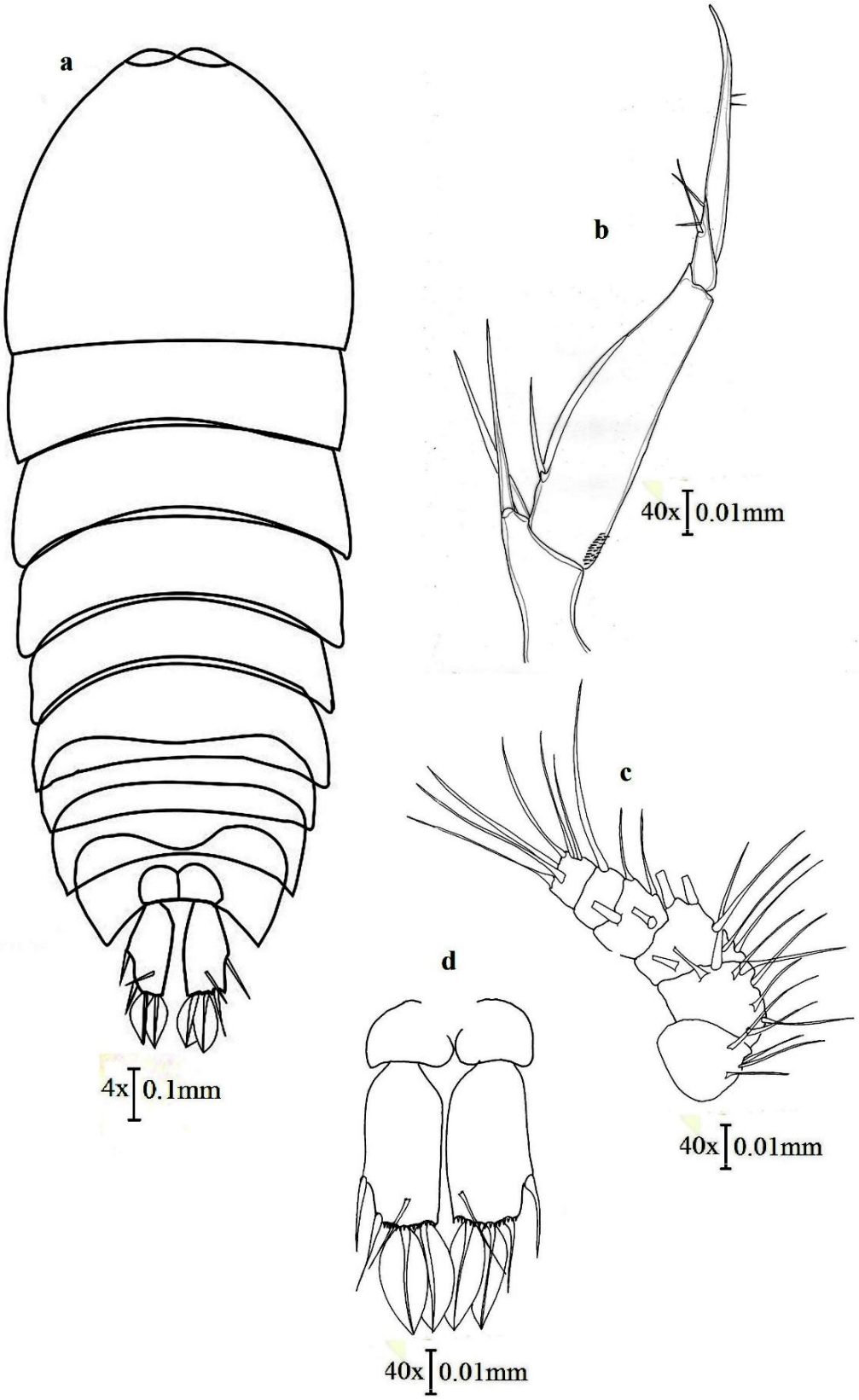


Fig.50.*S.metallina* male.a, Habitus; b,A2;c,A1;d,CR

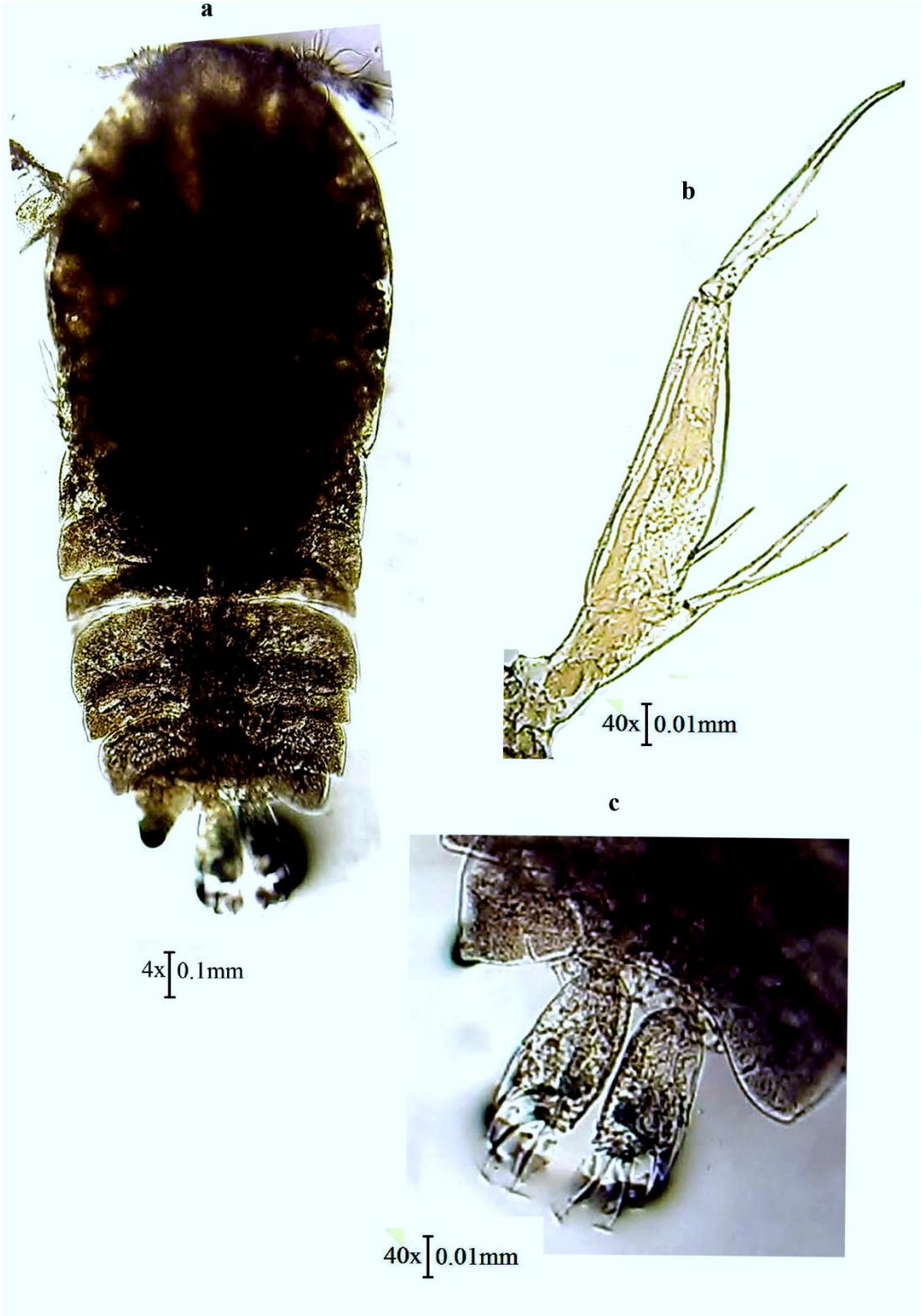


Plate.50.*S.metallina* male.a,Habitus;b,A2;c,CR.

Sapphirina opalina Dana,1849

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

Female (Fig.51,Plate.51) Total length(+CR) 1.91-2.5mm.Cephalosome 1.8 times wider than length. Prosome 1.96 times long as urosome. Prosome 2.32 times wider than urosome. Prosome anteriorly rounded and cuticular lenses visible dorsally. Lateral projections present which is pointed dorsally but blunt ventrally (Fig.51a).Caudal rami as long as wide. Antennule (Fig. 52a) 3 segmented. Antenna (Fig. 52b)4 segmented; longer than A1; with coxa and basis fused and three endopodal segments. Coxobasis 0.83 times wide as long; bears a setae along the inner distal margin; twice as long as wide. 1st endopodal segment; moderately rectangular 1.25 times as long as wide; bears a seta along the mid-inner distal margin.2nd endopodal segment 1.25 times as long as wide. Inner margin with 3 thin spines. 3rd endopodal segment, cylindrical and long ,thrice as long as wide bears six thin spines arising from the tip arranged diagonally and terminal spine which is drawn out as a claw.

Male (Fig.52, Plate 52) Total length (+CR) 1.4 -2.34mm (Fig. 51b).Prosome anterior rounded; slightly wider than urosome. Cuticular lenses separate and visible dorsally. Caudal rami similar to female. Antennule three segmented. Antenna (Fig.52c) with coxobasis fused with a short coxobasal spine and 3 endopodal segments. 1st endopodal segment bears a short spine. 2nd endopodal segment bears two thin spines at the inner distal corner. 3rd endopodal segment cylindrical with 4 elements; two spines on the outer margin and one at the inner margin and terminal spine drawn out as a claw.

Remarks: Morphological features of *S.opalina* male species like wider anterior round cephalosome; five segmented urosome and three segmented antennule and 4th segment of A2 longer than the terminal claw; in both sexes also exhibited close morphological proximity to *S.opalina* described previously (Scott, 1909; Mori, 1964; Crusafi&Mazza,1966; Giesbrecht, 1892;Zheng et.al,1982).

Distribution: Indian Ocean, Carribean Sea, Sargasso Sea, Red Sea, Meditteranean Sea, Black Sea, Japan Sea, North west and Central tropic Pacific Ocean, Central South Atlantic (http:// copepods. obs-banyuls.fr/en).

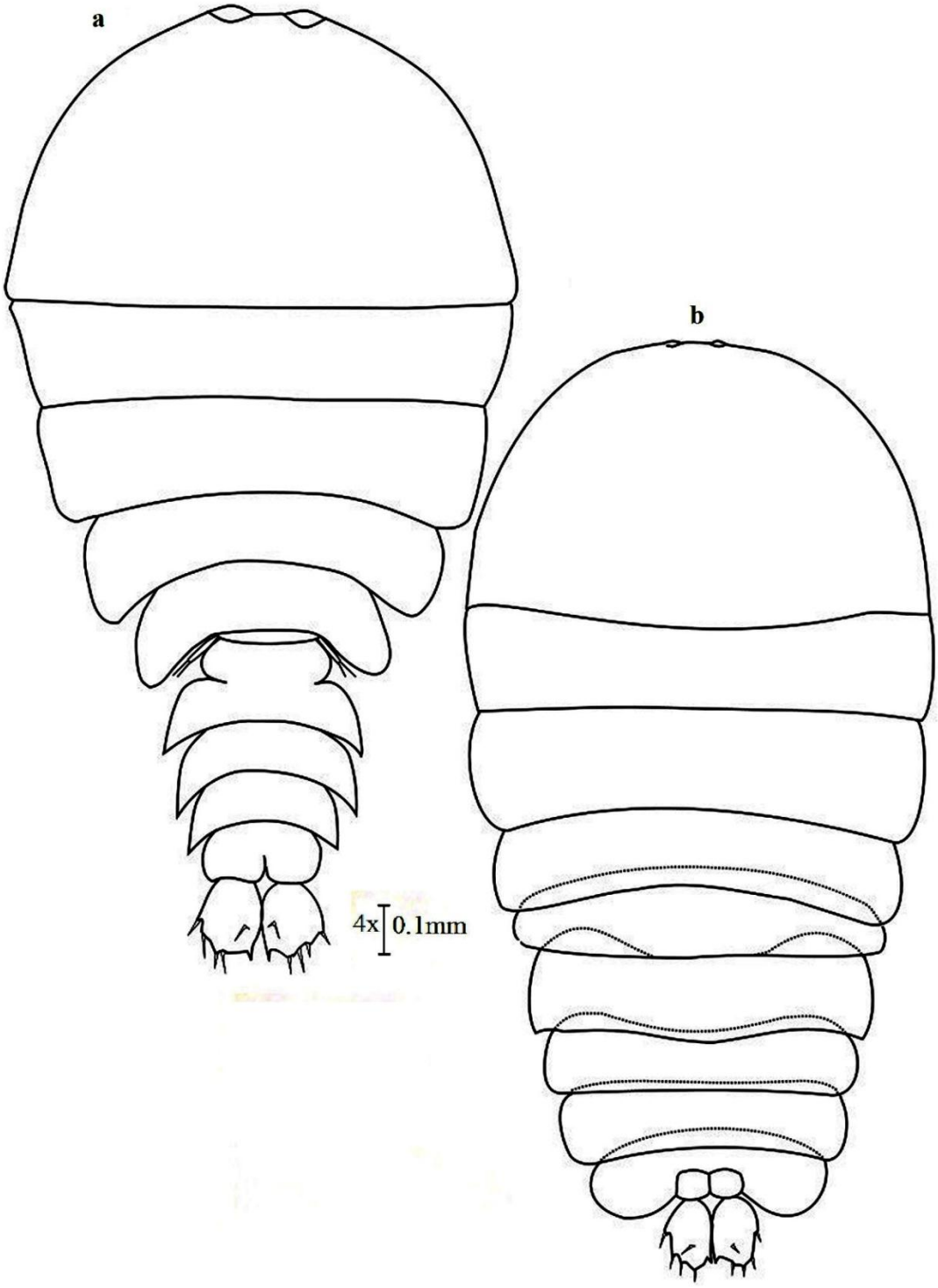


Fig 51.*S.opalina* female and male.a,Habitus (Female); b,Habitus(male).

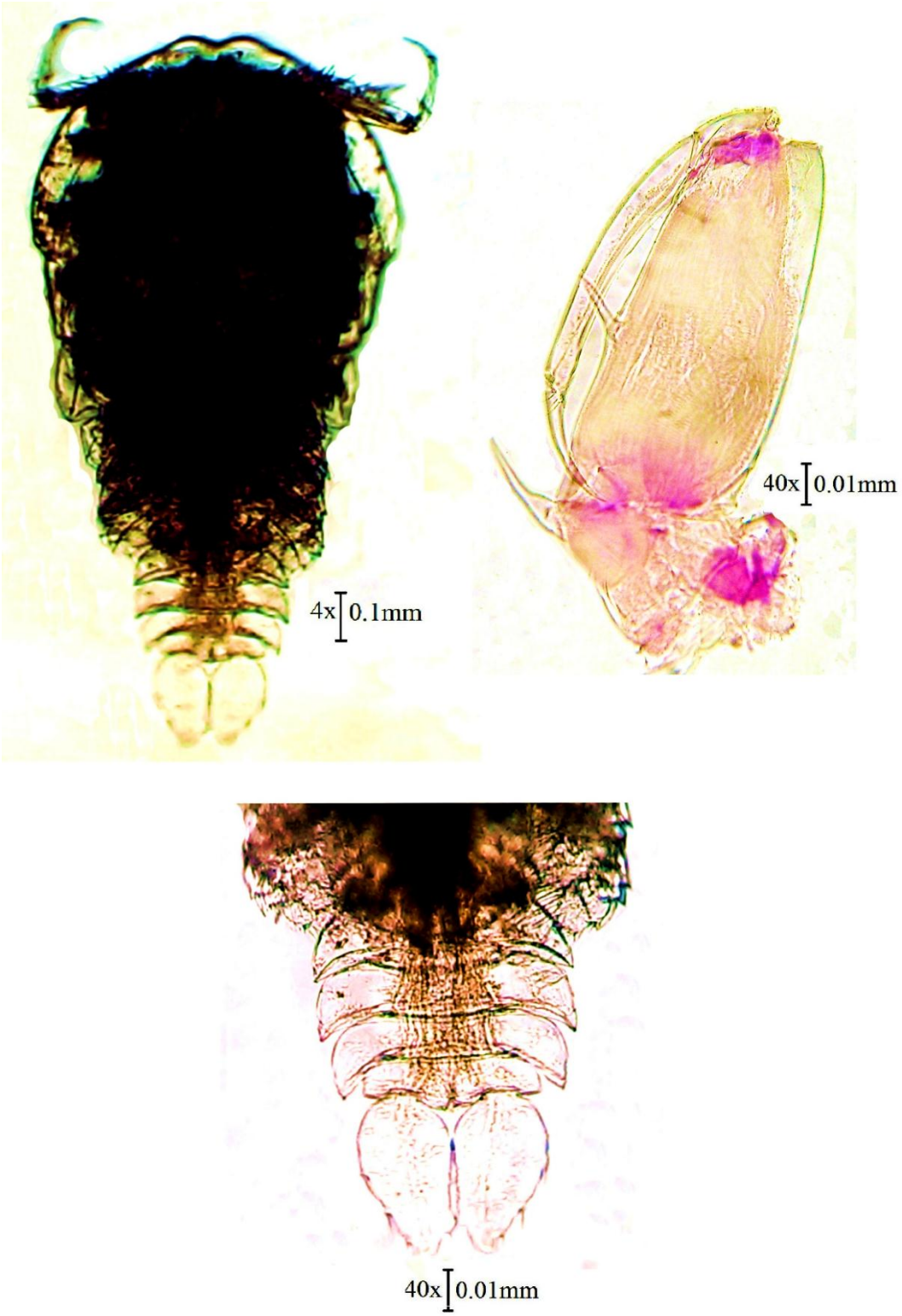


Plate.51.*S.opalina* female.a, Habitus;b,A2;c,Urosome.

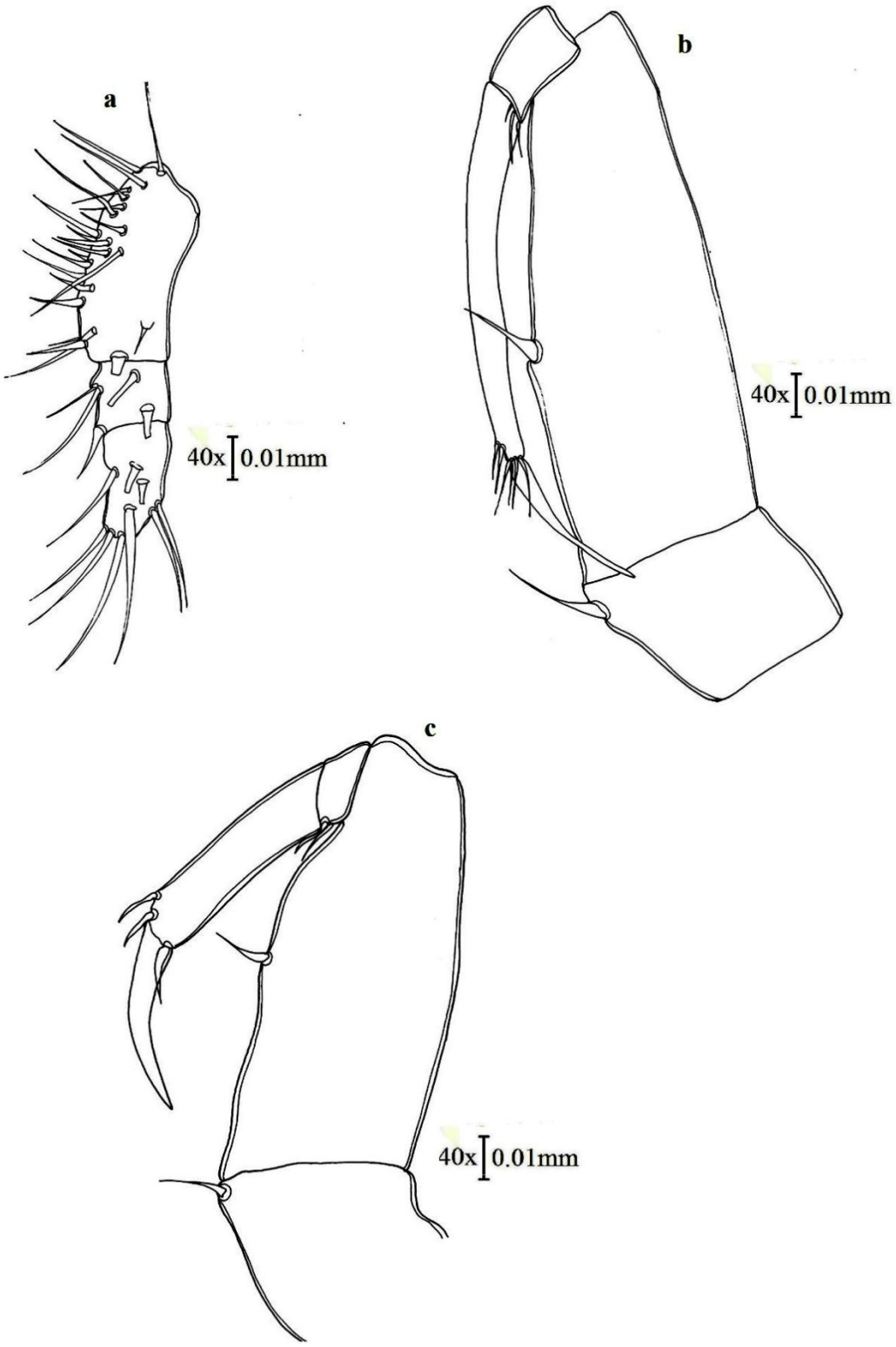


Fig 52.*S.opalina* female and male.a,A1;b,A2 (female);c,A2 (male).

Plate.52.*S.opalina* male. , Habitus; b, A2; c, A1.

***Sapphirina angusta* Dana, 1849**

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

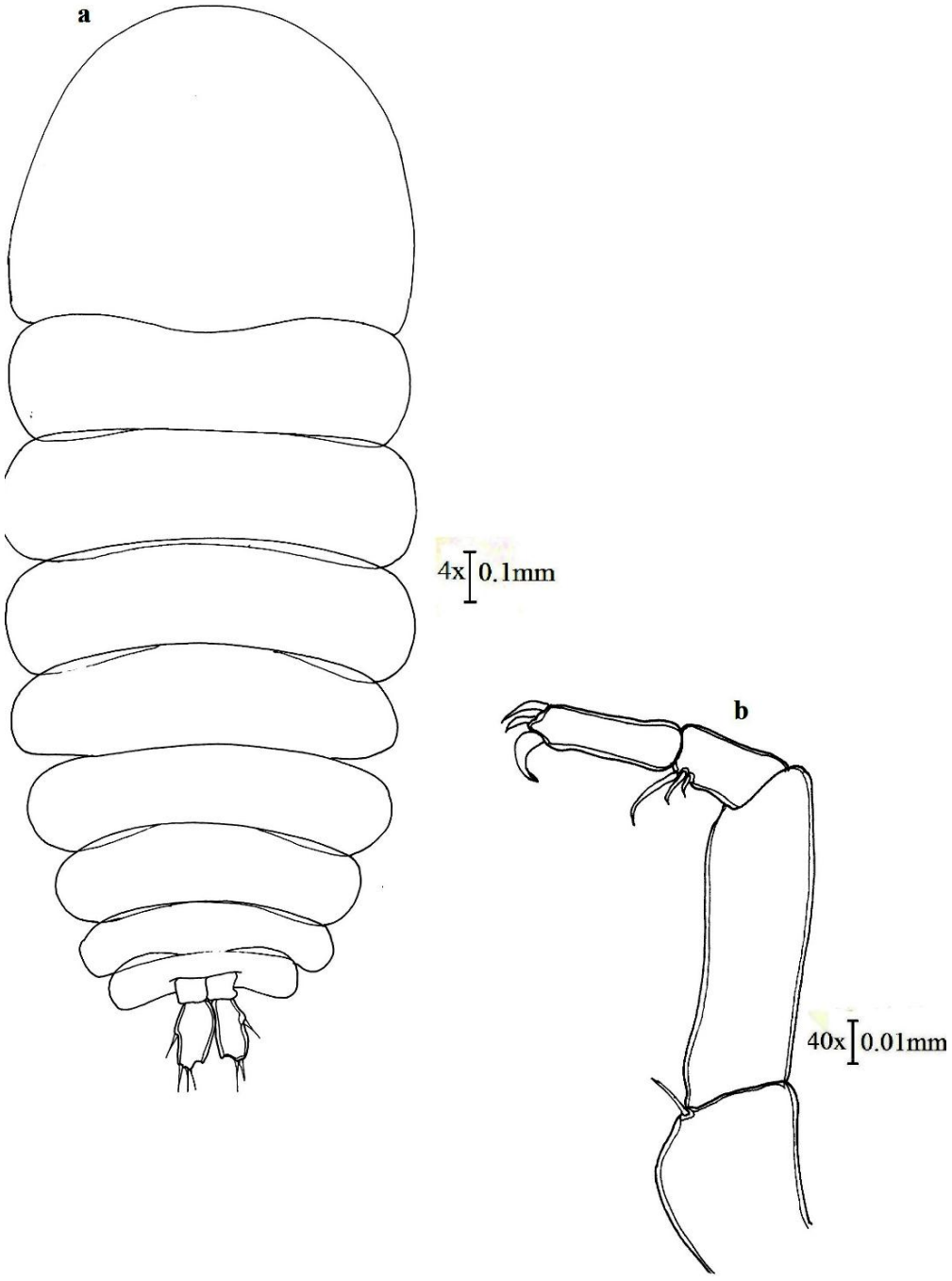


Fig.53.*S.angusta* male.a, Habitus;b,A2.

Male (Fig.53, Plate 53) Total length (+CR) 3.45-3.5mm. Semitransparent elongate depressed body. Cephalosome, anteriorly rounded 1.23 times wider than long. Prosome 1.76 times as long as wide and thrice as long as urosome (Fig. 53a).First

four metasomal segments wider than cephalosome. CR 1.72 times as long as wide. Antenna (Fig. 53b) four segmented with coxa and basis fused and three endopodal segments. Coxobasis bears a small setae along the inner distal margin. Endopodal segments unequal in length. 1st endopodal segment; moderately rectangular 3.04 times as long as wide and bears no seta. 2nd endopodal segment 1.66 times as long as wide. Inner margin with three thin unequal spines. 3rd endopodal segment, cylindrical and long ,thrice as long as wide bears three spines arising from the tip arranged diagonally and terminal spine which is drawn out as a claw.

Remarks: Th**e** combination of distinctive characters like 1) Semitransparent ovate depressed body; 2) Dorsally not visible cuticular lenses; 3) first 3 metasomal segments wider than the cephalosome; 4) CR approximately twice as long as wide ;confirmed the taxonomic identity of *S.angusta* male species. Only male specimens could be obtained.

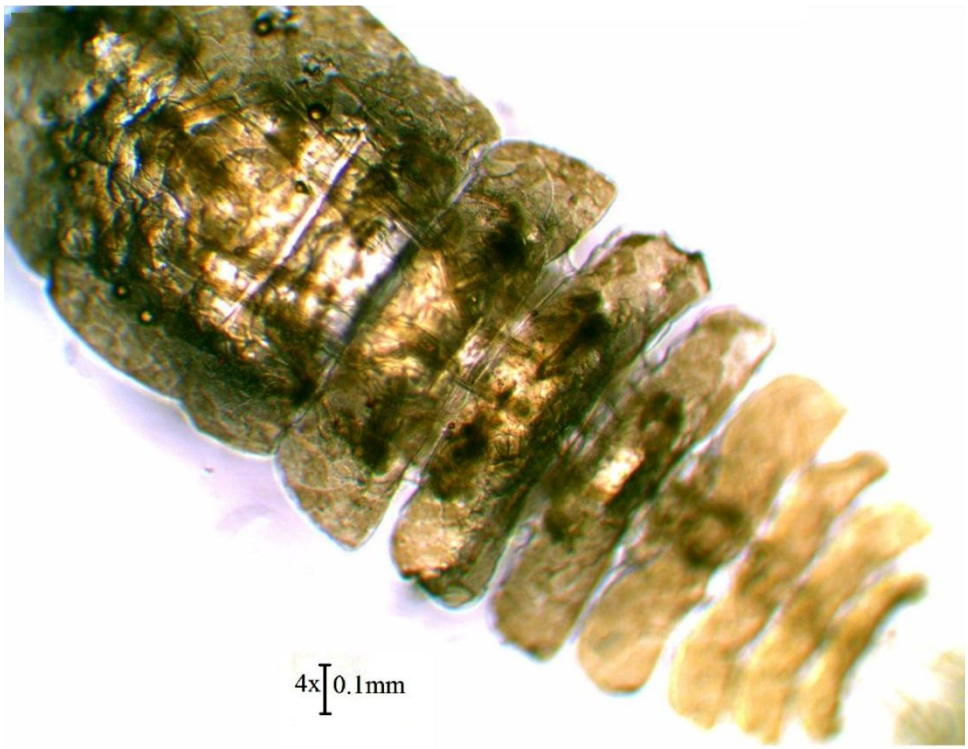


Plate.53.*S.angusta* male.a, Habitus

Distribution: Carribean Sea, Sargasso Sea, Arabian Sea, Indian Ocean, Arabian Gulf, Madagascar, Yellow Sea, China Sea, Indonasia, Pacific and Atlantic Ocean (http:// copepods. obs-banyuls.fr/en).

Sapphirina scarlata Giesbrecht , 1891

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean zones (CR#338) (Refer Table 3.2).

Female (Fig.54,Plate54) Total length(+CR)1.79-2.6mm.Cephalosome moderately broad, 1.46 times wider than long. Adjacent cuticular lenses just visible dorsally. Prosome 1.46 times longer than urososme (Fig.54a).UR narrower than PR; 2.05 times as long as wide.CR narrowly ovate; 1.66 times as long as wide; dorsal setae in front of the 1st marginal setae. Apical process present on the inner distal margin (Fig.54b).A1 5 segmented (Plate.54d). P4 endopod approximately half the length of the exopod. A2 four segmented with coxa and basis fused and 3 endopodal segments. Coxobasis bears a short coxobasal spine at the inner distal margin. First endopodal segment robust, 2.52 times longer than wide, bears short spine at its inner medial margin. Second endopodal segment, short, 1.22 times long as wide and is adorned with three short spines at the inner distal corner of which one is curved. Third endopodal segment cylindrical, 6 times as long as wide at base, armed with four elements. Two slender naked spines arising from outer distal margin, one from the medial margin, one from inner distal margin and 1 terminal spine long curved, drawn out as a claw (Fig.54b)

Male (Fig.55, Plate.55) Total length (+CR) 2.6-2.7mm.Cephalosome broad, 1.73 times wider than long. Prosome 1.75 times longer than urososme (Fig.55a).UR narrower than PR; 1.02 times as long as wide.CR narrowly ovate; 1.76 times as long as wide (Plate.55b) A1 five segmented. A2 four segmented with coxa and basis fused and three endopodal segments. Coxobasis bears a short coxobasal spine at the inner distal margin. 1st endopodal segment robust, 2.77 times longer than wide, bears short spine at its inner medial margin. 2nd endopodal segment, short, 1.55 times long as, ornamented with three short spines at the inner distal corner of which one is curved. 3rd endopodal segment cylindrical, 5.41 times as long as wide at base, armed with one element which is long curved, drawn out as a claw (Fig.55b).

Remarks and Discussion: Mori, 1964 could report only the female species but Giesbrecht, 1892 and Lehnhofer,1929 reported both sexes. The combination of distinctive characters in both sexes such as 1) CR narrowly ovate that is less than twice as long as wide; 2) CR inner distal margin produced into a well defined apical

process; 3) adjacent lenses not visible dorsally ;in both sexes provided a taxonomic status of *S.scarlata* species. All these features along with certain features of female specimens like 1) cephalosome approximately 1.49 times as long as wide; 2)A2 first segment (coxobasal segment) with one spine; were consistent with the description by Scot (1909); Giesbrecht (1892); Lehnhofer (1929); Chen and Zhang (1974). This confirmed the morphological identity of the species which in turn was again substantiated by molecular studies as distinct species.

Distribution: *S.scarlata* has been recorded from Atlantic, Indian and Pacific oceans, Mediterranean Sea and Madagascar (http:// copepods. obs-banyuls.fr/en).

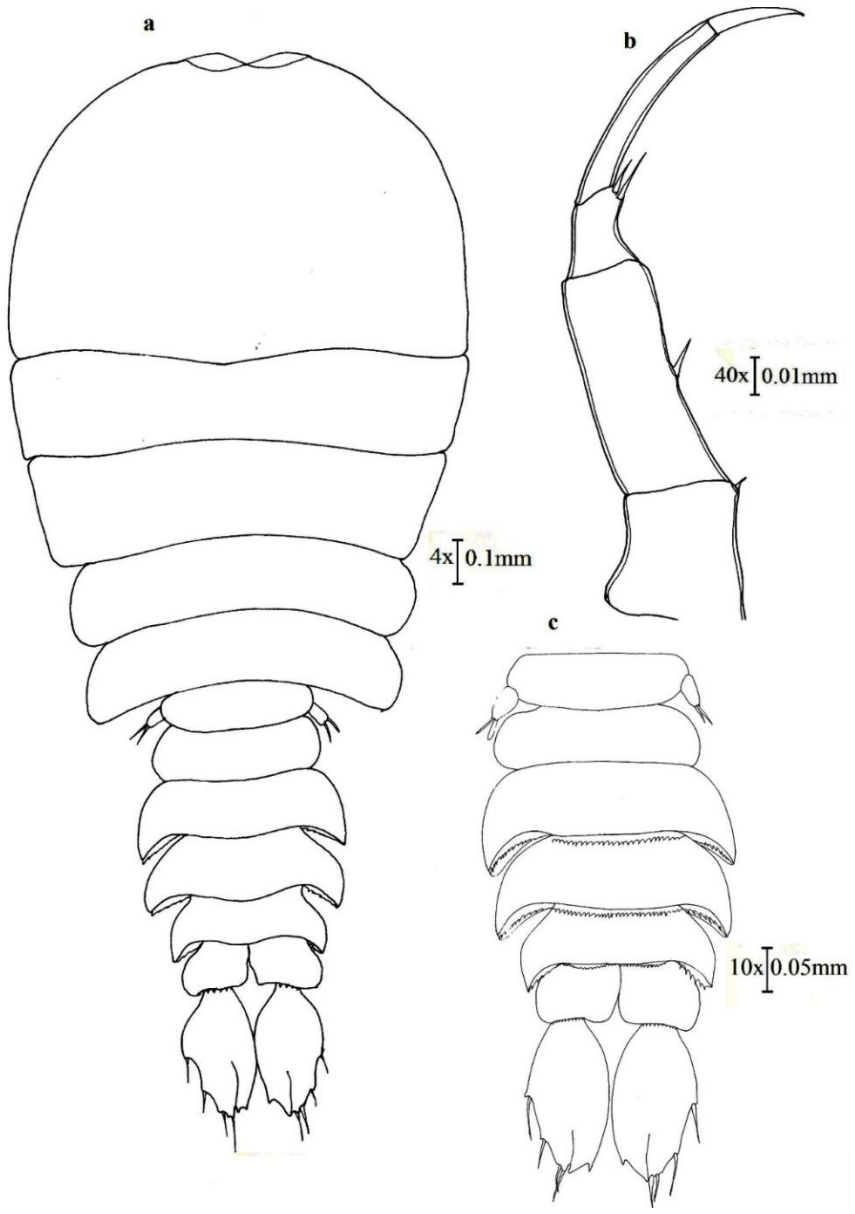


Fig.54.*S.scarlata* female.a, Habitus;b,A2;c,Urosome.

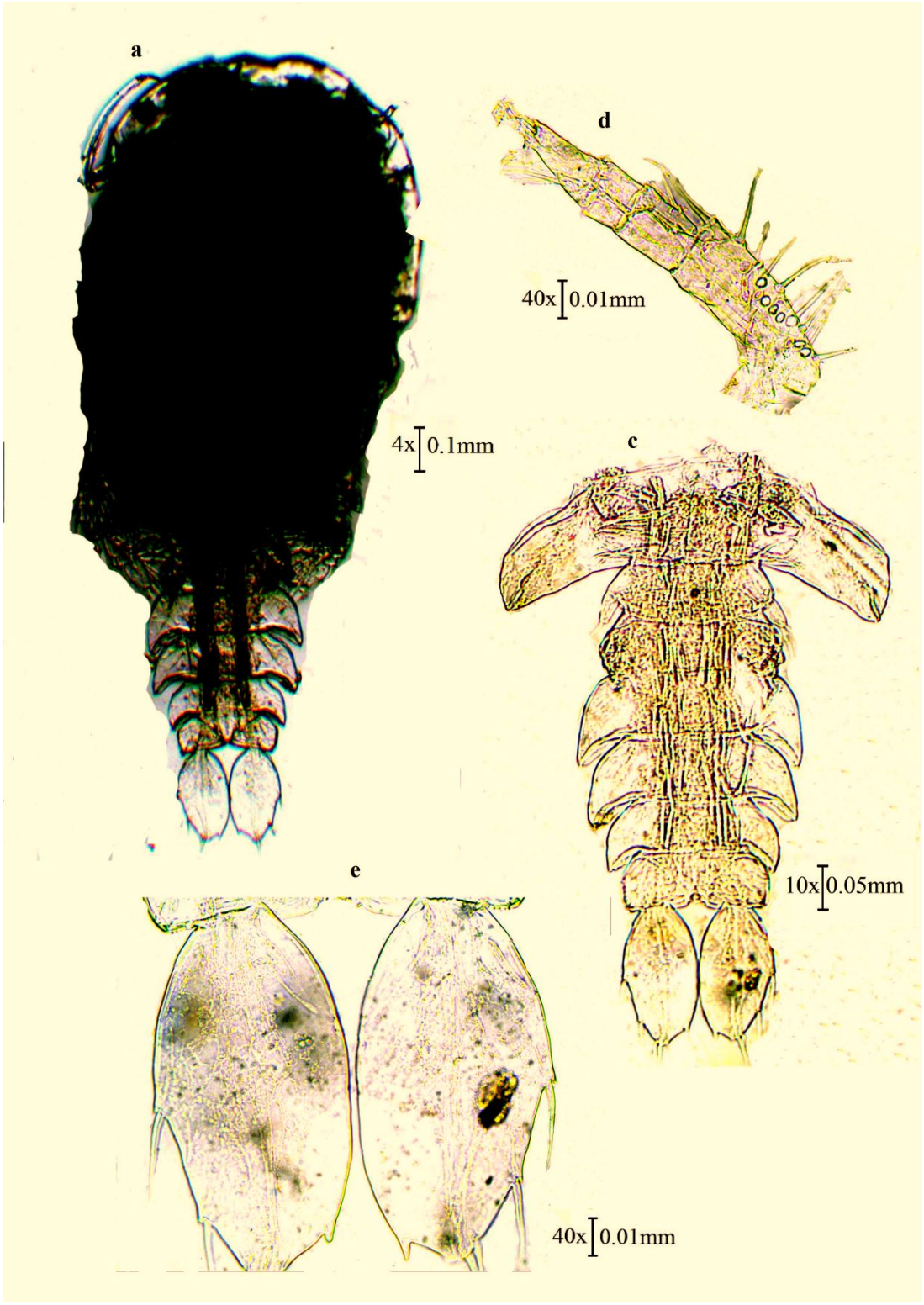


Plate.54. *S.scarlata* female. a, Habitus; c,Urosome;d,A1;e,CR.

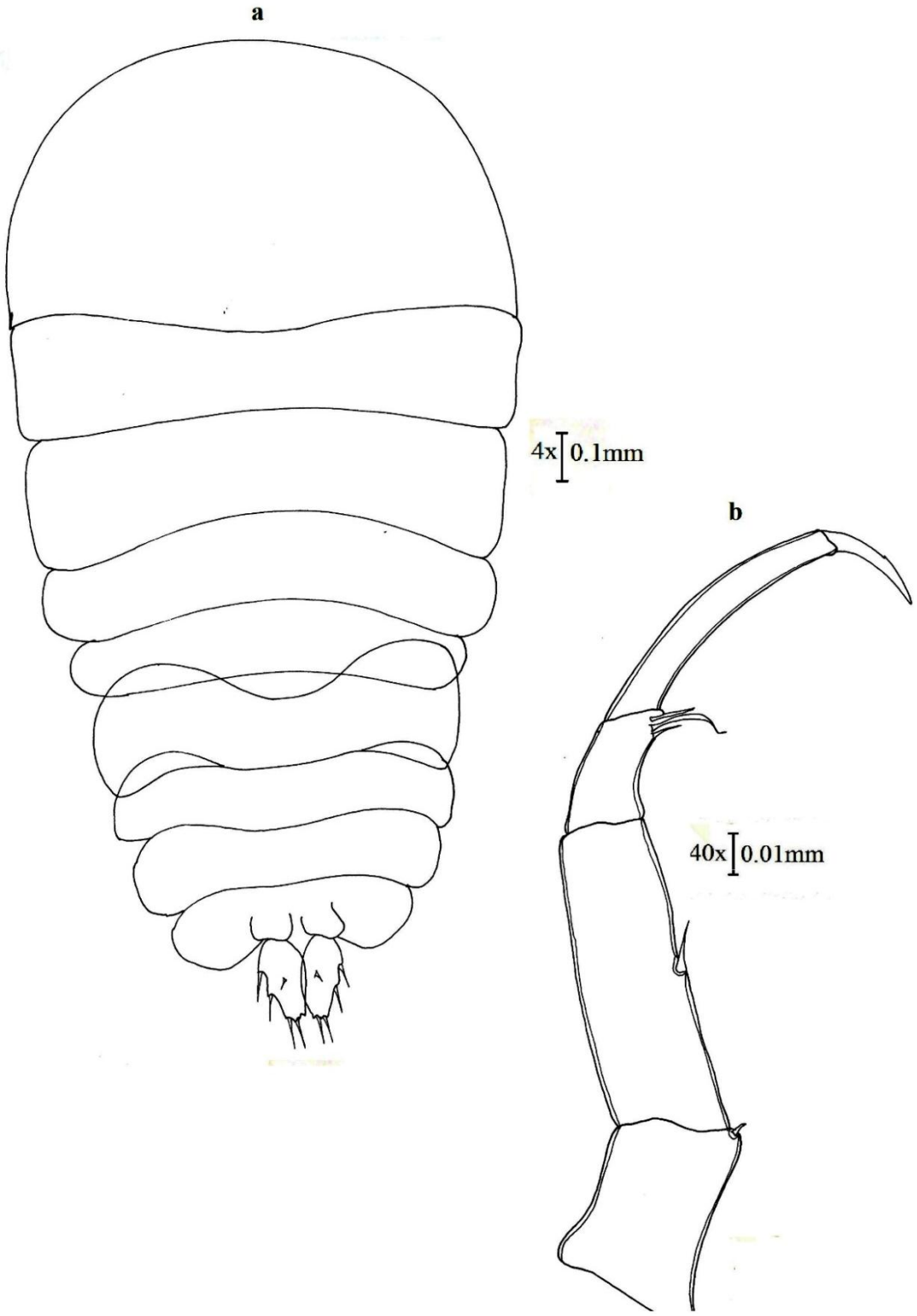


Fig.55.*S.scarlata* male.a,Habitus;b,A2;c,Urosome.

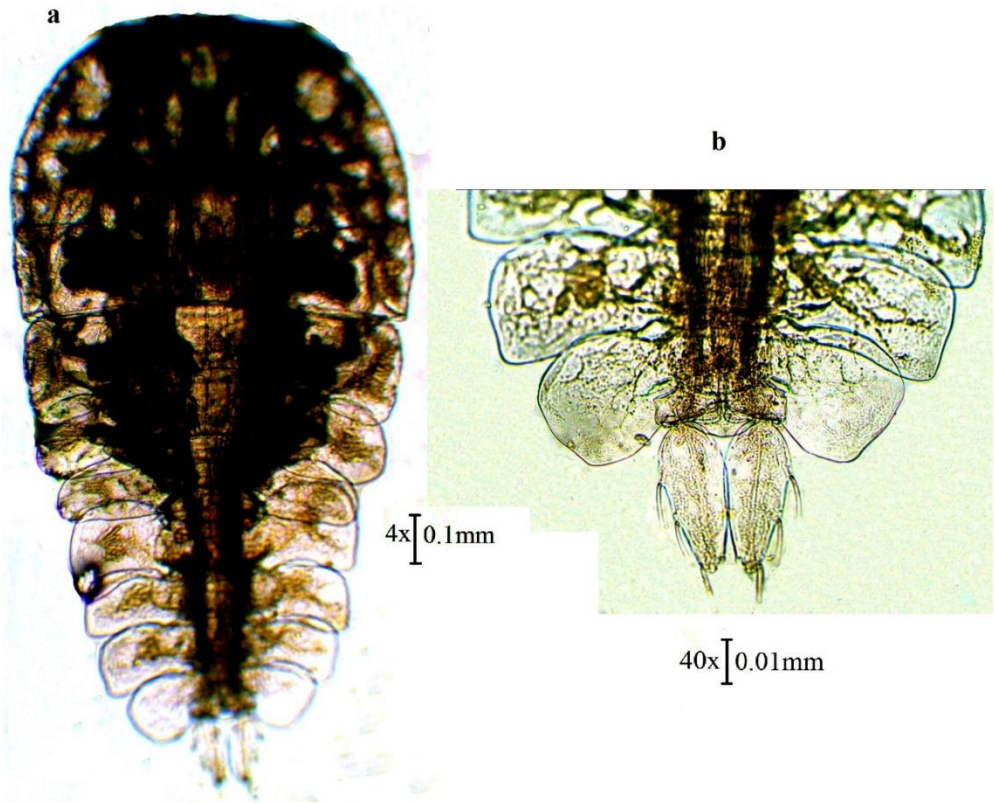


Plate.55. *S.scarlata* male.a,Habitus;b,A2.

***Sapphirina stellata* Giesbrecht, 1891**

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

Female **(Fig.56,Plate.56)** Total length (+CR) 2.38-3.1mm.Broad ovate body. Prosome 1.36times longer than wide (Fig.56a).Urosome twice wider than long. Caudal rami oval elongate, similar to male, longer than wide. Antennule (A1) 5 segmented. Antenna 4 segmented (Fig.56b) with coxa and basis fused and 3 endopodal segments.

Male **(Fig.57, Plate.57)** Total length (+CR)3.11-3.20mm. Broad ovate body. Prosome 2.12 times longer than wide (Fig.57a).Urosome 0.87 times wider than long. Caudal rami oval elongate (Fig.57d) similar to female, 1.19 times as long as wide. Antennule (A1) 5 segmented. Antenna 4 segmented (Fig.57b) with coxa and basis fused and 3 endopodal segments. Coxobasis bears a coxobasal spine at the inner distal margin which is bifid at its tip. First endopodal segment robust, 2.90 times longer than wide, bears short bifid spine at its inner medial margin. Second endopodal segment, short 2.26 times long as wide and is adorned with 2 spines at

the inner distal corner of which one is short and the other long. Third endopodal segment cylindrical armed with 3 elements. Two slender naked spines arising from outer distal margin, and 1 terminal spine long curved, drawn out as a claw.

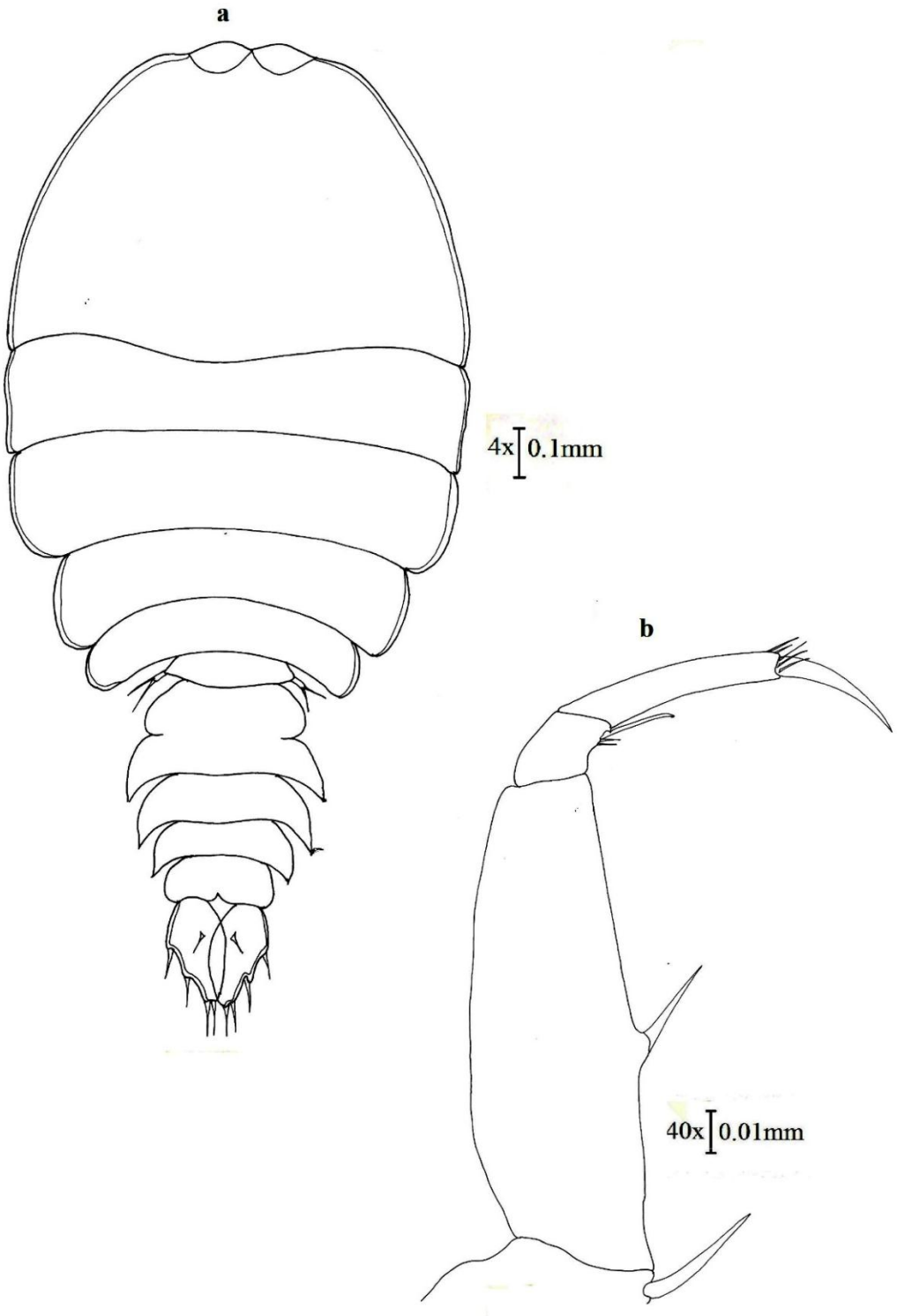


Fig.56. *S.Stellata* female.a,Habitus;b,A2.

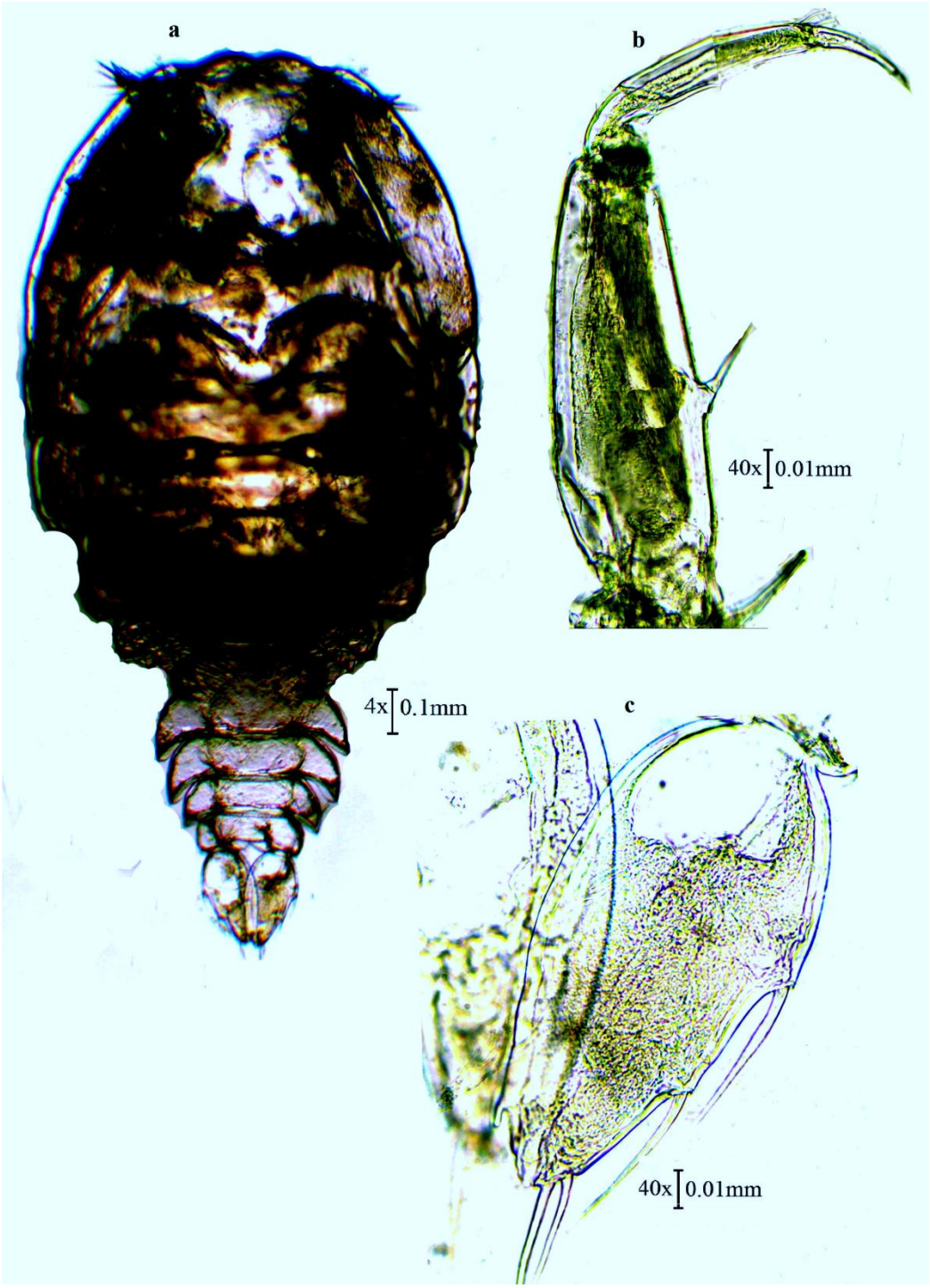


Plate.56.*S.Stellata* female.a,Habitus;b,A2;c,CR.

Remarks and Discussion: This species is distinctive in features like broad ovate prosome; 6 segmented urosome; adjacent cuticular lenses; elongate oval CR; 5 segmented A1; P4 endopodite shorter than half times as long as the exopodite in both sexes; presence of stout spines at the 3rd and 4th segment of A2 in females, elongate

ovate CR in males exhibited close morphological proximity to *S. stellata* described previously (Mori, 1964; Chen and Zhang ,1974; Giesbrecht 1892; Scott, 1909). The species analyzed here were confirmed by molecular analysis as distinct species.

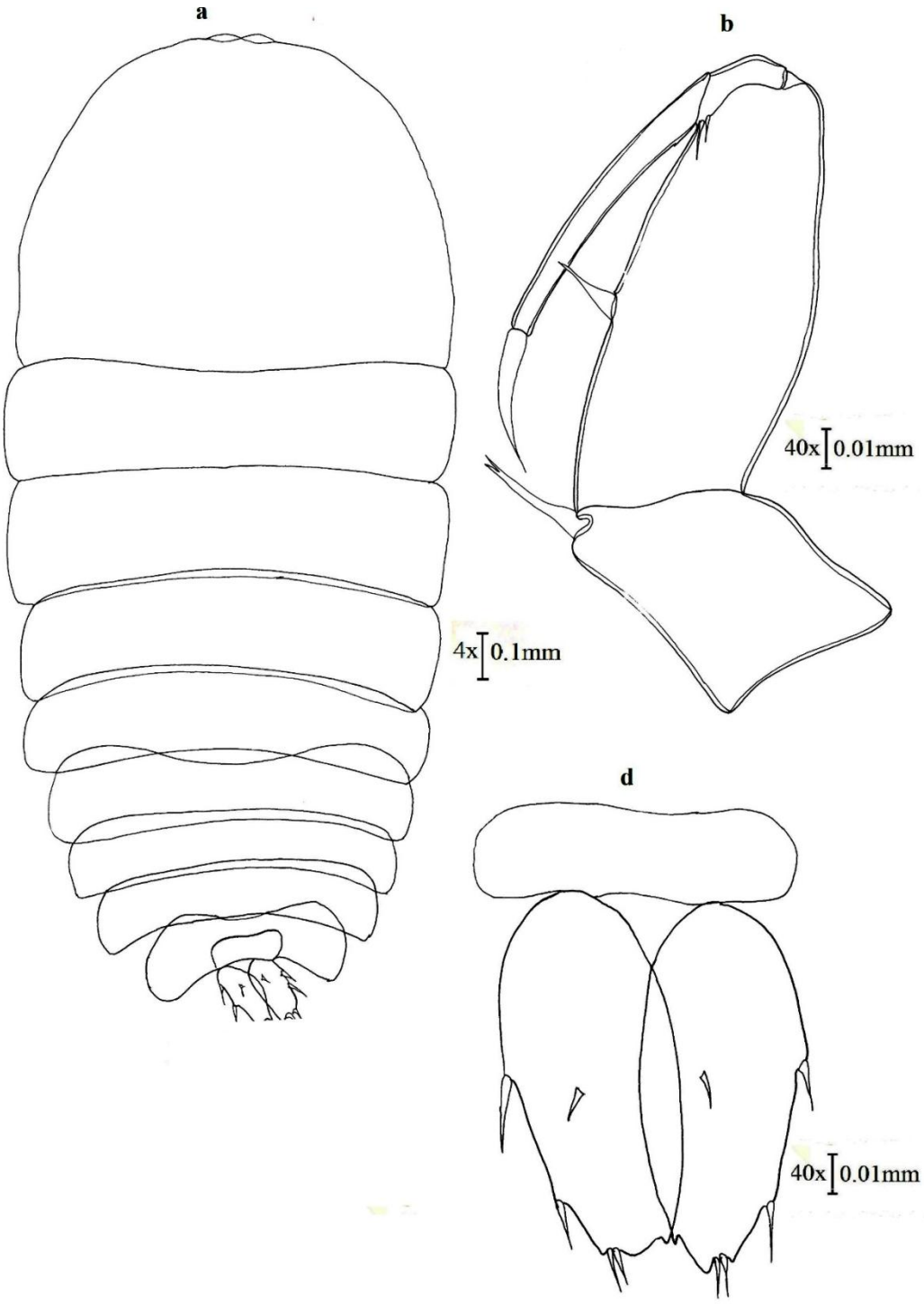


Fig.57.*S.stellata* male. a,Prosome;b,A2;d,CR

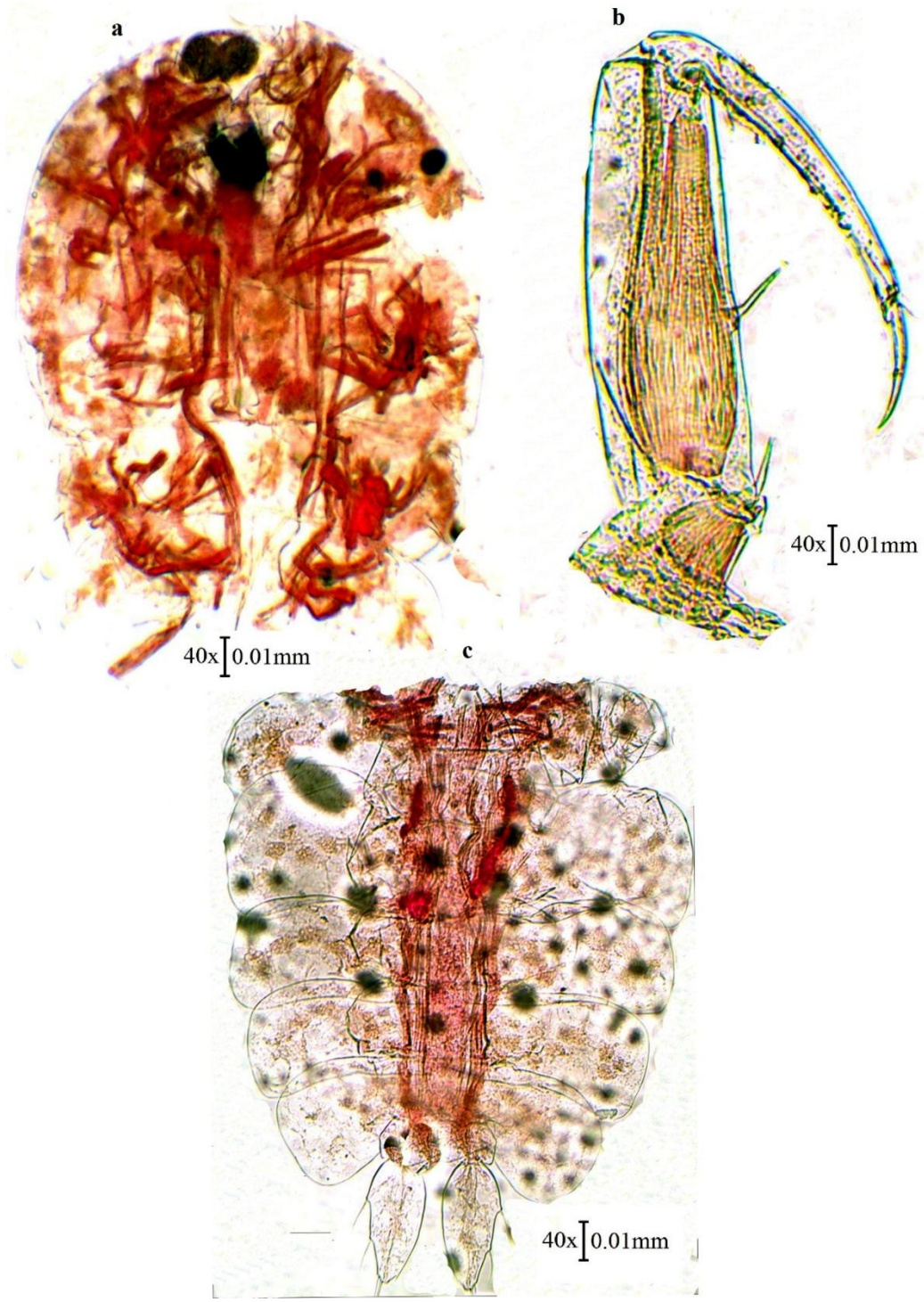


Fig.57.*S.stellata* male.a,Prosome;b,A2;c,Urosome.

Distribution: Recorded from tropical and subtropical zones of Atlantic, Indian and Pacific Ocean. This species appears in warm currents in Japan (http:// copepods. obs-banyuls.fr/en).

Sapphirina vorax Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean zones (CR#338) (Refer Table 3.2).

Female **(Fig.58, Plate.58)** Total length (+CR) 1.882-1.9mm.Cephalosome 1.63 times wider than long. Adjacent cuticular lenses visible dorsally. Prosome 2.36 times longer than urosome (Fig.58a).1stmetasomal segment as wide as cephalosome, 2nd metasomal segment narrower than 1st. Urosome, 1.13 times as long as wide, narrower than prosome. Distal margin of first urosomal segment produced into lateral projections.CR oval elongate, 1.61 times as long as wide. Antenna four segmented (Fig.58c).Coxobasis bears a short coxobasal spine at the inner distal margin. First endopodal segment robust 2.6 times longer than wide, bears short spine at its inner medial margin. Second endopodal segment, short, 1.41 times longer than wide and is adorned with three spines at the inner distal corner of which one is short and the other two long. Third endopodal segment cylindrical, 4.4 times as long as wide at base, armed with five elements. Two slender naked spines arising from outer distal margin, one from the medial margin, one from inner distal margin and one terminal spine long curved, drawn out as a claw.

Remarks : Distinct features of female specimen of this species like urosome twice as long as wide, Distal margin of first urosomal segment produced into lateral projections,1st metasomal segment as long as wide, five segmented antennule confirmed the morphological identity This species is considered as a variation of the species *Sapphirina auronitens- sinuicauda* by Lehnhofer, 1929. However this position was not approved by Crisafi & Mazza (1966).But Boxshall and Halsey (2004) do follows the position of Lehnofer and consider the single denomination of *Sapphirina auronitens.* The species analyzed here were confirmed by molecular analysis as distinct species.

Distribution: Mediterranean Sea, Black Sea, Indian Ocean, China Sea., Red Sea, Australia, Adriatic Sea (http:// copepods. obs-banyuls.fr/en).

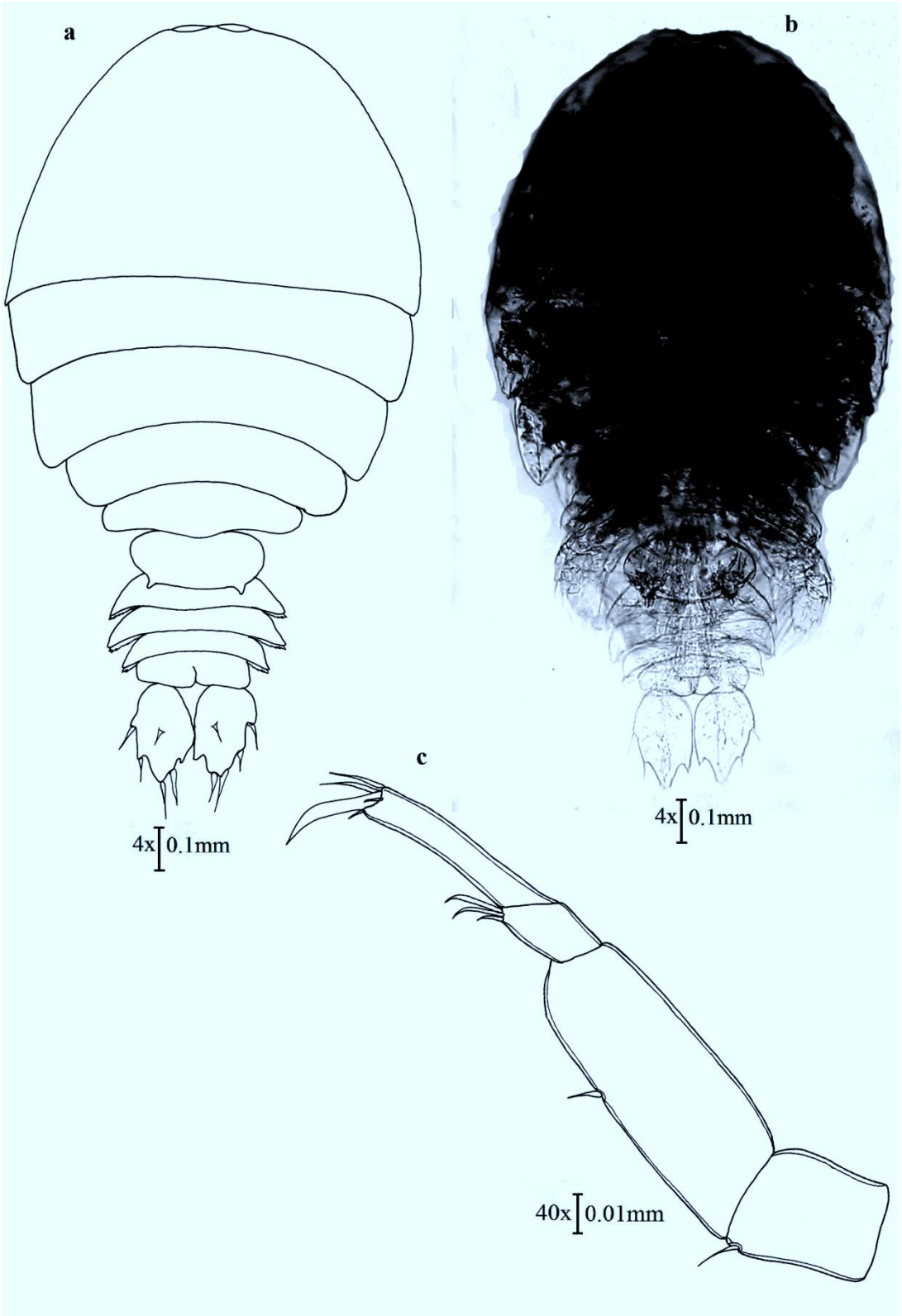


Fig 58 and Plate 58.*S.vorax*.a.b,Habitus;c,A2.

Sapphrirna gastrica Giesbrecht, 1891

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean (CR#338) (Refer Table 3.2).

Female **(Fig.59, Plate.59)** Total length (+CR)-1.01-1.21mm.Cephalosome 1.34 times longer than wide. Adjacent cuticular lenses visible dorsally. 4th and 5th metasomal segments narrower and bent downwards (Fig.59a).Urosome, 1.60 times long as wide, narrower than prosome. Caudal rami oval elongate, twice longer than wide and dorsal seta behind the first marginal seta. An apical process present in the inner distal corner. Antennule (A1) 5 segmented (Plate 59e). Antenna 4 segmented (Fig.59b) with coxa and basis fused and 3 endopodal segments. Coxobasis bears a short coxobasal spine at the inner distal margin. First endopodal segment robust, 2.36 times longer than wide, bears short spine at its inner medial margin. Coxobasal spine much longer than the endopodal spine (4.2 vs 2.8) Second endopodal segment, short, as long as wide and is adorned with 3 spines at the inner distal corner of which one comparatively longer than the other two. Third endopodal segment cylindrical, 4.2 times as long as wide at base, armed with 6 elements. Two comparatively long spines in the outer distal corner, one small spine in the middle ,two in the inner distal corner margin and 1 terminal spine curved and drawn out as a claw.

Remarks: This Lakshadweep specimen is consistent with Scott, 1909 in his "Siboga" expedition in the shape of CR as ovate elongate, twice as long as wide; A2 first endopodal segment longer than the 2nd and 3rd endopodal segments combined;P4 endopod less than half the length of exopod ; Coxobasal spines much longer than the endopodal spine. The female specimen of this species resembles *S.nigromaculata* except in the position of dorsal seta of CR being behind the first marginal seta and the ornamentation of spines in the 3rd endopodal segment. The only discrepancy found from the previous descriptions is only on the size being slightly lower (0.909mm).Rest of the distinguishing characters like P4 endopodite shorter than the exopodite; segmentation and length width ratio of A1; postion of the dorsal seta of CR exhibited close proximity towards the female descriptions of this species. Only the female specimen being recorded from the Pacific Ocean

Distribution: Red Sea, Gulf of Oman, Indian Ocean, Bay of Bengal, W Australia, Straits of Malacca, G. of Thailand, Indonesia-Malaysia, E Philippines, China Seas (East China Sea, South China Sea), Taiwan, Japan, Kuchinoerabu Is., Tanabe Bay, off SE Hawaii, W Baja California, Pacific(W equatorial), Australia (http:// copepods. obs-banyuls.fr/en).

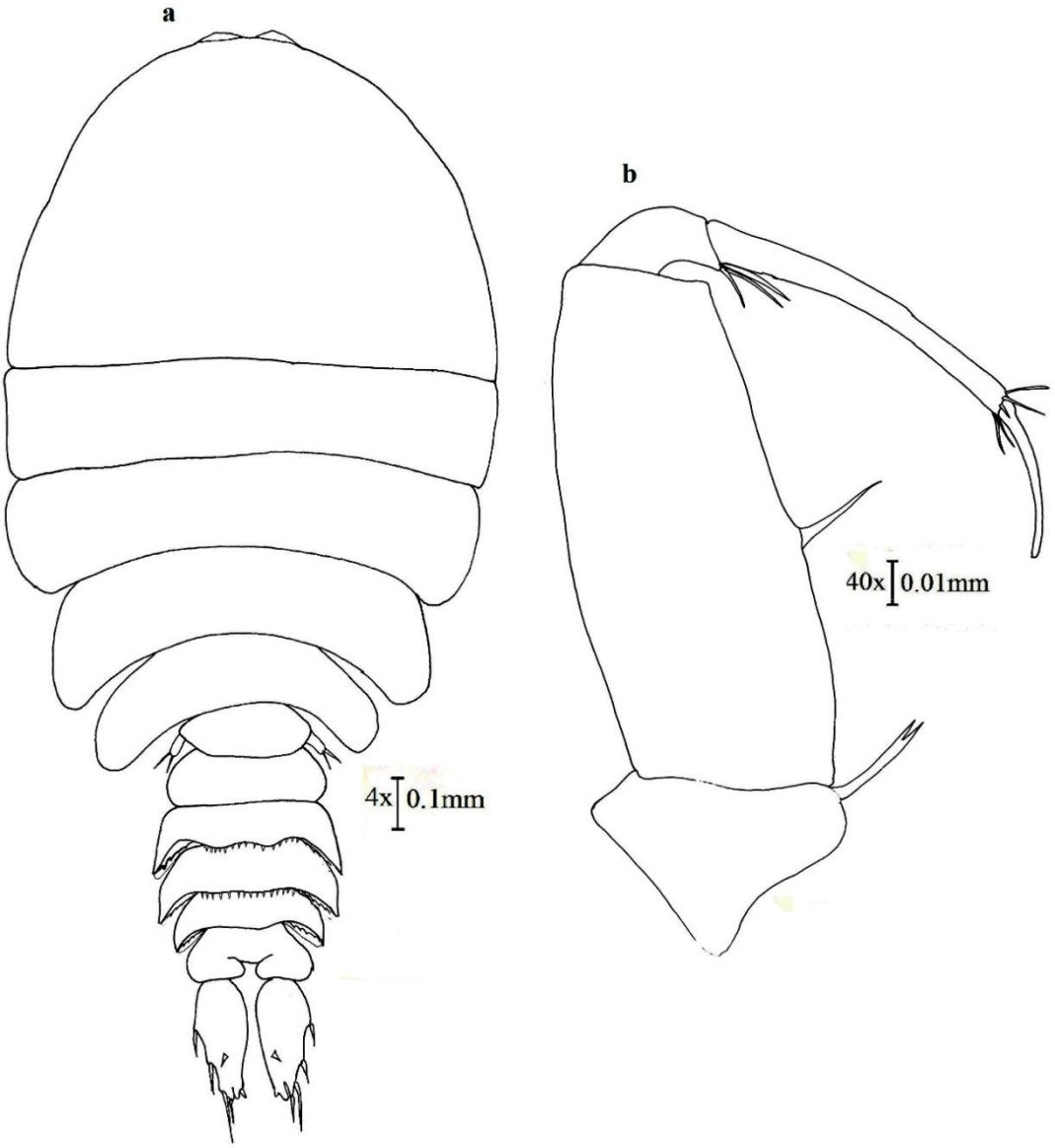
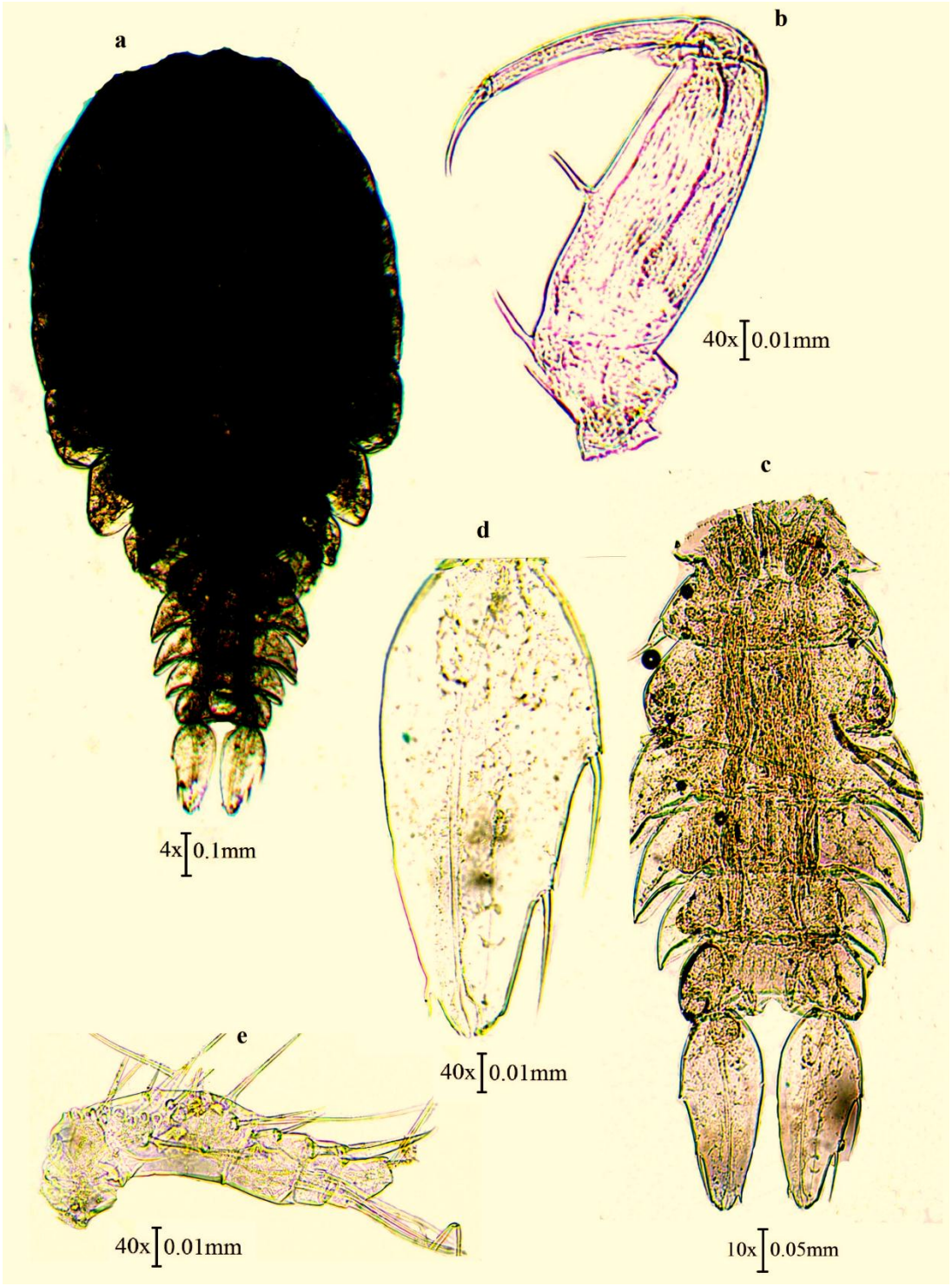


Fig.59.*S.gastrica* female.a,Habitus;b,A2.



Palte.59. *S.gastrica* female.a,Habitus;b,A2;c,urosome;d,CR;e,A1.

Sapphrina nigromaculata Claus, 1863

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean zones (CR#338) (Refer Table 3.2).

Female **(Fig.60, Plate.60)** Total length (+CR)1.30-2.4mm.Cephalosome 1.72 times wider than long.Prosome 1.64 times as long as wide.Adjacent cuticular lenses visible dorsally.Urosome, 1.72 times long as wide, narrower than prosome.CR oval elongate, twice as long as wide. Antenna 4 segmented with coxa and basis fused and three endopodal segments. Coxobasis bears a short coxobasal spine at the inner distal margin. First endopodal segment robust, 2.04 times longer than wide, bears short spine at its inner medial margin. Second endopodal segment, short, 1.06 times long as wide ,with 3 spines at the inner distal corner of which one comparatively longer than the other two. Third endopodal segment cylindrical, 4.7 times as long as wide at base, armed with four elements.Three slender naked spines arising from outer distal margin and one terminal spine curved and drawn out as a claw.

Remarks: Morphological features of *S.nigromaculata* female species include moderately broad cephalosome; ovate elongate CR which is twice as long as wide; five segmented urosome ;A2 first endopodal segment longer than the 2nd and 3rd endopodal segments combined; exhibited close morphological proximity to *S. nigromaculata* described previously (Scott, 1909; Mori, 1937; Crusafi&Mazza, 1966; Giesbrecht, 1892; Zheng *et al*, 1982; Chen and Zhang,1974; Al Yamani and Prusova, 2003; Farran,1900).

Distribution: Recorded from the Atlantic, Indian and Pacific Oceans, Seychelles, Madagascar and from the Mediterranean, and Red Sea (http:// copepods. obs-banyuls.fr/en).

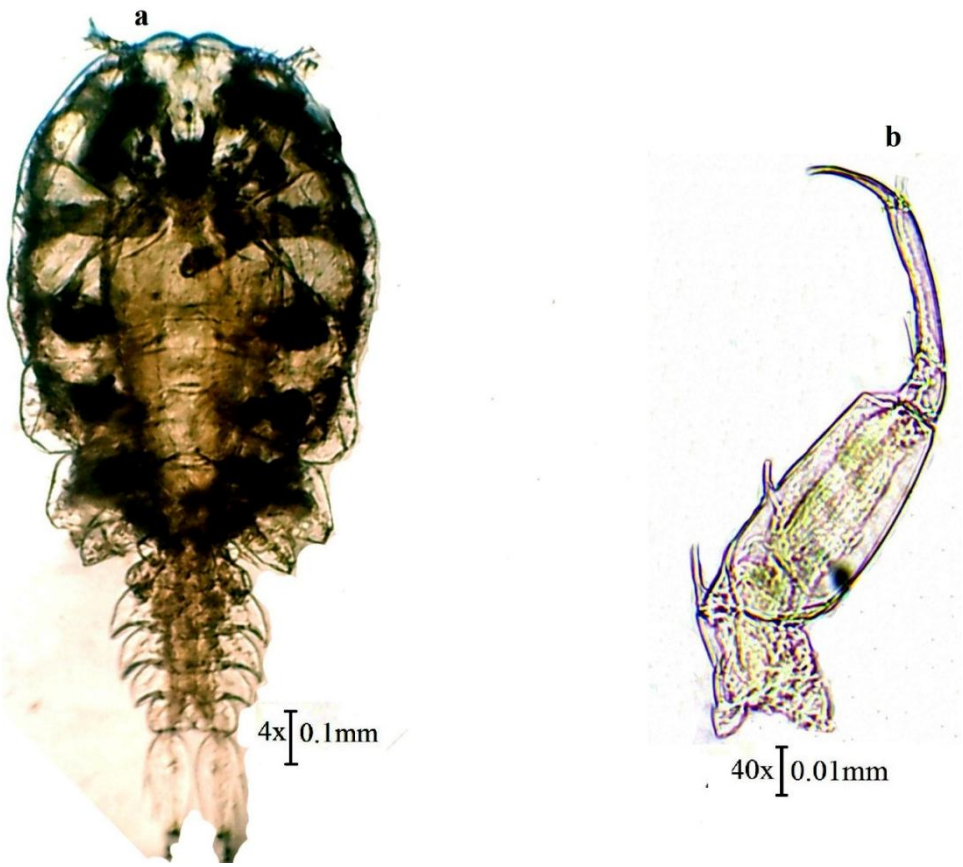


Plate.60.*S.nigromaculata* female.a,Habitus;b,A2.

***Sapphrina siniuicauda* Brady, 1883**

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean zones (CR#338) (Refer Table 3.2).

Male **(Fig.61, Plate.61)** Total length (+CR)1.96-2.1mm.Cephalosome 1.56 times wider than long.Prosome 1.5 times longer than wide.Adjacent cuticular lenses visible dorsally. Urosome, 1.11 times long as wide. CR elongate, 0.92 times long as wide. Antenna four segmented. Coxobasis bears a short coxobasal spine at the inner distal margin. First endopodal segment robust, 2.83 times longer than wide, bears short spine at its inner medial margin. Second endopodal segment, short,2.30 times long as wide ,adorned with three curved lean spines at the inner distal corner. Third endopodal segment cylindrical, 5.15 times as long as wide at base, armed with five elements. Two slender naked spines arising from outer distal margin, two spines arising from inner distal margin and one terminal spine curved and drawn out as a claw.

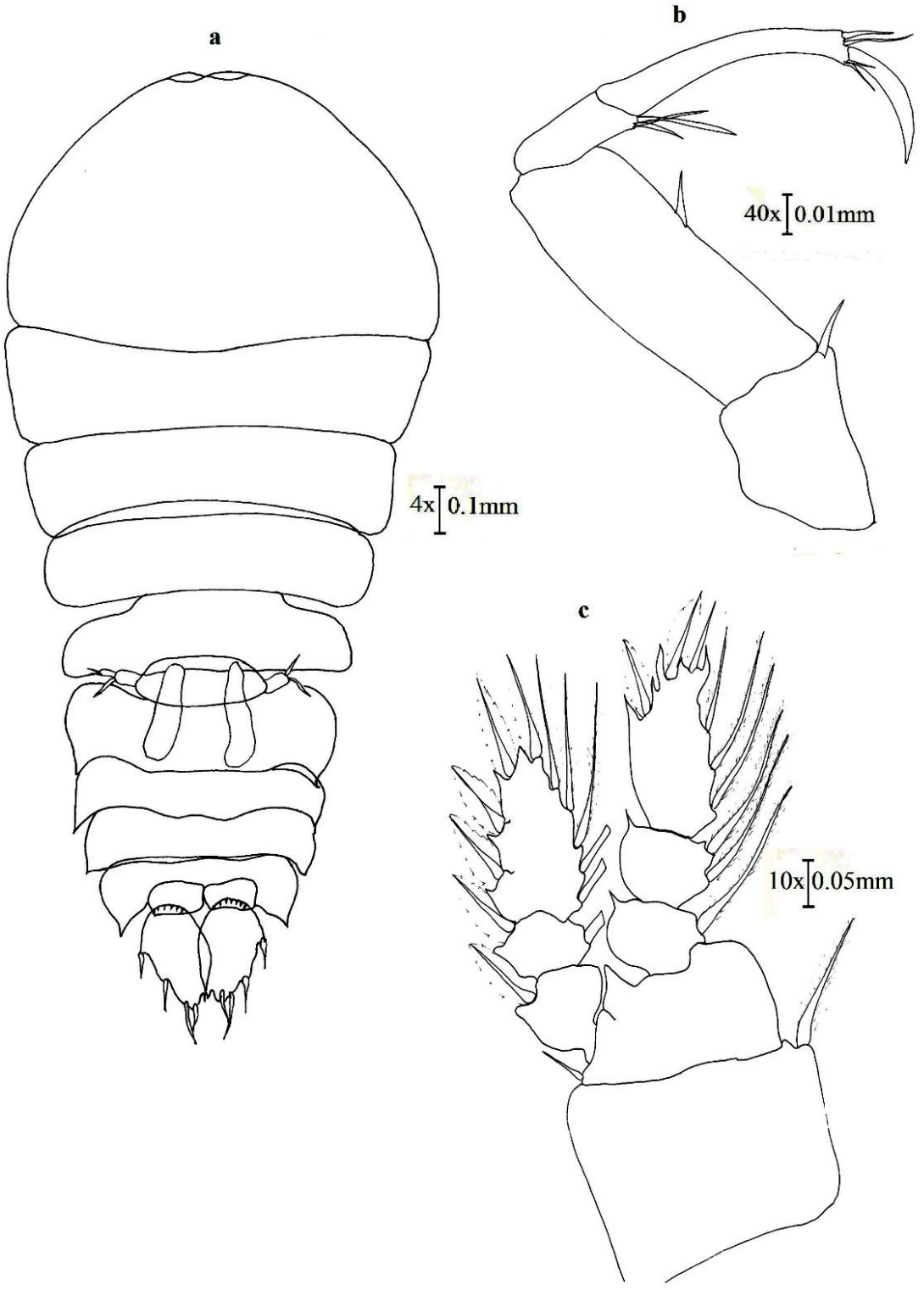


Plate.61.*S.sinuicauda* male.a,Habitus;b,A2;c,P2.

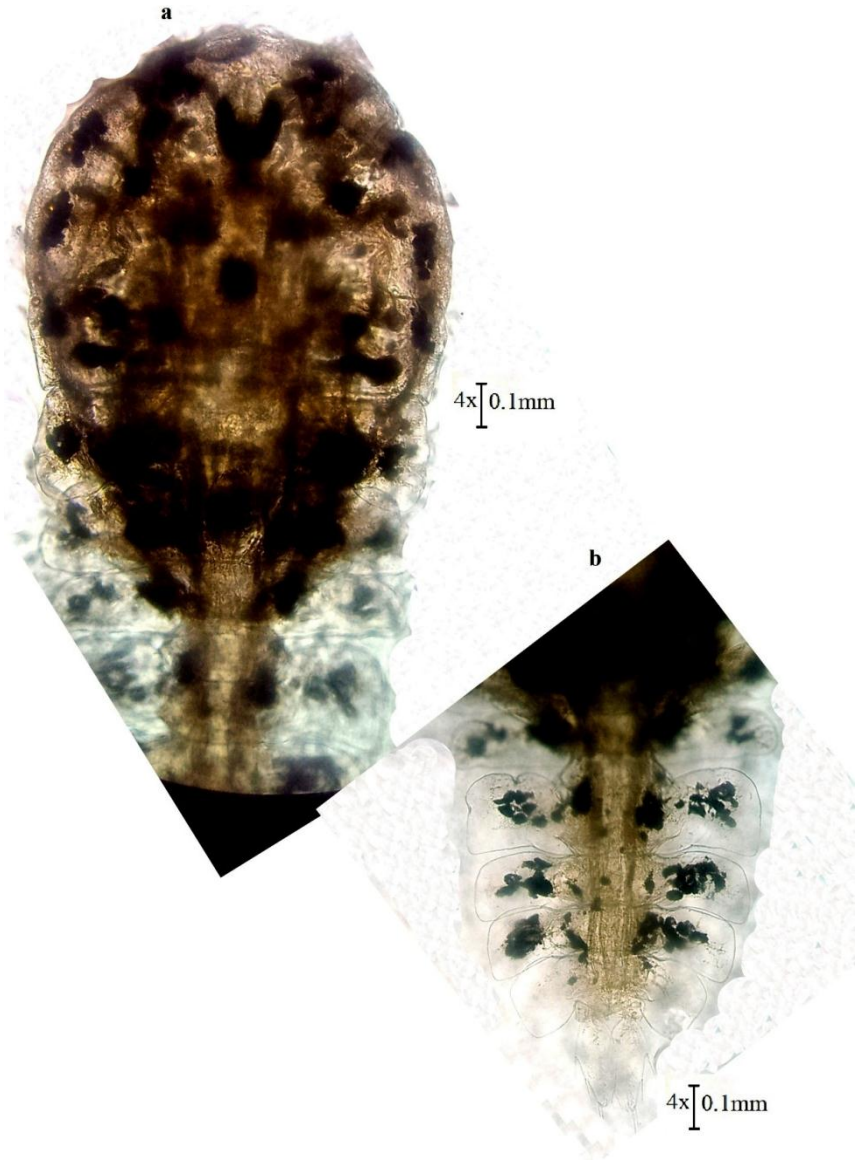


Fig.61.*S.sinuicauda* male.a,Habitus;b.urosome

Remarks: This species is distinctive in features like wider cephalosome; six segmented urosome; 3rd thoracic segment broader than the second; adjacent cuticular lenses; oval CR; five segmented antennule in males exhibited close morphological proximity to *S.scinuicauda* described previously by Chen and Zhang(1974); Giesbrecht (1892); Scott, (1909), Crissafi and Mazza (1966); Lehnhofer (1929).This species is considered as a variation of *S.auronitens* by Lehnhofer (1929).But this is not followed by other authors. Boxshall & Haley (2004) consider only the species *Sapphirina auronitens.*

Distribution: South Africa,G. of Guinea, Venezuela, Chesapeake Bay, Medit. (Alboran Sea, NW Basin, Ligurian Sea, Tyrrhenian Sea, Strait of Messina, Malta, N & S Adriatic Sea), Red Sea, Arabian Sea, Laccadive Is., off Sri Lanka, Durban, Madagascar, Indonesia-Malaysia, Philippines, China Seas (Yellow Sea, East China Sea, South China Sea), Taiwan, S Japan (Kuchinoerabu Is.) (http:// copepods. obs-banyuls.fr/en).

Copilia mirabilis Dana, 1849

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean St.3 &4(CR#338) (Refer Table 3.2).

Female **(Fig.62, Plate.62)** Total length (+CR)3.10-4mm. Prosome rectangular shaped; 1.75 times longer than wide with prominent anterior cuticular lenses dorsally. Space between the cuticular lenses almost twice the diameter of the lenses. Urosome elongated,8.25 times longer than wide, with a row of spines at the distal margin.AS 2.81 times as long as wide;longer than rest of the urosomal segments (excluding CR).CR elongated 3.4 times longer than wide at the distal margin, longer than rest of urosomal segments. Antennule(A1)six segmented. Antenna 4 segmented. Coxobasis adorned with numerous spines dorso-laterally as well as a long spine at the inner distal margin covered by spinules. First endopodal segment robust, bears short spine at its inner medial margin adorned with four small spines in a curved manner. Second endopodal segment, short adorned with three lean spines at the inner distal corner.Third endopodal segment drawn out as a claw.

Remarks : Female specimens of *C.mirabilis* can be easily distinguished by 1) rectangular shape of PR; 2) Ornamentation of A2; 3) Space between the cuticular lenses almost twice the diameter of the lenses; 3) AS longer than rest of the urosomal segments; 4) CR elongated wider at the distal end. Only females were encountered.

Distribution: Caribbean Sea,Sargasso Sea,Red Sea, Arabian Sea, Arabian Gulf (UAE coast, Kuwait), Madagascar, Rodrigues Island-Seychelles, Mascarene Basin, Indian, Indonesia-Malaysia, Bintulu coast, China Seas (Yellow Sea, East China Sea, South

China Sea), Tanabe Bay, Australia, Hawaii, Pacific (http:// copepods. obs-banyuls.fr/en).

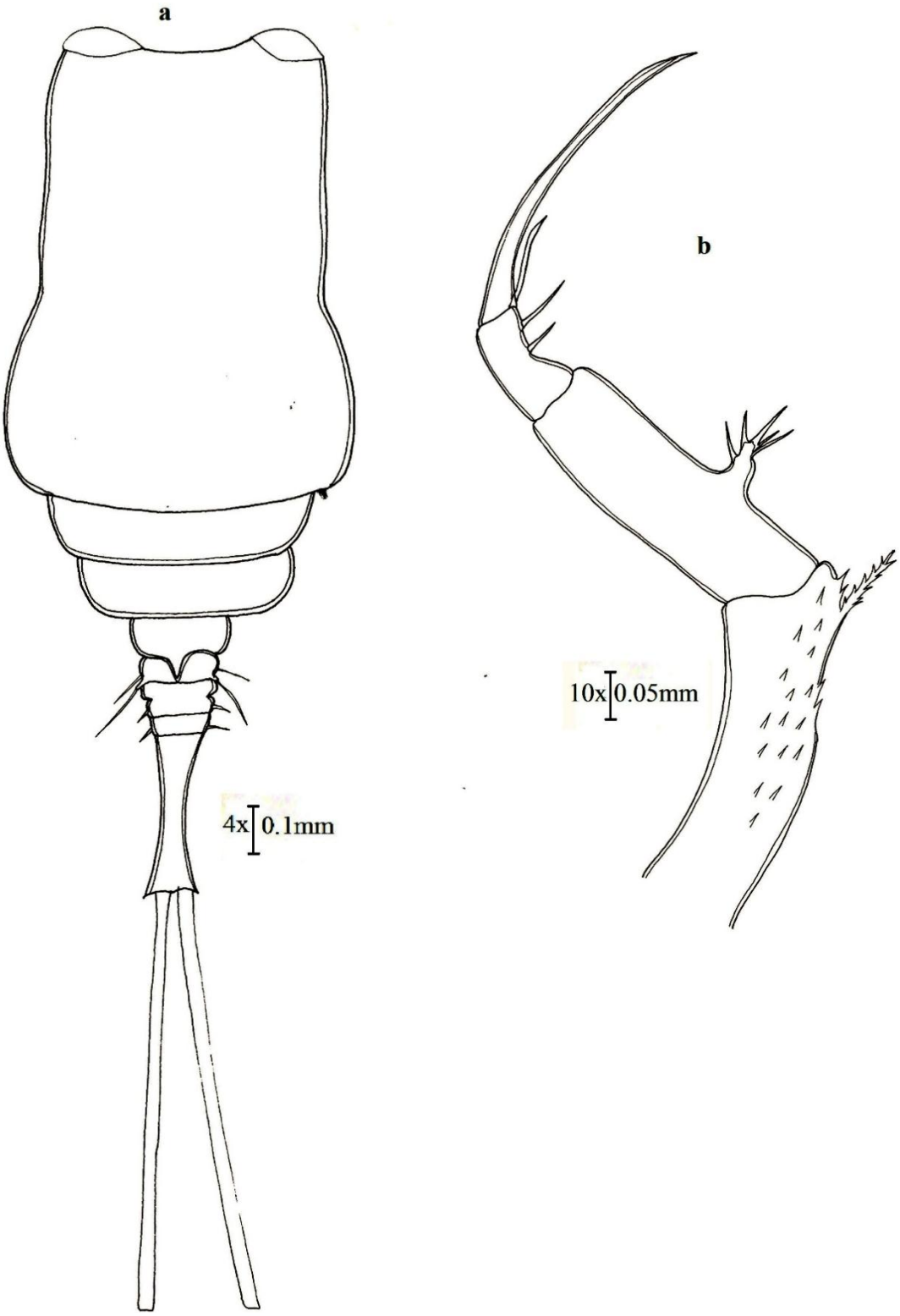


Fig.62.*Copilia mirabilis* female.a, Habitus; b, A2

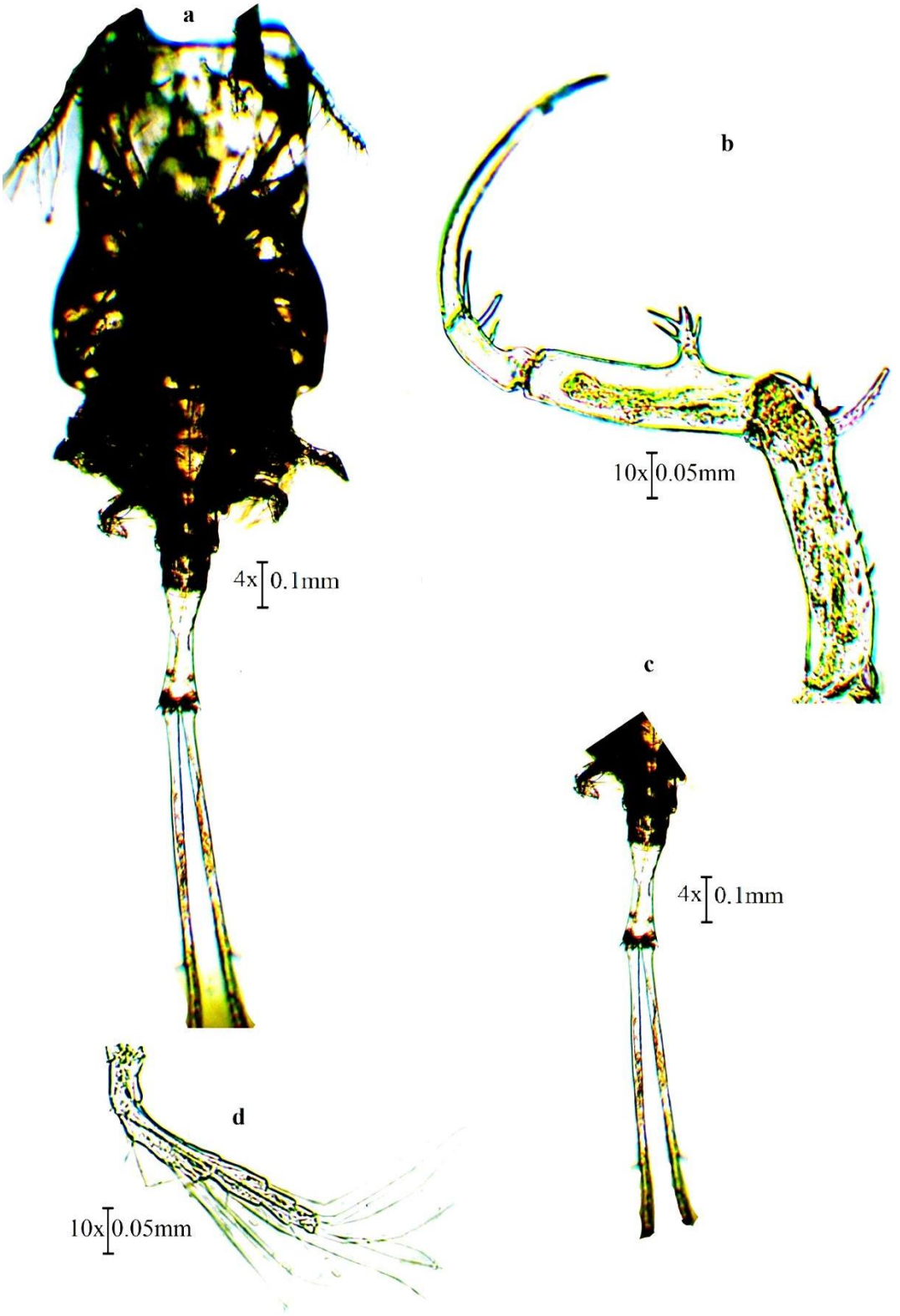


Plate.62.*Copilia mirabilis* female. a,Habitus;b,A2;c,Urosome;d.A1.

Copilia hendorffi Dahl, 1892

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean St.3 &4(CR#338) (Refer Table 3.2).

Male **(Fig.63,Plat.63)**Total length(+CR)5.55-6mm.Cephalosome rounded anteriorly;1.65 times wider than long. Prosome 1.26 times longer than wide. Urosome 133 times longer than wide with lateral margins tapered downwards.CR elongated 8.75 times longer than wide at the distal margin.CR is shorter than UR.

Remarks: The most distinguishing character of *C.hendorffi* male species is the flipping of the urosome upwards and protuberation of the last metasomal segment into a notch. The lateral margins of the metasomal segments as well as the proximal margins of the urosomal segments is festooned with minute spines. Unisex of this species were only observed of the Minicoy open ocean in most of the stations. This species is closely allied to the previously described species in its general appearance. However it strictly agrees to those described by Lehnhofer (1926), Conway *et al*.,2003 in the length of the cephalosome being shorter than wide. The notching of last metasome, flipping of the UR, segmentation of A2, could also be observed clearly,thus being consistent with the previous descriptions.

Distribution: Rodrigues Island, Central South Atlantic, Indian Ocean, Arabian Sea, Australia (http:// copepods. obs-banyuls.fr/en).

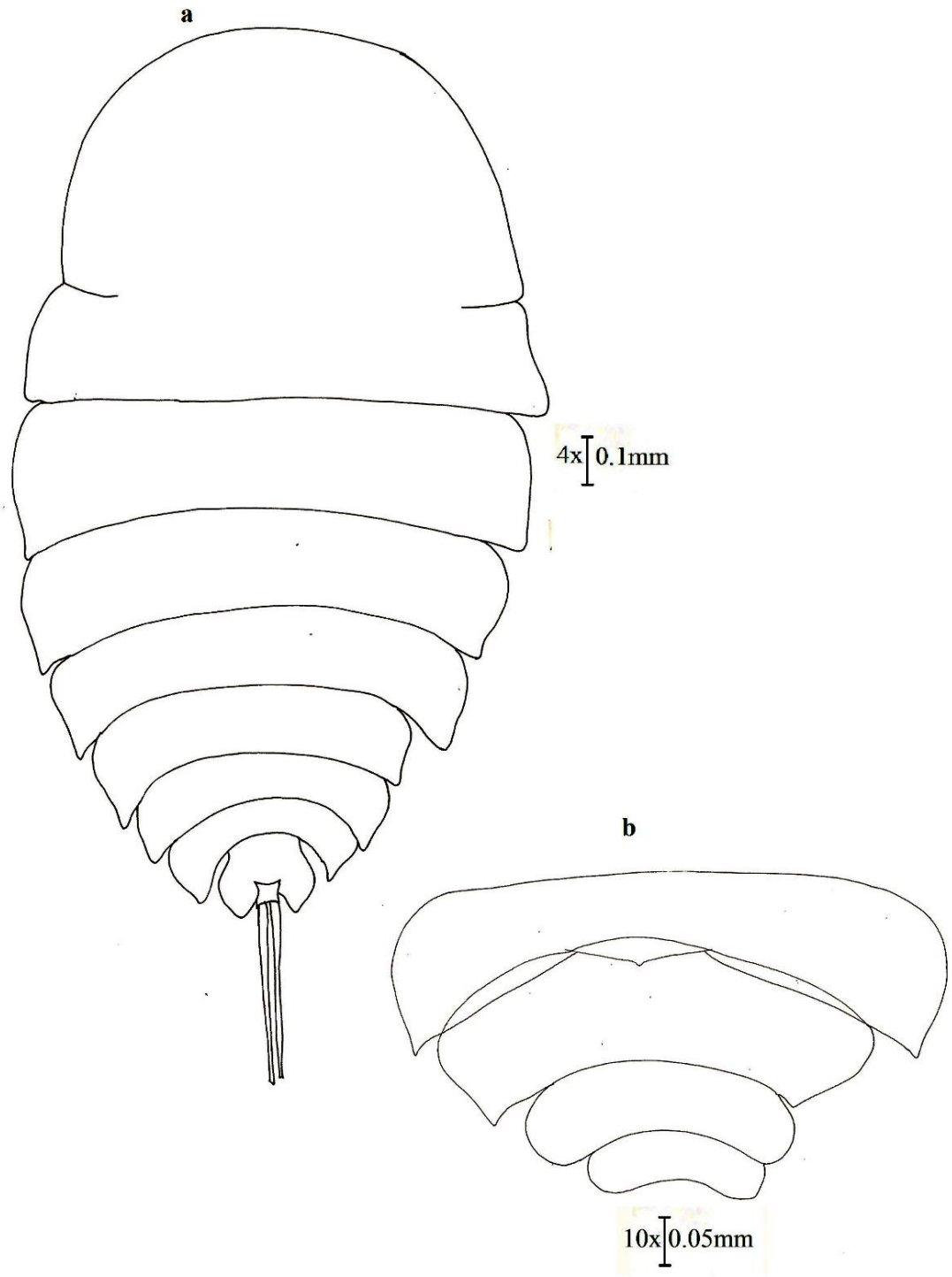


Fig.63. ***C.hendorffi*** **male. a,Habtus; b, Urosome (**protuberation of the last metasomal segment into a notch).

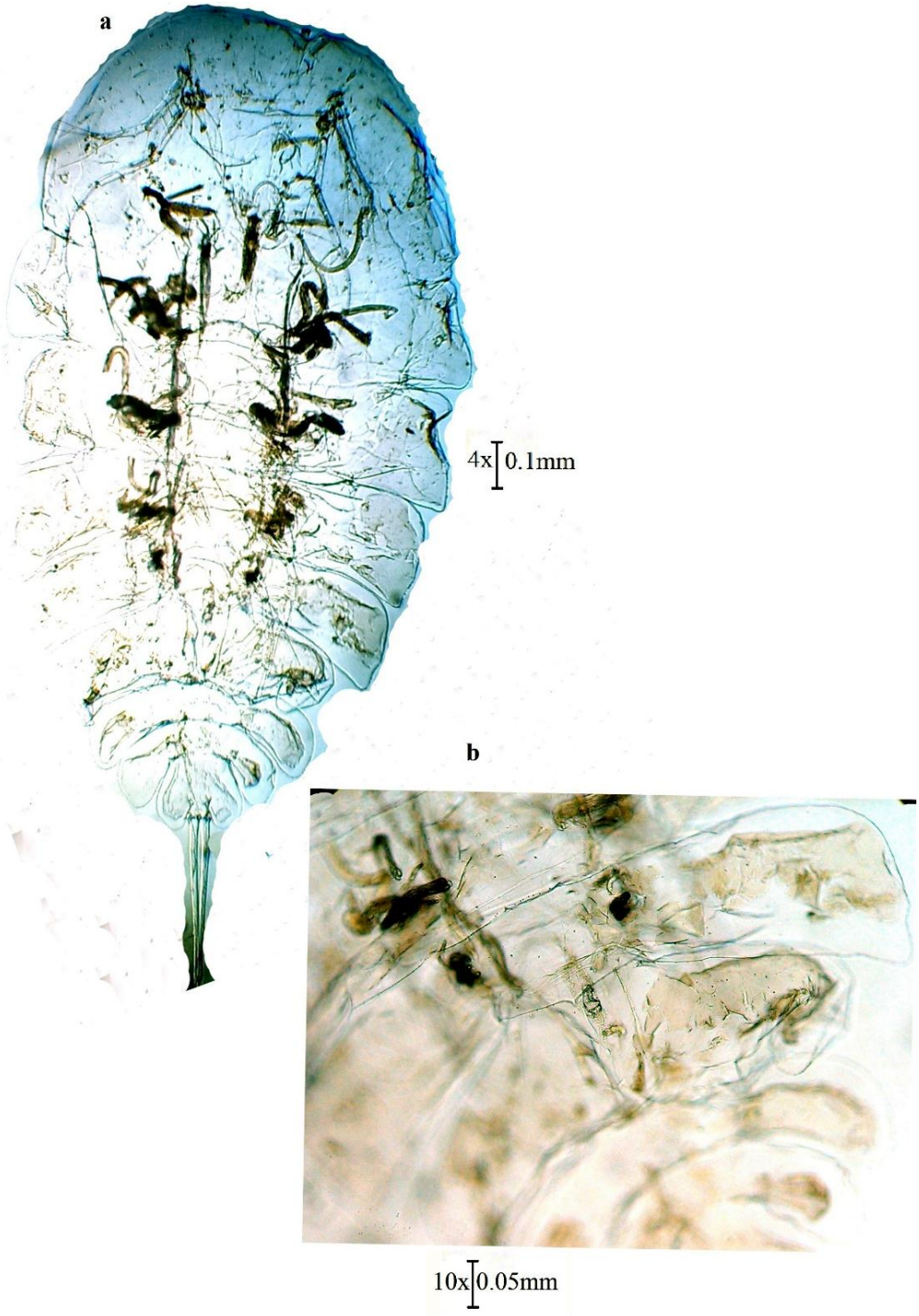


Plate.63. ***C.hendorffi*** **male.a,Habtus; b, Urosome (**protruberation of the last metasomal segment into a notch).

Copilia quadrata Dana, 1849

Material examined: The samples were sorted out from plankton samples collected from Minicoy open ocean St.3 &4(CR#338) (Refer Table 3.2).

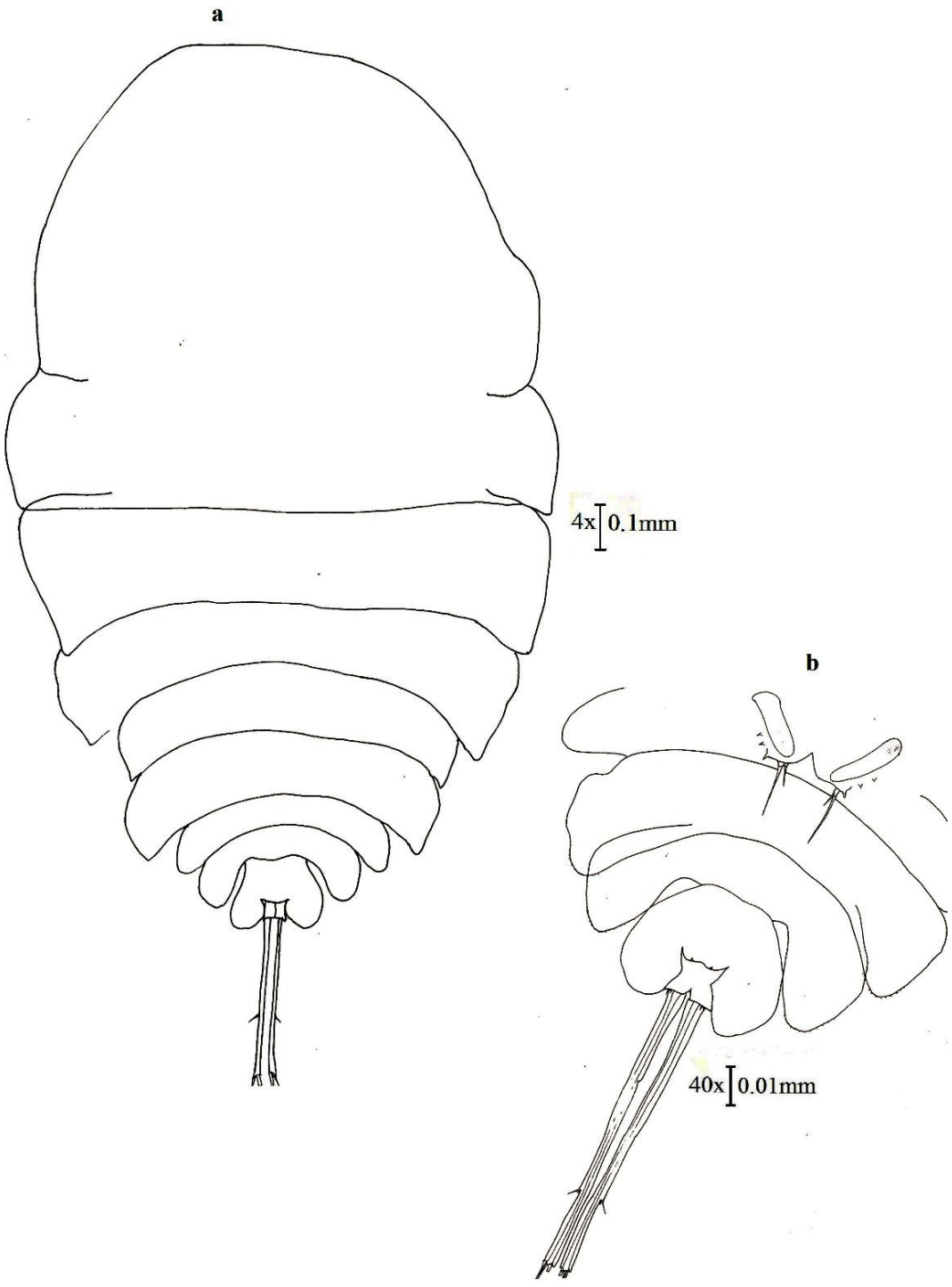


Fig.64.*C.quadrata* male. a,Habitus; b, Urosome (presence of diagonal patch).

Male **(Fig.64, Plate.64)** Total length (+CR)4.09-4.2mm. Cephalosome 0.75 times shorter than wide. Prosome slightly concave; 1.31 times longer than wide. Urosome including CR 1.15 times longer than wide with lateral margins tapered downwards.CR elongated 11times longer than wide at the distal margin.

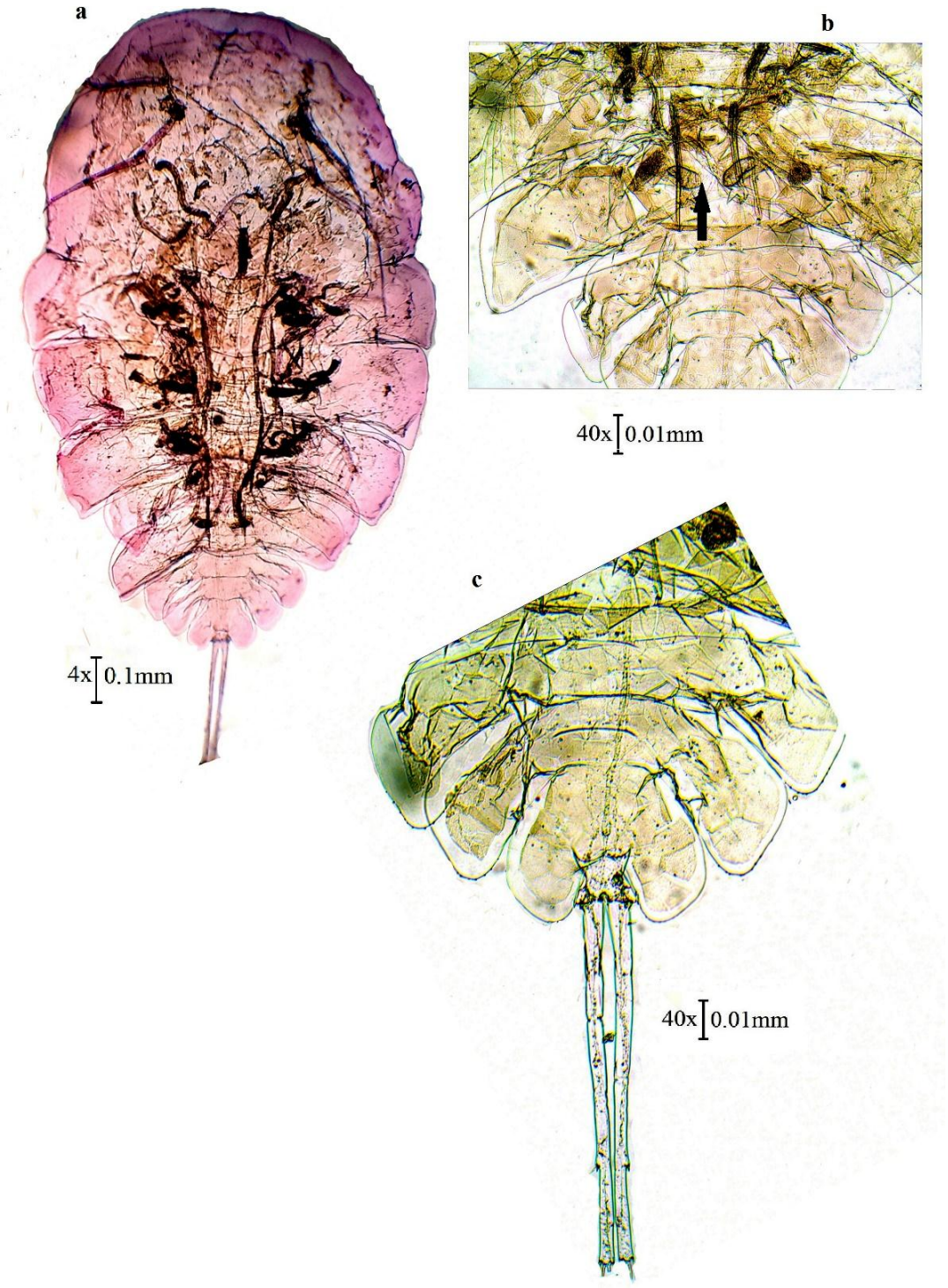


Plate.64.*C.quadrata* male.a, Habitus;b, presence of diagonal patch;c,Urosome.

Remarks: *Copilia quadrata* males can be distinguished from other species by the presence of dark diagonal patch in the middle of the urosomal segment. Unisex of this species were only observed of the Minicoy open ocean in most of the stations. This species is closely allied to the previously described species in its general appearance. However it strictly agrees to those described by Giesbrecht (1892) in its special character which has not been mentioned by any other previous workers.

Distribution: Caribbean Sea, Sargasso Sea, Pacific Ocean, Atlantic Ocean, Indian Ocean, China Sea, Japan Sea, Australia (http:// copepods. obs-banyuls.fr/en).

6.4. Discussion

Order Cyclopoida incorporates free living species commensal as well as parasitic species. Even if cyclopoids bears a resemblance to calanoids in the sharp division between prosome and urosome, variation also exists in the articulation between thoracic segments. In cyclopoids it is between thoracic segments 4 and 5 whereas in calanoids it exists between thoracic segment 5 and abdominal segment 1.Cyclopoids bear P5 in the 5th thoracic segment. Females have elongated antennule (A1) though not as long as that of calanoids and uniramous antenna (A2).

Despite the importance of cyclopoid copepod community in the global carbon cycle, diversity studies on copepods in Lakshadweep islands have usually been concentrated on calanoid group and little is known about the marine cyclopoid groups. Studies related to classical taxonomy and molecular systematics of Indian marine cyclopoids are limited, even though several similar studies are being carried out in calanoid copepods. However, proper taxonomic studies hold much significance in an ecological as well as taxonomical point of view (Radhika *et al*., 2014b)

Ecology of marine as well as freshwater cylopoids have been dealt with by many workers. However, taxonomy of Lakshadweep (a part of Indian Ocean) cyclopoids have not been attempted much in the Indian scenario. The available taxonomic works on marine cylopoids of Indian waters with valid identification key include the works of Kasthurirangan (1963), Mori (1964), Scott (1909), Giesbrecht (1892), Dahl (1912), Farran (1911) and Motoda (1963) which are considered as emblematic references in the present work. Species reported and taxonomically described from various parts of Indian Ocean are given in Table.6.1

Table.6.1. Species reported and taxonomically described from various parts of Indian Ocean

Region	Reported species	Taxonomic description	Reference
Indian Ocean	199 spp	199spp	
Lakshadweep and Maldives	16 spp 7spp 1spp 6spp 118spp		Goswami (1973) Madhuprathap (1977) Achuthankutty *et al*(1991) Usha goswami (1990) Wolfeden (1905)
Indian Coastal waters		18spp	Kasthurirangan (1963)
Indo-Pacific (Malay archipelago)		338spp 40cyclopoids	Scott (1903)
Indian Ocean(Lakshadweep)	2spp (new reports) *O. macilenta* *C.vitreus*	51spp	PRESENT STUDY

Here, in the present study, fifty one species from four important families and ten genera have been identified and systematically reviewed based on both classical as well as molecular methods. For a precise taxonomic identification right from the family to species level, several features have been considered as unique, even if the same exhibit prominent variations.

The family Corycaeidae (Dana 1852) including five genera, viz, *Corycaeus*, *Onychocorycaeus*, *Urocorycaeus, Ditrichocorycaeus* and *Farranula* are marine pelagic copepods occurring typically in epipelagic zone of tropical to temperate seas (Motoda, 1963; Boxshall and Halsey, 2004;Wi *et al*.,2013a). These groups of copepods are easily recognized by their peculiar body structure and large paired eyes and are very useful indicator forms of warm ocean currents (Motoda, 1963; Mulyadi, 2003). According to Tanaka (1957), until 1937, only six species were known from the family Corycaeidae which were *C.speciosus*, *C.robustus*, *C.ovalis*, *C.danae* (*C.crassiusculus*), *C.anglicus* and *C.rostratus*.

Genus *Corycaeus* Dana, 1846 can be easily recognized by their elongate subcyclindrical body, one or two segmented urosome and by the presence of a pair of reasonably large dorsal eyes on the frontal margin of the cephalosome or prosome (Scott, 1909). The genus *Corycaeus,* established by Dana(1846) is widely distributed in the Mediterranean Sea (Wilson,1942); the Indian and Pacific Oceans (Giesbrecht,1893,1892);Farran (1911); Dahl (1912);Sewell (1947);Tanaka

(1957,1960);the North Pacific Ocean (Motoda, 1963); the East China Sea and Yellow Sea (Chen *et al*.,1974; Zheng *et al*.,1982;Kang *et al.*,1990) and Japanese waters (Itoh, 1997). Seven subgenera have been recognized under a single genus *Corycaeus* (Dahl, 1912).They are *Corycaeus* (*Agetus*) (Kröyer, 1849), *Corycaeus* (*Corycaeus*) (Dana, 1845), *Corycaeus* (*Ditrichocorycaeus*) (Dahl, 1912), *Corycaeus* (*Monocorycaeus*) (Dahl, 1912), *Corycaeus* (*Onychocorycaeus*) (Dahl, 1912), *Corycaeus* (*Urocorycaeus*) (Dahl, 1912), and *Corycaeus* (*Corycella*) (Farran, 1911). But now all these subgenera has been raised to Genus level.

Four species during the present study represented the genus *Corycaeus* which are *C.crassiusculus*, *C.speciosus*, *C.clausi* and *C.vitreus.* While females of *C.crassiusculus* could be identified by the overlapping of genital segment on anal segment at the dorsal margin, *C.clausi* males exhibited a row of minute spines on the lateral portion of first endopodal segment of the A2 which was absent is *C.vitreus* males. *C.spesiosus* species was first reported in the Arabian Sea by Sewell in 1947 which is distinguished by its divergent CR, rounded forehead in female and broad one in male. Farran opined that the males of *C.vitreus* differs from that of *C.crassiusculus* and *C.clausi* by its short head which is broad anteriorly and tapers posteriorly short anal segment and fine transparent edge on the longest furcal setae.

Eventhough subgenus *Ditrichocorycaeus* was raised at the generic level by Boxshall and Halsey (2004), he himself considers this subgenus as full generic status pending and phylogenetic revision of the whole family. But anyhow, at present the accepted status of *Ditrichocorycaeus* is at genus level. Genus *Ditrichocorycaeus* M. Dahl (1912) is characterized by the procession two setae on endopod of P4.Due to deficient identification keys and more analogous morphological features, taxonomic ambiguity still continued until Wi *et al*(2013) and Vidjak (2008) provided a detailed description of *D.dahli, D.lubocki*, *D.subtilis* and redescription of *D.minimus*. Genus *Ditrichocorycaeus* includes fourteen valid species that are widely distributed and so far been described from world oceans including Indo-Pacific, Atlantic, East-China Sea and Meditteranean Sea (Farran 1911; Wilson 1942; Sewell 1947; Chen *et al*.,1974; Vidjak 2008; Wi *et al*., 2013c). From this, six species was recorded during the present study from Lakshadweep Sea, a part of Indian Ocean. They are *D.andrewsi*, *D.affinis*, *D.dahli*, *D.tenius*,

D.subulatus and *D.lubbocki.* Genus *Ditrichocorycaeus* is divided into two groups based on relative lengths of the caudal ramus. The first group has short caudal rami almost equal to anal somite but shorter than genital somite and the second group is characterized by the possession of caudal ramus longer than both anal somite and genital somite (Dahl 1912; Tanaka 1957).Based on this classification, out of the six species identified from Lakshadweep waters, *D.andrewsi*, *D.subulatus*, *D.affinis* can be categorized into group 1 and *D.dahli, D.tenius* and *D.lubbocki* into the second group. On comparing the length ratio urosomal segments, CR, presence/absence of ventral hook on GDS/GS, Tanaka (1957) differentiated nine species of *Ditrichocorycaeus* and named two species as *D. lubbock*i Dahl (1912) and *D. tenuis* Farran (1911). *D.africanus* Sewell (1947) was assigned as new species and *D. dahli* as *Corycaeus* (*Ditrichocorycaeus*) *dahli*.

Nonetheless, the ecological and taxonomical record for *Ditrichocorycaeus* species of Lakshadweep Sea barely exists. In this perspective, a taxonomic identification of six species including scientific drawings and photographs during the present study seems to be significant in all aspects. Nevertheless, recently Johan *et al* (2013) and Veronica and Nagappa (2013) have recorded four species of *Ditrichocorycaeus* from Malaysia and one species from Bay of Bengal respectively which indeed are the parts of Indian Ocean. Al-Yamani (2011) also recorded three species of *Ditrichocorycaeus* from North western Arabian Gulf waters.

Among the seven species comprising the genus *Onychocorycaeus* (Dahl, 1912) which are widely distributed in world oceans**,** the present study recorded six species. They are *Onychocorycaeus giesbrechti* (Dahl, 1894), *Onychocorycaeus agilis* (Dana, 1849), *Onychocorycaeus catus* (Dahl, 1894), *Onychocorycaeus latus* (Dana, 1849), *Onychocorycaeus pacificus* (Dahl, 1894), and *Onychocorycaeus pumilus* (Dahl, 1912). *O.catus* and *O.pumilus* had already been reported by Karanovic (2003) from Australian waters*. O.catus* from Kavaratti is the smallest ever reported (0.65mm).Interestingly, it is noted that*, O.pumilus* reported by Dahl (1912) and *O.catus* reported by Karanovic (2003) with an abnormal armature of the second swimming leg has only three spines on the third exopodal segment while Kavaratti specimen has four spines on the third exopodal segment . This certainly is an abnormality that also occurs on the first and the third swimming leg

with only three spines on the third exopodal segment of *O.catus* reported by Karanovic (2003).While Kavaratti specimen has four spines in the third exopodal segment of first and third swimming leg. This undoubtedly is a difference that is useful in species identification as the armature of first three swimming legs is very conservative in the family Corycaeidae Dana, 1852.

Most of the *Onychocorycaeus* species are distinguished mainly by the ornamentation of A2 and the number of setae on P4 endopod being one. Most of male specimens look alike in shape as well A1 ornamentation. However females differ in the above said character. The inner distal margin of the first endopodal segment of A2 produced into two stout teeth is yet another distinguishing character especially in females. Eventhough secondary, the shape and length width ratio of prosome also differs in females but in males the prosome shape is broad in almost all species. Due to the small size, barcoding of species under this genus was satisfactory only for one species ie *O.catus* which is discussed in chapter 7. Boxshall and Halsey (2004) considered a full phylogenetic revision at its generic level.

Genus *Urocorycaeus* is characterized by the presence of long and nearly parallel, but ends slightly divergent CR in both sexes measuring at least twice the length of the rest of the urosome. From this genus, only two species could be taxonomically identified which is distributed in Indian, Pacific and Atlantic oceans. They are *U.furcifer* and *U.lautus.* Species under this genus is primarily identified by the lengthy CR measuring atleast twice its length. Another distinguishing character of male specimen of *U.furcifer* from that of its allied species *U.longistylis* is the differentiation of UR into GS and AS. *U.lautus* can be differentiated by the presence of 2 setae (1long and 1 rudimentary) in the P4 endopodite whereas *U.furcifer* has only one. Size of the former is too large when compared to the latter one. Here in the present specimens from Lakshadweep islands has this differentiation very well that confirms their taxonomic identity.

The most conspicuous characters that makes the *Farranula* species distinct in both sexes are 1)two segmented prosome; 2)presence of ventral keel like knob in females; 3) combined GS and AS; 4) uniramous P4 lacking the endopod ;5) exopodal spines lacking for P1 to P3 except for the distal and terminal spines on

the distal exopodal segment. Additional morphological features that was included by Wi and Soh (2013) with the salient features of *Farranula* species from Korean waters are 1) P1 and P3 of *Farranula* species lack coxal setae, which are present on those legs of other Corycaeidae; 2) a vestigial coxal seta on P2 coxa, and a minute process on inner margin; and 3) the basis of P4 is fringed with spinules along inner median margin.

The genus *Farranula* includes seven species of which five were found in Lakshadweep waters during the present study. Due to the small size (more or less 1mm), very similar morphology as well as non-detailed previous descriptions of *Farranula* species lead to difficulty in identification. Wi and Soh (2013) mentioned about the incompleteness and mistakes of three *Farranula* species made in previously published descriptions by Motoda (1963).Those included the lack of ornamentation on the surface of the first endopodal segment and coxobasis of the antenna; dorsal habitus of *F. carinata* (Motoda 1963: figure 21a) probably represents *F. curta*, judging by figure of genital double-somite and degree of expansion of the pleural areas of second prosomal somite; incorrect setal formula for P4 in all three species. The dorsal habitus of female *F. rostrata* described by Chen *et al* (1974) is also considered as *F. curta*, because of the shape of the genital double-somite and the relatively longer caudal ramus as compared with *F. rostrata*.

Besides the lack of specific criteria for the identification of males of different species, their similar appearance also proved to be an obscurity in species differentiation. *F.gibbula*, *F.concinna* and *F.carinata* could not be matched by Farran (1911) to their respective females. Moreover, neither any specific difference of *F.gracilis* males could be displayed by both Dana (1852) and Dahl(1912) from the Atlantic Ocean. Without proper examination of the dissected appendages and also because of similar length-width proportions of PR and CR, identification of *F.concinna* and *F.carinata* seems to be very difficult.

Kiefer (1929) grouped the family Oithonidae into two subfamilies: Limnoithoninae Kiefer 1928, and Oithoninae Kiefer, 1928 and two generas: *Oithona* Baird, 1843 and *Paraoithona* Farran, 1908. Kiefer (1935) separated a new genus *Dioithona* from *Oithona* Baird, where the former is characterized by well-

developed P5 that bears two setae, one terminal and the other median besides the basal seta. In contrast, the genus *Oithona* Baird includes those having very small P5 bearing only one seta (Wellershaus,1970).But, Vervoort (1964) and Wellershaus (1970) reduced it only as a subgenus of *Oithona. Dioithona* genus could not be recognized by Nishida (1985), whereas Boxshall and Halsey (2004) did recognize it, which included *Dioithona minuta* Scott, 1894; *Dioithona rigida* Giesbrecht, 1896;*Dioithona oculata* Farran, 1913;*Dioithona alia* Kiefer, 1935; *Dioithona aurea* Lindberg, 1947;*Dioithona propinqua* Herbst, 1964 and *Dioithona horai* Sewell, 1934. During the course of study, four species under the genus *Oithona* and two under genus *Dioithona* were identified. They were *O.similis*, *O.simplex*, *O.plumifera*, *O.brevicornis*, *D.rigida* and *D.oculata*. Recently Radhika *et al* (2016) during the course of study, clearly recognized a distinct differentiation of *Dioithona rigida* from other *Oithona* species, being in agreement with Boxshall and Halsey (2004).

Family Sapphirinidae includes three genera-*Copilia*, *Sapphirina* and *Vettoria.* The Sapphirinid copepods (family *Sapphirinidae*) are distributed widely in the tropical and subtropical waters of the world oceans (Lehnhofer 1926, 1929; Sewell 1947).They are common inhabitants of Eastern Indian Ocean, the South China Sea and the tropical and subtropical western Pacific where they predominate in the epipelagic zone mainly in the upper 200m.Their unique characteristic, the iridescence of male and scanning eyes have attracted the attention of many biologists (Gregory *et al*.,1964;Elofsson,1969; Moray 1972; Land,1981,1984).The genus *Sapphirina* Thompson,1829 are characterized by its semi-transparent, ovate or subovate depressed body, comparatively short lamelliform furcal joints and the presence of a pair of eye-lenses on frontal margin of the cephalic segment (Scott, 1909; Chae & Nishida 1995;Razouls *et al*., 2015).Owing to morphological variations, Lehnhofer (1929) attempted grouping of the species under this genus. Recently, Boxshall and Halsey (2004) reduced the number of species under this genera from 20 to 15 valid species. The prosome consists of a cephalosome and four pedigerous segments. Five segmented UR in females and six segmented in males is a distinguishing feature. Another distinguishing feature of females is the width of the first urosomal segment being half of the preceding segment. Rest of the urosomal segments are of the same width whereas in males, the GS is just

about as wide as the last prosomal segment. AS is males is also small when compared to females. A general leaf like shape is allied to CR of Sapphirinid species with a superficial seta (Dorsal Setae) originating from the blade and 4 marginal setae from the outer margin. However the exact shape of CR varies with each species which can also be considered as a distinctive character. Segmentation pattern of antennule (A1) varies from 3-6. Antenna (A2) is generally four segmented terminating in a claw. Uniramous one segmented with two minute spines is the characteristic of P5 (Conway *et al.,* 2003).During the present study, ten *Sapphirina* species were identified and differentiated according to the CR shape, proportional lengths of the prosome and urosome, A1 segmentation and A2 ornamentation. *Sapphirina* males are typically larger than females.

Species under genus *Copilia* are relatively large transparent copepods in which males and females differ primarily in their body shape. Females are relatively smaller than males with distinct rectangular shaped prosome with anterior large cuticular lenses. Distance between the lenses differs in different species. Urosome narrower with four segments and CR usually longer than the urosome. The 3rd metasomal segment distal margin adorned with a backwardly pointed stout median spine mid-dorsally in females. However males resembles *Sapphirina* in their body shape but CR being long and slender and absence of cuticular lenses. A1 usually six segmented in females and four segmented in males. In females there is a noticeable differentiation between prosome and urosome whereas in males there is not. Three of the *Copilia* species were taxonomically identified ie *C. mirabilis*, *C.hendorffi* and *C.quadrata*.

Venusta and clevie are the two subgroups of genus Oncaea in which former is characterized by the absence of dorso-posterior projection on second pedigerous somite and latter by its presence. Wi et al (2009) reported seven Oncaea species from Korean waters in which *O. venusta, O. venella, O. mediterranea, O. media, O. scottodicarloi* and *O. waldmari* are included in *venusta* sub group and *O.clevie* in clevie subgroup. Regardless of their morphological similarities different variant forms have been represented. Through detailed redescriptions and phylogentic analysis, *O.venusta* was separated into three form variants ie. *O. venusta, O. venella* and *O. frosti (*Heron, 2002); *O.media* into *O.*

scottodicarloi (Heron and Bradford 1995) and *O. waldemari* (Böttger-Schnack, 2001). Even though, until now, variants of *O.mediterranea* could not be ascertained as distinct different species; two forms (a smaller and slender one, and a larger and more robust one) of this species could be described by Böttger-Schnack and Huys (1997) from the Mediterranean Sea. However, three form variants of the same species were reported from the Gulf of Mexico and northern Carribbean Sea by Ferrari (1973, 1975)in which two larger differed only in size and one small one in CR length width ratio. Three forms (small form, typical form and large form) of *O.mediterranea* have been reported by Itoh (1997) from Japanese waters. Farran (1929) too reported the same from the south of New Zealand. On the contrary, three other Oncaed species like *O. scottodicarloi, O. waldemari* and *O. clevei* too witnessed variations in CR width ratio and body size.

Anyways, Heron and Bradford (1995) has already suggested on the co-occurrence of morphologically similar species and creation of new form or size due to mating between them. While Heron and Bradford opined on the inappropriateness of simple morphology to align size variants as distinct species, Bottger-Schnack and Huys (1997) also joined hand to hand to this opinion by recommending alternative methods such as breeding experiments or ribosomal RNA sequencing.

Another group of Oncaed copepods, the *zernovi* group, as suggested by Böttger- Schnack and Huys (1997), which is now presently undergoing a preliminary version of phylogenetic study of Oncaedae, includes three species ie *Oncaea tenella*, Sars, 1916; *O. zernovi* Shmeleva 1966 and *O. tenella sensu* (Malt *et al.*,1989). Oncea group of zernovi type have not yet been identified or reported outside these specified areas like Red Sea, Arabian Sea and Adriatic Seas and upwelling area off northwest Africa due to its very small size of 0.3mm even in the adult stage. Despite Lakshadweep being a part of Arabian Sea, these particular groups of species have not been recorded in the present study area or time formerly.

Chapter 7

Morphotaxonomy and molecular analysis of selected species of Family Corycaedae

Contents

7.1 Introduction

Family Corycaeidae Dana,1852 was formerly regarded to be consisting of only two genera(*Corycaeus* Dana,1845 and *Farranula* Wilson,1932).Even though Farran in 1911 assigned the species, characterized by a ventral cephalothoracic process, as a new genus *Corycella,* the same could be replaced with the genus name "*Farranula"* only in 1932 by Wilson why because the generic name *Corycella* was already preoccupied in the Phylum Protozoa by Légar (1893).However, Dahl (1912) had already recognized seven subgenera under single genus *Corycaeus* Dana,1845.They were *Corycaeus* (*Agetus*) (Kröyer,1849), *Corycaeus* (*Corycaeus*) (Dana,1845), *Corycaeus* (*Ditrichocorycaeus*) (Dahl,1912), *Corycaeus* (*Monocorycaeus*) (Dahl,1912), *Corycaeus* (*Onychocorycaeus*) (Dahl,1912), *Corycaeus* (*Urocorycaeus*) (Dahl,1912) and *Corycaeus* (*Corycella*) (Farran,1911).But, Boxshall and Halsey (2004) through a major phylogenetic revision, established all the remaining six subgenera mentioned above as valid genera. Nevertheless appropriate morphological criteria for all generic status could not be presented for the same. Corycaeid group of copepods which are easily recognized by their peculiar body structure and large paired eyes seems to be very useful indicator forms of warm ocean currents and typically occur in epipelagic zone of tropical to temperate seas (Motoda, 1963; Boxshall Halsey, 2004; Wi *et al*., 2013a,b).

Small Corycaeid group of copepods were sampled in high abundance from almost all lagoons of the Lakshadweep archipelago. The majority of the research topics have spotlighted on their community structure and biology, thus providing

new insights into the largely unknown ecological importance of this copepod family (Robin *et al*., 2012; Radhika *et al*., 2014). Apart from ecological issues, the taxonomy of the Corycaedae family has been the subject of progressively more detailed studies over the past two decades. Nevertheless, despite these efforts, the taxonomy of many species under this family is still inadequate and have not been described in ample detail. Moreover, the species belonging to this family could be distinguished only by a very few characters, since many of the congenic species are morphologically very similar. These include micro structures like ornamentation of endopodal segments of antenna, spination of exopodal segments of the swimming legs and length-width ratio of the concerned parts, which in turn require a level of detail, which is not by and large, adopted in most taxonomic descriptions.

A frequent taxonomic confusion have been confronted for Corycaeid copepods due to identification difficulties coupled with insufficient knowledge, small body size and similar general morphology. Besides, morphological identification is tedious, ambiguous and more vulnerable to misidentification of rare species (Bucklin *et al*., 2003; Jagadeesan *et al*., 2009). Recently molecular (PCR based techniques) and morphological methods have been considered complementary and when applied in combination, constitute a powerful application for morphogenetic characterization of organisms with special reference to cyclopoid copepods in the present study.

Cytochrome c oxidase subunit (mtCOI) being considered as the most conservative protein coding genes found in the mitochondrial genomes of animals (Brown, 1985) is contemplated as one of the extensively used markers in population genetics and evolution studies (Shao *et al*., 2007) and has been proven to be efficacious in species recognition (Hebert *et al*., 2003; Waugh, 2007) especially in copepods (Bucklin *et al*., 1999; Hill *et al*., 2001). Furthermore, intraspecific variation of mtCOI gene is less when compared with that of interspecific variation thus making COI a worthy diagnostic molecular marker (Bucklin *et al*.,1998).Many recent studies have made successful DNA barcoding studies to confirm species identification (Bucklin *et al*., 1999, 2010 a, b; Costa *et al*., 2007; Ortman *et al*., 2010;Jungbluth and Lenz, 2013) thus making it an effective

tool in species identification in eukaryotes including copepods (Stoeckle,2008; Bucklin *et al*., 2010b,2011).

The phylogenetic relationship of the Corycaeid group is not well understood since molecular records for the family *Corycaedae* barely exists. Though, there exists, some molecular records of very few species of genus *Corycaeus*; the same for genus *Onychocorycaeus* and *Ditrichocorycaeu*s is completely undersupplied. Due to subtle morphological characters and small size, the species under these genera is really very difficult to identify. And therefore for this reason itself, molecular analysis outcome on these are very rare. Moreover, in the present study, the taxonomically identified species when subjected to DNA barcoding, yielded less successful results, for most of the species, with exception to few species.

Therefore, for a better understanding, this chapter in its first section provides a detailed redescription of female specimens of *Corycaeus crassiusculus* and *Onychocorycaeus catus* species and its second section details on the molecular characterization of the above said species along with three more species (*Farranula gibbula, Corycaeus speciosus and Ditrichocorycaeus andrewsi*) belonging to the Family *Corycaedae* using mtCOI gene. In earlier descriptions of *C.crassiusculus*, the ornamentation of the first endopodal segment of A2 and ventro-distal ornamentation of genital and anal somite were not given. In the case of *O.catus* too, many of the features like presence of extra spines on the 3rd exopodal segments of the 1st, 2nd and 3rd swimming legs, length ratio of coxal to 1st endopodal seta and length ratio of the spines of swimming legs were not provided in earlier descriptions (Sewell, 1947; Tanaka, 1957; Karanovic, 2003: Motoda, 1963).

Taking all these into consideration, we have provided a detailed redescription of the female specimens of *C.crassiusculus* and *O.catus* species coming under the order Cyclopoida/Poicilostomatoida and a comparison of the morphological variability with existing descriptions from other regions along with additional information on morphometry, from Kavaratti Island, Lakshadweep (South Eastern Arabian Sea). A comparison of length width proportions of the body segments of *C.crassiusculus* and *O.catus* with previous records have also provided.

These results have been published in an international peer reviewed journal *Biosystematica*, 2014, ISSN: 0973-9955, Vol.8 (1&2).

However, fortunately, the current study could present the phylogeny of some of the representative species under four genera (*Corycaeus, Onychocorycaeus, Ditrichocorycaeus* and *Farranula*) of the family Corycaedae. This obviously forms the primary barcodes of the species *Farranula gibbula*, *Corycaeus speciosus*, *Corycaeus crassiusculus*, *Onychocoycaeus catus* and *Ditrichocorycaeus andrewsi* along with the molecular *chara*cterization of two redescribed species *O.catus* and *C.crassiusculus* from Indian Ocean.

7.2 Materials and Methods

7.2.1 Sample collection and species identification

Zooplankton samples were collected from Lakshadweep islands using modified WP(working Party)plankton net (mesh size 200 µm) with an attached calibrated flow meter (General Oceanics model number-2030 R, 2012) by towing it horizontally just below the surface with a fixed speed of ~1 knot for the duration of 10 minutes. The samples were then preserved in 4% buffered formaldehyde prepared in seawater for morphological examination and 95% ethyl alcohol for molecular analysis. Specimens of *O.catus* and *C.crassiusculus* were sorted under the stereomicroscope, taxonomically important parts were dissected, observed under higher magnifications and mounted in glycerol. Drawings were made with the aid of *camera lucida* using an ALCO CM/L-967.1904 AM-25microscope. Specimens were measured using an ocular micrometer.

7.2.2 DNA isolation

Genomic DNA was extracted from single adult female specimens of *O.catus, D. andrewsi, C.speciosus*, *C.crassiusculus* and *F.gibbula* that had been alcohol preserved and were rehydrated in 500µl milliQ for 10-12hrs at room temperature (Bucklin *et al*.,1995, 1996a,b).Individual copepods, cut into pieces with a needle, were transferred to a 2ml tube. Total DNA extraction was performed with the DNeasy Blood and Tissue Kit (Qiagen) using spin column protocol and the isolates were stored at -20°C for further analysis. PCR amplification was performed with 25µl samples using a gradient thermal cycler (BIO-RAD Model Number 621BR07085).

The PCR reaction mixture (25µl) contained: 12.5 µl PCR Master mix (Takara Clontech Emerald Amp® GT PCR Master Mix (Takara Bio, Otsu,Shiga Prefecture, Japan), 1µl LCO 1490,1 µl HCO 2198,4 µl template DNA and 6.5 µl milliQ.

7.2.3 Amplification and sequencing of mitochondrial cytochrome c-oxidase sub unit I (COI) gene

PCR primers used were LCO-1490 (5-GGTCAACAAATCATAAAGATATTGG-3′) and HCO-2198 (5′-AAACTTCAGGGTGACCAAAAAATCA-3′).The PCR protocol started with preheating for polymerase activation at 94°C for 5min followed by 40 cycles of 1min each at 94°C for denaturation,37°C for 2min for annealing, extension of 72°C for 3min,a final extension for 10min at 72°C.

7.2.4 Agarose gel Electrophoresis

For analysis of the PCR products, 1% agarose gel was prepared by pouring 0.3g agarose powder into microwave flask along with 30ml of 1xTAE buffer. It was then microwaved for 1min until the agarose is completely dissolved. After cooling, 1µl EDTA was added to this solution and was poured on to the gel tray and was allowed to solidify. The gel tray was submerged in 1xTBE buffer filled in a buffer tank. Approximately 4µl of each PCR product was mixed with 1µl loading dye and loaded into the well. Electrophoresis was carried out and the gel was visualized on a UV transilluminator using the Gel Doc system (Genei™).

7.2.5 Sequencing

The PCR products were sent to ScieGenom labs (ScieGenom labs Pvt, Ltd, Kerala, India) for purification and sequencing. All the sequences developed in this study and obtained sequences from NCBI, were manually checked and aligned using the default parameters by Clustal X (Karanovic *et al*., 2014; Thompson *et al*., 1997). Phylogenetic and molecular evolutionary analyses were conducted using a Maximum Likelihood tree and intra/inter-specific pair wise distance matrix was calculated using Kimura 2 parameter model in MEGA5 (Tamura *et al*.,2011; Karanovic *et al*., 2014).

7.3 Results

7.3.1 Redescription of female specimens of *C.crassiusculus* and *O.catus* from Kavaratti Island, Lakshadweep

7.3.1.1 Systematics of *Corycaeus crassiusculus*

Order: Cyclopoida Burmeister, 1835

Family: Corycaeidae Dana, 1852

Genus: *Corycaeus*

Corycaeus (Corycaeus) crassiusculus Dana, 1848

Material examined*: Holotype:* female, INDIA: Kerala, Lakshadweep, Kavaratti, 10˚32'-10˚35'N and 72˚35'-72˚40'E, collected by Radhika.R and party on April 2013, MBM/DBT/01/14.

Female

Dorsally total length measured 0.78mm (Fig.7.2A).Measurements were taken from the anterior end of the prosome to the posterior margin of caudal rami.

Prosome four-segmented, frontal margin arc shaped, with two large separate cuticular lenses; distance between the lenses 0.044mm;prosome about twice longer than urosome including caudal rami (2.6:1.3),about 1.8 times as long as wide (2.6:1.4). Genital segment is shorter than anal somite and caudal rami combined.

Urosome (Fig.7.2D) two segmented with very divergent caudal rami. Genital somite overlaps anal somite at dorsal margin. Width of the anal somite at proximal margin is more than that at the distal margin (12.6:10.2).Proportional lengths of the urosomal somites and CR is 14.7:8.5:10. Genital somite is oval and shorter than anal somite and caudal rami combined. Distal margin of the genital somite bear a horizontal row of spines ventrolaterally. Genital segment is as long as wide.

Anal somite is rectangular shaped with its distal margin ornamented with spinules ventrolaterally; 0.98 times as long as wide at base; slightly shorter than genital somite.

Caudal rami (Fig.7.2A) divergent, about 1.3 times longer than maximum width at base; 1.1 times longer than anal somite and slightly shorter than genital

somite. Each ramus armed with six setae: slender anterolateral setae II, outer posterolateral seta III, shorter, robust and spiniform, outer terminal seta IV reduced, Inner terminal seta V longest terminal accessory seta VI short and stout and dorsal seta VII .

Antennule (Fig.7.2C) short, six segmented. Armatureformula-1-[2],2-[8],3-[2+ae],4-[3+ae],6-[5+(1+ae)]. Proportional lengths of the segments taken along posterior non setiferous margin 32.5:22.5:27.5:50:27.5:17.5.

Antenna (Fig.7.2B) four-segmented, with coxa and basis fused bearing three endopodal segments. Coxobasis 1.6 times longer than wide; inner distal margin bears a long stout setae fringed with minute spinules along the inner distal and terminal margin. Endopod three segmented and unequal; first endopodal segment robust, extremely longer than other two endopodal segments, about 2.3 times as long as wide at base; bears unipinnate setae, on inner proximal margin;2.5 times shorter than coxobasal setae.Midventral surface vertically adorned with smooth denticles along the length of the first endopodal segment. Outer lateral margin randomly decorated with small denticles in which anterolateral margin bears a serial row of five denticles; marginal two are placed equidistant and other three serially .Adjacent to mid ventral row of denticles, along the anteroventral margin two more denticles are also present in which the proximal one is the longest .Inner distal margin formed of two comparatively stout teeth like process. Second endopodal segment, shortest of the three bears three elements (a) curved hook like stout spine arising from outer distal margin and is longest (b) a small spine adjacent to its base (c) a blunt end curved spine arising from the inner margin. Third endopodal segment cylindrical slightly as long as wide at base, with a humb like protrusion at the distal part bearing a naked spiniform setae and is drawn into a curved terminal claw with a small blunt spine at inner base.

Maxilla (Fig.7.3A) two segmented with syncoxa unarmed. Inner margin of the allobasis bears one element with comb like spine. The other one forms unipinnate spine distally tapering.

Mandible (Fig.7.3B) with gnathobase bearing two elements ie,spine and blade where spine is slightly broad and robust. Blade forms spinous process surrounded by patch of spinules around base.

Maxillule (Fig.7.3C) with precoxal arthrite bearing four articulated spine like process: 1) innermost one is blunt like without spinules; 2) longest, solid and distal margin has spine like process; 3) short with some spinules on lateral margin and has spine like process on distal margin; 4) short & naked & almost equal in length of (3). Length ratio of the spines 15:25:15:15.

Maxilliped (Fig.7.3D) three segmented; solid and expanded basis; 1.8 times as long as wide at base, with an element adorned with spinules at the anterior inner margin. 3.5 times longer than width at base; Endopodal segment formed into a long curved claw, naked and slightly shorter than basis.

Legs 1-3(Fig.7.3E-G) with coxa, basis and three-segmented rami.Intercoxal sclerite well developed, P1 and P2 with plumose inner seta; basis of P1 & P3 with outer seta; exopods distinctly longer than endopods.

Exopods P1 to P3: inner margin of proximal segments fringed with long setules, relative length ratios of the terminal spine to distal outer spine and distal segment of P1-3 different: in P1, 1.8:1.1 and 1.8:1, in P2, 2.3:1 and 2.3:1and in P3, 7:2.3 and 7:3

Endopods of P1 to P3: outer margin of segment fringed with long setules; distal segment of P2 longest and that of P1shortest; length ratio of the distal segments of P1-3 approximately 30:40:37.5.

P4(Fig.7.3H)with transversely extended intercoxal sclerite,coxa present, basis with outer basal seta arising from posterior surface.Exopod well developed, three segmented, bears spinules along inner margin of the first segment; proportional length ratio of proximal, distal and terminal segment respectively,80:50:75 (along setiferous margin);distal segment about 1.3 times as long as terminal spine.Endopod reduced to knob like segment with long plumose/bipinnate seta extending up to the distal portion of outer terminal setae of exp(2). Basal seta 1.6 times longer than that. Armature formula is shown in Table.7.1.Comparison of morphometry with previous records given in Table.7.4

Table.7.1 Aramture formula of P1 to P4 of *Corycaeus crassuisculus* female

Leg	Coxa	Basis	Exopod	Endopod
P1	0-1	1-0	1-0;1-1;III,I,4	0-1;0-1;0,2,3
P2	0-1	0-0	1-0;1-1;III,I,5	0-1;0-2;0,1,3
P3	0-0	1-0	1-0;1-1;III,I,5	0-1;0-2;0,1,1
P4	0-0	1-0	1-0;1-1;I,6	0,1,0

Roman numerals indicate spine, Arabic numerals indicate setae

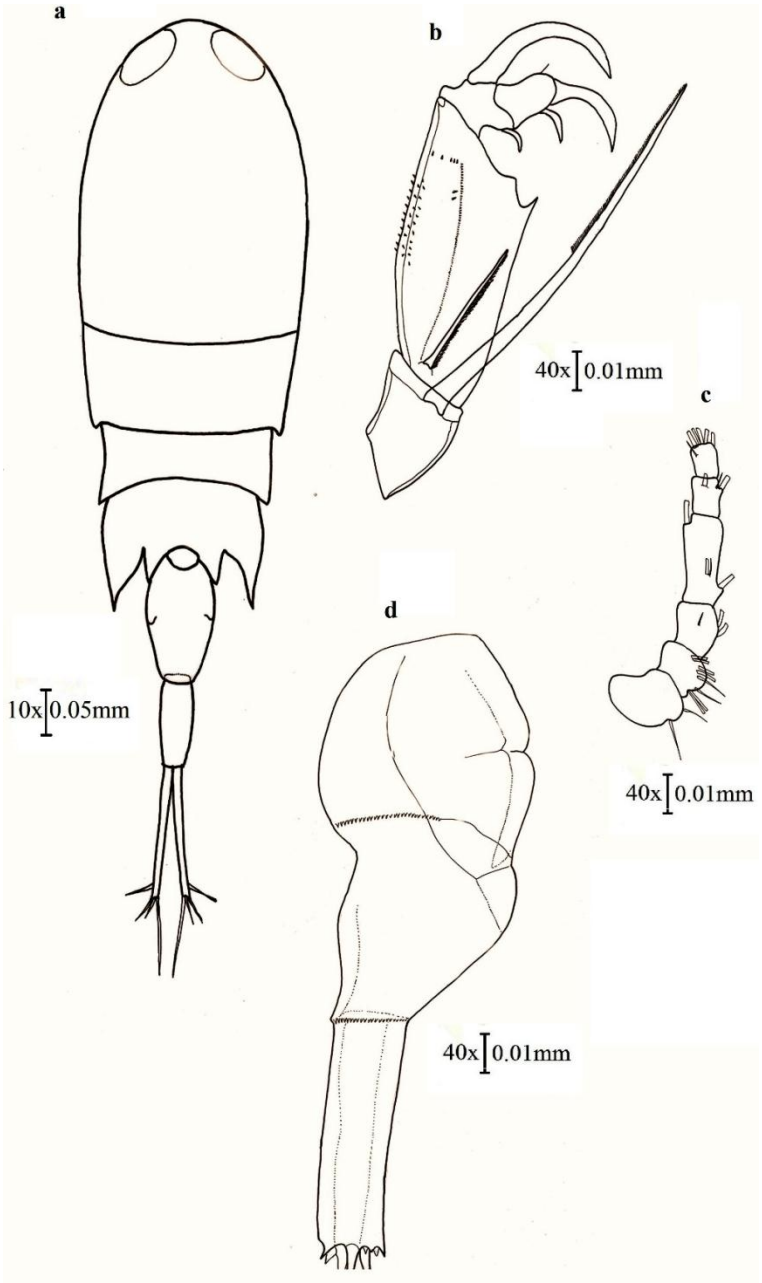


Fig.7.2.A-D. *Corycaeus crassiusculus* female. A, Habitus (dorsal); B, Antenna; C, Antennule; D, Urosome (lateral view).Measurements expressed in μm.

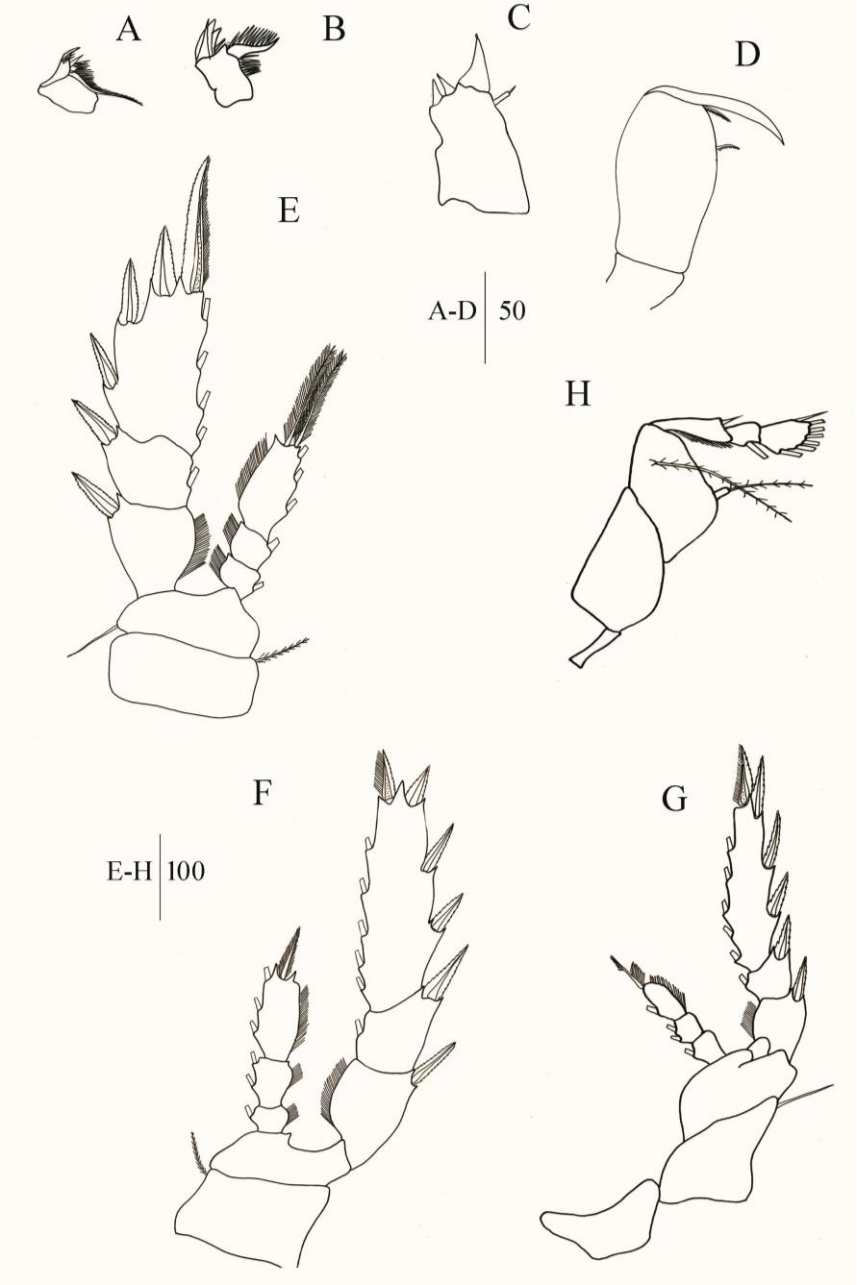


Fig.7.3.A-H. *Corycaeus crassiusculus* female. A, maxilla B, mandible; C, maxillule; D, maxilliped; E, P1; F, P2; G,P3; H,P4. Measurements expressed in μm

7.3.2 Systematics of *Onychocorycaeus catus*

Order Cyclopoida Burmeister, 1835

Family Corycaeidae Dana, 1852

Subgenus *Onychocorycaeus Dahl, 1894*

Corycaeus (Onychocorycaeus) catus Dahl, 1894

Female

Body cylindrical, tapering posteriorly. Total length measured dorsally 0.65mm (Fig.7.4A) measured from the anterior end of the prosome to the posterior margin of the caudal rami. Urosome narrower than the prosome.

Prosome four-segmented, frontal part arc shaped, with two large separate cuticular lenses with a distance of about 50µm; more than twice as long as urosome including caudal rami (4.9:1.9), about 3.39 times as long as urosome excluding caudal rami (4.9:1.4), about 1.75 times as long as wide (4.9:2.8).

Urosome (Fig.6.4B) two segmented with divergent caudal rami. Genital somite oval, 1.5 times as long as maximum width at anterior mid region (1.8:1.2); longer than anal somite and caudal rami combined; Genital area formed into flaps derived from P6 (but not figured and could not be mounted satisfactorily).

Anal somite rectangular shaped, about 1.3 times as long as wide at base (4.5:3.5); distal margin bears spinules ventrolaterally; 3.9 times shorter than genital somite and 1.3 times shorter than caudal rami.

Caudal rami divergent, 1.67 times longer than wide at base, about 0.35 times shorter as long as genital somite and 1.38 times as long as anal somite. Each ramus antiparallel, divergent, armed with six setae.

Antennule (Fig.7.4F) short, six segmented. Armature formula- 1-[2], 2-[5], 3-[2+ae], 4-[2+ae], 5-[1], 6-[4].Proportional lengths of the segments taken along posterior non setiferous margin 25:17.5:25:30:15:15.

Antenna(Fig.7.4C) four segmented with coxa and basis with strong unipinnate setae on inner distal margin.Endopod three segmented and unequal in length; first segment about 1.86 times a long as width at base bearing short unipinnate seta on ventral proximal margin much shorter than coxobasal seta, inner distal margin formed into two stout teeth. Second segment short bearing two elements a) curved stout short spine arising from outer distal margin and is longer than the other and b)comparatively smaller spine arising from the inner margin; third segment cylindrical, 1.2 times as long as wide at base, armed with a curved terminal claw and a short spine arising from the inner distal margin.

Mandible (Fig.7.4D) with gnathobase bearing two elements ie, spine & blade where spine is slightly broad and robust. Blade forms spinous process surrounded by patch of spinules around base.

Maxillule not mounted satisfactorily to allow detailed examination.

Maxilla (Fig.7.4E) with syncoxa unarmed and unornamented. Inner margin of the allobasis produced into spiniform process and bears two elements; one is broad and robust with comb like spine; the other is smaller than former with smaller combs but have many spinous processes adjacent to it.

Maxilliped (Fig.7.5E) three segmented, strong and expanded basis, syncoxa unarmed, with an element ornamented with spinules along inner margin, 2.5 times longer than width at base;endopodal segment produced into a long curved claw which is 5.2 times as long as wide at base; longer than basis and unornamented; accessory armature consists unipinnate spine on inner proximal margin of claw.

Legs 1-3 (Fig.7.5A-C) with coxa, basis and three-segmented rami.Intercoxal sclerite well developed, .P1 and P2 with plumose inner seta; basis of P1 & P3 without outer seta; exopods distinctly longer than endopods.

Exopods P1 to P3: inner margin of proximal segments fringed with long setules, relative length ratios of the terminal spine to distal outer spine and distal segment of P1-3 different: in P11.8:1.1 and 1.8:1, in P2 1.6:1 and 1.6:1and in P3 2.4:1 and 2.4:1

Endopods of P1 to P3: outer margin of segment fringed with long setules; distal segment of P2 longest and that of P1shortest; length ratio of the distal segments of P1-3 approximately 27.5:37.5:32.5.

P4(Fig.7.5D) with transversely extended intercoxal sclerite,coxa present, basis with outer basal seta arising from posterior surface.Exopod well developed, three segmented, bears spinules along inner margin of the proximal segment; proportional length ratio of proximal, distal and terminal segment respectively,27.5:15:20 (along setiferous margin);terminal spine twice longer than distal segment (2:1).Endopod reduced to knob like segment with long plumose terminal seta extending upto the distal portion of outer proximal spine of exopod two; Endopodal seta slightly longer than basal seta (1.09:1.0).Armature formula is shown in Table.7.2.

P5 and P6 present but not figured satisfactorily. P6 represented by genital flap; armed with long naked seta (but not figured)

Comparison of morphometry with previous records given in Table.7.4

Table.6.2.Aramture formula of P1 to P4 of *Onychocorycaeus catus* female

Leg	Coxa	Basis	Exopod	Endopod
P1	0-1	1-0	1-0;1-1;III,I,4	0-1;0-1;0,2,3
P2	0-1	0-0	1-0;1-1;III,I,4	0-1;0-2;0,2,2
P3	0-0	1-0	1-0;1-1;III,I,5	0-1;0-2;0,1,1
P4	0-0	1-0	1-0;0-1;I,5	0,1,0

Roman numerals indicate spine, Arabic numerals indicate setae

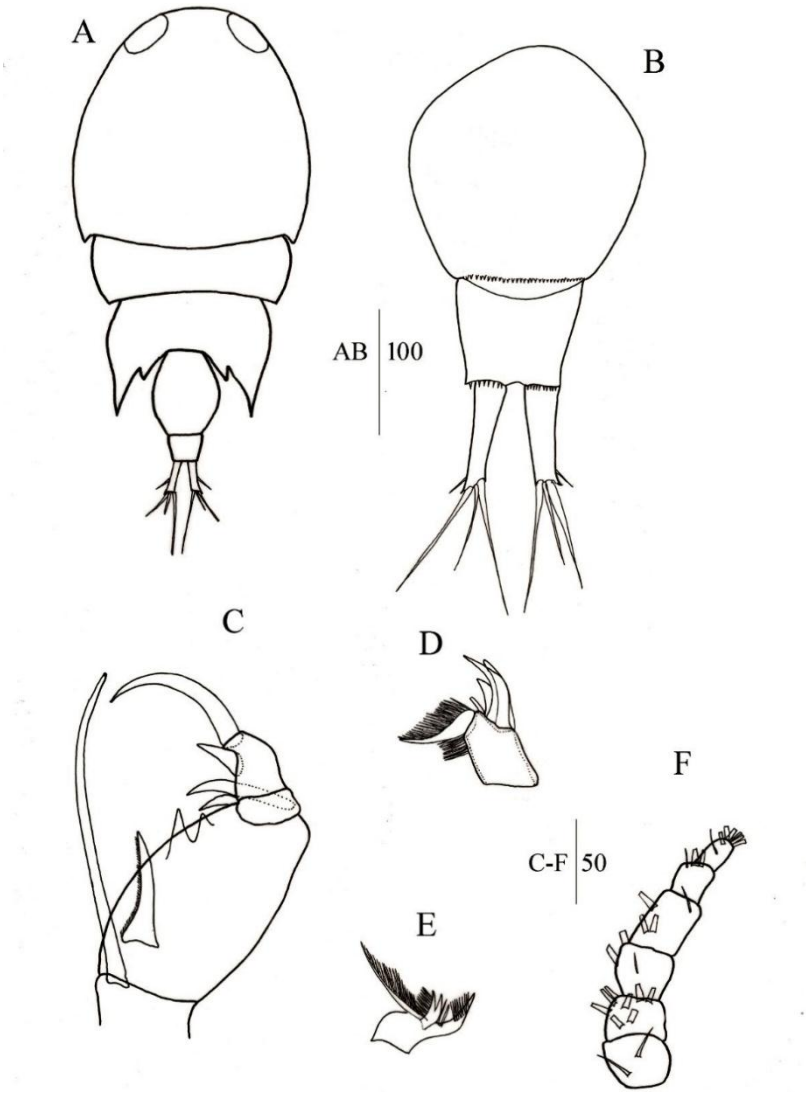


Fig.7.4A-F *O.catus* female. A, Habitus (dorsal); B, Urosome (ventral view); C, Antenna; D, Mandible; E, Maxilla; F, Antennule. Measurements expressed in µm.

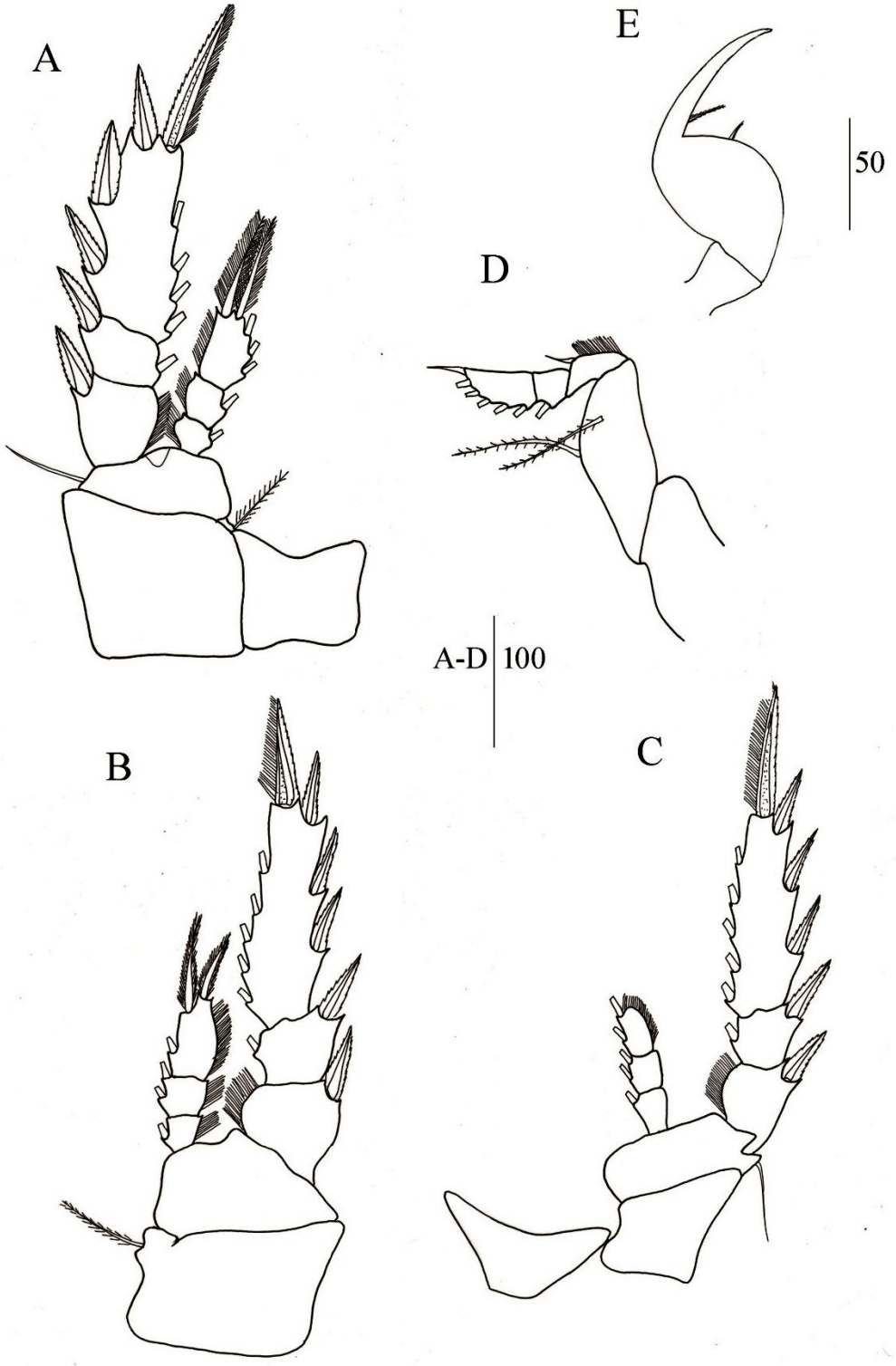


Fig.7.5.A-D *O.catus* female. A, P1; B, P2; C, P3; D, P4; E, maxilliped. Measurements expressed in µm.

Table.7.3 Length and width proportions of body segments of *C.crassiusculus* female and *O.catus* female (PR,prosome; UR,urosome; GS,Genital Somite; CR, caudal rami;P1-P4,1-4 thoracopods; exp,exopods.)

Character/species (F)	***Corycaeus crassiusculus*** female	***Onychocorycaeus catus*** female
Total Length	0.78mm	0.65mm
GS:AS:CR	14.7:8.5:10	177.5:45:62.5
PR		
Ratio of length to maximum width of PR	2.6:1.4	4.9:2.8
PR:UR (+CR)	2.6:1.3	4.9:1.9
Length ratio of PR to GS	5.2:1.02	4.9:5.2
GS/GDS		
Ratio of length to maximum width of GS	1.4:1.5	1.8:1.2
Length ratio of GS to CR	1.4:1	2.84:1
GS:anal somite	1.73:1	3.94;1
AS		
Length to width at base	1.47:1.5	4.5:3.5
CR		
Length to width	1.3:1.0	1.67:1
Antenna		
Length to width of 1st endopodal segment	2.3:1	1.86:1.0
Length ratio of coxal seta:1st endopodal seta	2.48:1.0	2.5:1
Maxilliped		
length to width of basis	1.8:1	1.93:1
Length to width of endopodal element	3.5:1	5.28:1
P1/P2/P3exp-3		
Distal segment to terminal spine	1:1.8/1:2.3/2.3:1	1:1.8/1:1.6/1.0:2.4
Terminal spine to distal outer spine	1.8:1.1/2.3:1/3:1	1.8:1.1/1.6:1/2.4:1
P4exp		
proximal spine to terminal spine	1.0:1.36	1.0:1.0
terminal spine to distal segment	1.0:1.3	2.0:1.0
Endopodal seta to Basal seta	1.0:1.6	1.09:1.0

Table.7.4. Comparison of total length and respective proportion for each segment of *C. crassiusculus* and *O.catus* with previous records

Character/species (F/M)	*Corycaeus crassiusculus*	*Onychocorycaeus catus*
Total length	0.78mm* 1.44 -1.57mm £	0.65mm* 0.92-1.01mm€ 0.80 - 0.867§ 0.93 -1mm£ 0.89 - 0.96® 1.14mm¶ 0.87 -0.95© 1.06mm¥
Length ratio of prosome to Urosome	2.6:1.3* 2.1:1.1£	4.9:1.9* 9:4£ 2:1¶
Length ratio of Urosomal somite to caudal ramus	14.7:8.5:10* 40:21:39£	177.54.5:62.5* 58:20:22£
Ratio of length to width of genital somite	1.4:1.5* 1.3:1£	
Ratio of length to width of caudal ramus	1.33:1* 6:1£	1.67:1*
Ratio of length to width of Anal somite(distal margin)	0.98* 1.8¶ 1.5†	1.3* 0.87£ 1.3¶ 0.8¥
Length ratio of caudal rami to remaining abdominal segments	0.43* 0.8¶ 0.5§	

*,present study;†, M.Dahl (1912);€, Farran(1936);§,Sewell(1947);£.Tanaka.(1957);®, Vilela (1968);¶, Motoda. (1963); ©Kang et.al (1990); ¥,Karanovic. (2003).

7.3.3 Molecular characterization of selected species under the Family Corycaedae

Twenty three species under the family Corycaedae have been taxonomically detailed in Chapter 5.Among this, DNA barcode of five species was developed based on mtCOI gene sequences. They are *F.gibbula* (NCBI accession numbers: KM114216.1, KP985538.1, KP9725 42. 1), *D.andrewsi* (KY321186, KY321187), *O.catus* (KY368180, KY368181), *C.speciosus* (KR007641, KR816563) and *C.crassiusculus* (KY923193, MF457915).

7.3.3.1 mtCOI sequence analysis of the family Corycaedae

Mitochondrial DNA COI sequences of *F.gibbula, C.speciosus, C.crassiusculus, D.andrewsi and O.catus* with average sequence length of 432 to 650 base pairs were

obtained. Developed sequences were submitted to NCBI database and accession numbers were obtained. In order to construct the maximum likelihood tree (Fig.7.6), when searched for supplementary sequences in NCBI database, mtCOI based sequences of only *C.affinis* species were available (HQ718595.1, HQ718596.1,HQ718597.1). Therefore those sequences were also included to construct maximum likelihood tree(Table.7.5).The developed and obtained sequences were of copepod origin and were substantiated by BLAST analyses of Genbank. *Paracyclopina nana* (KP899609.1) represented a preferred outgroup.

7.3.3.2 Intra/Inter specific phylogeny of *Corycaeid* species.

The cladistic array of corresponding mtCOI gene sequences in Maximum Likelihood tree supported the morphological identification as well as speciation. *C.crassiusculus* and *C.speciosus* converged into sister clades according to speciation each with a bootstrap value of 99-100%. Similarly *C.affinis* and *D.andrewsi* formed sister clades each with high bootstrap value of 99-100% and appeared as the descendants of a common ancestor. Another relative assemblage according to speciation was exhibited by *F.gibbula* next to *C.affinis* with 99% bootstrap value. *O.catus* sequences converged into a single clade forming neighbor of *F.gibbula* with 100% bootstrap value. However, the sequences of the same species developed in the present study converged into single clades exhibiting congruence within and that of different species exhibited divergence. *Paracyclopina nana* (KP899609.1) which was selected as an out-group showed a diverged array.

Phylogenetic inference obtained from Maximum Likelihood tree was scrutinized with distance matrix data .Persisting levels of intraspecific and interspecific divergence within the analyzed sequences are detailed in (Table.7.6).As evidenced from distance matrix data, the sequences of *F.gibbula, C.speciosus, C.crassiusculus, D.andrewsi and O.catus* revealed 0-1% intraspecific divergence which established their genetic identity. On the contrary, the higher interspecific divergence between *O.catus* and *F.gibbula* (42%),*O.catus* and *C.speciosus* (55%), *D.andrewsi* and *C.crassiusculus* (31%), *D.andrewsi* and *C.speciosus (*33%) and all the other species with *C.affinis* (28-47%) displayed their diverged cladistic array in the dendrogram as two different species. As expected, *Paracyclopina nana*, the selected outgroup, displayed maximum genetic distance.

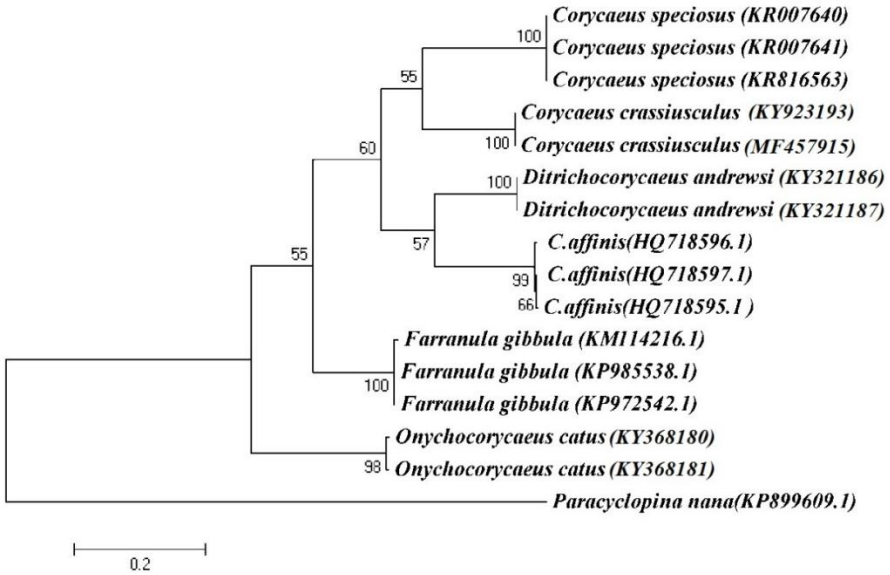


Fig.7.6 Maximum Likelihood tree (ML) tree based on 1000 pseudoreplicates. *Paracyclopina nana* is selected as an outgroup

Table.7.5 List of accession numbers used for constructing maximum likelihood tree

Sl.No	Species	Accession numbers	Remarks
1	*Farranula gibbula*	KM114216.1,KP985538.1,KP972542.1	Devoloped
2	*Ditrichocorycaeus andrewsi*	KY321186.1,KY321187.1	Devoloped
3	*Onychocorycaeus catus*	KY368180.1,KY368181.1	Devoloped
4	*Corycaeus speciosus*	KR007641.1,KR816563.1	Devoloped
5	*Corycaeus crassiusculus*	KY923193.1,MF457915.1	Devoloped
6	*Corycaeus affinis*	HQ718596.1,HQ718597.1,HQ718595.1	Obtained

7.3.3.8 Agarose gel electrophoretogram of mtCOI

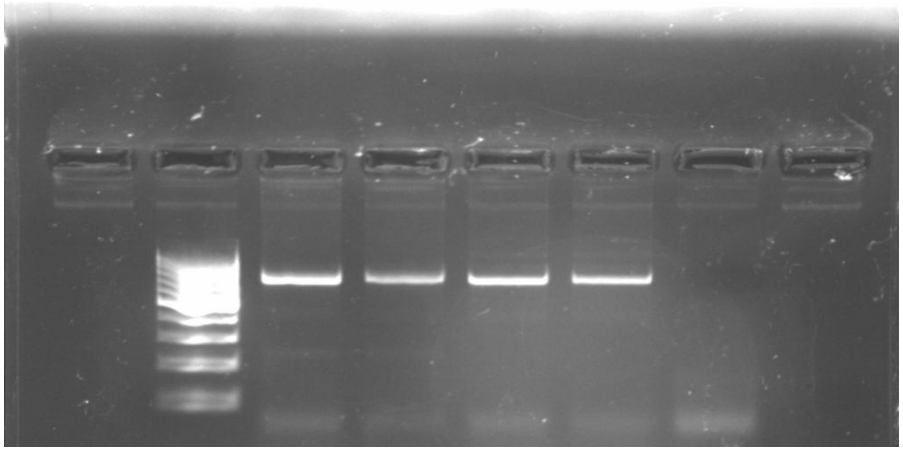


Fig.7.7 Agarose Gel Electrophoretogram of mtCOI region of species under Family *Corycaeidae*. Lane 1: Blank,Lane 2: 100bp ladder, Lane 7: Negative control.

Table.7.6 Average pairwise distance matrix among mtCOI sequences between and within species

	Oc1	Oc2	Fg1	Fg2	Fg3	Csp1	Csp2	Csp3	Da1	Da2	Ccr1	Ccr2	Ca1	Ca2	Ca3
O.catus (Oc1)															
O.catus (Oc2)	0.01														
F.gibbula (Fg1)	0.41	0.42													
F.gibbula (Fg2)	0.40	0.41	0.01												
F.gibbula (Fg3)	0.40	0.41	0.01	0.00											
C.speciosus(Csp1)	0.55	0.55	0.41	0.40	0.40										
C.speciosus(Csp2)	0.55	0.55	0.41	0.40	0.40	0.00									
C.speciosus(Csp3)	0.55	0.55	0.41	0.40	0.40	0.00	0.00								
D.andrewsi (Da1)	0.48	0.48	0.38	0.38	0.38	0.33	0.33	0.33							
D.andrewsi (Da2)	0.48	0.48	0.38	0.38	0.38	0.33	0.33	0.33	0.00						
C.crassiusculus(Ccr1)	0.55	0.57	0.34	0.33	0.33	0.31	0.31	0.31	0.31	0.31					
C.crassiusculus(Ccr2)	0.55	0.57	0.34	0.33	0.33	0.31	0.31	0.31	0.31	0.31	0.00				
C.affinis (Ca1)	0.46	0.46	0.38	0.37	0.37	0.34	0.34	0.34	0.28	0.28	0.36	0.36			
C.affinis (Ca2)	0.47	0.47	0.38	0.37	0.37	0.34	0.34	0.34	0.28	0.28	0.36	0.36	0.01		
C.affinis (Ca3)	0.46	0.46	0.38	0.37	0.37	0.34	0.34	0.34	0.28	0.28	0.36	0.36	0.00	0.01	
Pn	1.46	1.45	1.42	1.43	1.43	1.42	1.42	1.42	1.65	1.65	1.51	1.51	1.41	1.44	1.41

7.4. Discussion

7.4.1. Taxonomy of *C.crassiusculus* female

Females of *C.crassiusculus* are largely identified by the overlapping of genital segment on anal segment at the dorsal margin. The specimen described here is characterized by body length

of 0.78mm;two segmented urosome with very divergent caudal rami; ventro lateral ornamentation of the anal somite; six segmented antennule and ornamentation of the first endopodal segment of the antenna.

Females of *C.crassiusculus* showed variations from the illustrations given by Tanaka (1957) from Japanese waters in some morphological features: total length generally greater (1.44-1.57mm) than those of Kavaratti specimens (0.78mm); length ratio of the PR: UR (including CR)(2.1:1.1) slightly lesser than those of Kavaratti specimen(2.6:1.3);proportional lengths of the Urosomal somites and CR greater (40:21:39) as compared to Kavaratti specimens(14.7:8.5:10);length width ratio of the genital segment more in Japanese waters (1.3)when compared to Kavaratti specimen(1.0);length width ratio of the CR much more(6:1) when compared to those of Kavaratti specimen(1.33:1).On the other hand similar features also existed such as identical width ratio of the anal somite at proximal margin to distal margin (12.6:10.2) almost similar to those of Japanese waters (8:7) and genital somite overlaps anal somite at dorsal margin.

Descriptions of C.*crassiusculus* by Dana's (1848, 1952-55) were based exclusively on male specimens. Yet, the female of C.*venustus* described in the same papers was later identified by M. Dahl (1912) as the female of C.*crassiusculus.* Therefore the name C.*venustus* was dropped.

Females of *C.crassiusculus* described from Kavaratti waters of Lakshadweep is consistent with the typical morphological characteristics of the descriptions of Motoda(1963) from Hawaiian waters i.e. length ratio of the PR:UR is almost equal (1.6 to 1.9 vs. 2 in Kavaratti specimen);divergent and shorter CR .Conversely, variations were also there in the following features such as length ratio of the CR to remaining abdominal segments is 0.43 times shorter than GS and AS combined in Kavaratti specimen vs. 0.5 to 0.8 times longer in Hawaiian specimens; the ratio of length to breadth of the anal segment (distal margin) varied with the range of 1.1-1.8 in

Hawaiian specimen while that of Kavaratti specimen being a value of 1.43.Besides, Motoda(1963) identified Hawaiian specimens as female of *C.crassiusculus* largely because of the overlapping of genital segment over the anal segment at the dorsal margin; the feature which was very much evident in Kavaratti specimen as well.

Sewell, 1947 got the values for the proportional length of CR to the remainder of the abdomen as 0.5-0.6 which shows only slight variation with that of Kavaratti specimen being 0.43. The deformity of the CR in this species and overlapping of genital segment to anal segment at dorsal margin unlike that of female *C.speciosus* was reported by Chiba, 1955; Farran ,1929(page-292, figs. 35, 36) mentioned that, the females of this species from New Zealand waters do not have such a slender abdomen as those figured by (Giesbrecht, 1892) or (Dahl, 1912)and they closely resemble the female of *C.clausi.* Dahl(1912) in page 22 opined that the length of the CR in *C.crassiusculus* may vary with individuals and also described the anal segment of the female C.*crassiusculus* as tapering posteriorly and being 1.5 times as long as the breadth at its distal margin. Whereas the present study revealed that AS of female *C.crassiusculus* is only 0.98 times as long as wide at base. Eventhough (Dahl,1912) has mentioned of such an overlap of the genital segment on anal segment in the female of C.(C.) *clausi* (page -12), his key and figure (plate -2, fig. 6) do not show it.

7.4.2. Taxonomy of *O.catus* female

When compared with the descriptions of Tanaka (1957) from Japanese waters, females of *O.catus* from Kavaratti waters, Lakshadweep showed almost similar length ratio of PR:UR (including CR) where PR being more than 2 times the length of UR (4.9:1.9 vs. 9:4).However, a few morphological variations in the former description were also there regarding the total body length being smaller (0.65mm vs 0.93-1mm), length width ratio of the anal somite being slightly different (4.5:3.5 vs 7:8), length width ratio of the CR being smaller (1.67 vs.4) and length proportion of the GS: AS: CR being much large (177.5:45:62.5 vs. 58:20:22).The present study provides a detailed description on the morphometry of A1,A2,UR,P1-P4,mouth parts such as maxilla, mandible ,maxillule and maxilliped in addition.

On the contrary, females of *O.catus* described by Motoda (1963) from Hawaiian waters differed from those of the Kavaratti specimens in the proportional lengths of PR: UR (including CR) where PR about twice the length of UR in Hawaiian waters vs.

more than twice in Kavaratti specimen and the total body length being larger(1.14 mm vs.0.65mm) whereas the morphological characteristics such as GS longer than AS and CR combined; AS 1.3 times as long as wide (4.5:3.5) and slightly shorter than CR, were found to be similar.

In contrast, from the descriptions of female *O.catus* by Karanovic (2003) from Australian waters, the body length seems larger being 1.06mm when compared to 0.65mm of Kavaratti specimen. Variations also appear in the length width ratio of prosome which being larger in Kavaratti specimen from that of Australian specimen (1.75 vs. 1.0) as well the details like surface of the cephalic shield of the prosomites with numerous small sensilla and cuticular pores. While Karanovic (2003) explains that genital somite is only slightly longer than wide in Australian specimen, Kavaratti specimens varies from it by the genital somite being 1.5 times longer than the maximum width and anal somite about 0.8 times as long as wide in Australian specimen which is smaller to that of Kavaratti specimen (0.8 vs.1.3). Anal somite 3.9 times shorter than genital somite in Kavaratti specimen while that of Australian specimen is only 0.4 times as long as genital somite, which explains another variation.

O.catus from Kavaratti is the smallest ever reported (0.65mm).Interestingly, it is noted that, *O.pumilus* reported by Dahl(1912) and *O.catus* reported by Karanovic (2003) with an abnormal armature of the second swimming leg has only three spines on the third exopodal segment while Kavaratti specimen has four spines on the third exopodal segment. This certainly is an abnormality that also occurs on the first and the third swimming leg with only three spines on the third exopodal segment of *O.catus* reported by Karanovic (2003) while Kavaratti specimen has four spines in the third exopodal segment of first and third swimming leg. This certainly is a difference that is useful in species identification as the armature of first three swimming legs is very conservative in the family Corycaeidae Dana, 1852.

7.4.3. DNA barcoding of selected species under Family Corycaedae.

Inspite the abundance and diversity of Corycaeid copepods, only five species could be molecularly characterized. This may be due to their small size and subtle morphological variations. A scrupulous literature survey on the molecular characterization of the Corycaeid group revealed little information. Sequence data based on mtCOI gene in the NCBI database barely existed except one or two. The

molecular analysis clearly indicated the differentiation of the species according to their genus.

Wang.M; Sun,S; Cheng,F and Wang,R (2016) identified and obtained three sequences of *Corycaeus afffinis* based on mtCOI gene from the samples collected from Jiaozhou Bay along the western coast of Yellow sea. These are the only sequences available of *Corycaeus* sp. based on mtCOI gene. Rest of the few species are completely sequenced based on 18s rRNA, ITS2 and 28s rRNA out of which most of the data are unpublished. J.Hirai *et al*(2013) made use of 28s rRNA based gene sequences to resolve the phylogenetic relationships among the subtropical western North Pacific calanoid copepods along with *Corycaeus sp*. Molecular characterization of *Corycaeus danae* was done by Jagadeesan *et al* (2010) from Paragipettai coastal waters along north west coast of India based on 18s rRNA gene sequence. 18s and 28s rRNA based gene sequences of *C.speciosus* and *Corycaeus sp*. were only available in the NCBI database. All these revealed the fact that DNA barcode database of species under the Corycaedae family was lacking.

At this context of paucity of molecular information, present study provides the primary molecular barcode of the species *F.gibbula, C. speciosus ,D.andrewsi ,O. catus and C.crassiusculus* based on mitochondrial COI sequence that would help future researchers to resolve the taxonomic ambiguity.

Chapter 8

Morphotaxonomy and DNA barcoding of selected species of Family Oithonidae and Family Oncaedae

Contents

8.1 Introduction

Cyclopoid copepods of the family Oithonidae are small sized, slender cyclopiform bodied organisms with thin and transparent integuments (Kiefer, 1935; Zhong *et al.,*1989; Boxshall & Halsey, 2004; Sars,1913).They are the abundant members of the planktonic fauna of many temperate and tropical marine ecosystems (Ferrari and Orsi, 1984) and form the dominant copepod species in coastal and oceanic ecosystems (Roman *et al*., 1985; Paffenhofer *et al*.,1987 ;Jose *et al*.,2014).They range from free-living and associated forms to ecto, meso and endo-parasitic forms with amazingly diverse in body form and mode of life. They comprise nearly 11500 species (Bowman and Abele, 1982) of which approximately 2300 are marine planktonic species (Razouls *et al*., 2011; Jose *et al*., 2014).

Members of this family possess a moderately dilated prosome and long-slender urosome that makes it different from the members of other families. The prosome bears a cephalosome and four metasomal segments each bearing a pair of swimming legs. Oithonids have a distinct head with a nauplius eye and a variable rostrum. The rostrum is either curved or pointed or blunt which is directed anteriorly or ventrally (Kiefer, 1929; Boxshall & Halsey, 2004).

Species within the family *Oithonidae* have very slender A1 (antennule) generally of 10-15 segments with long diverging setae in females. Aesthetascs are present only in males. Male A1 is more markedly geniculate which is modified as grasping organs. A2 (Antenna) are small with 2-4 segments and are uniramous without an expopod (Sars 1918; Kiefer 1929; González and Bowman, 1965; Zhong,

1989).Urosome is 5 segmented in males and 6 segmented in females. The GS (genital segment) and the first abdominal segment are fused to a genital double somite (GDS) in females. GDS of females bear paired genital apertures including copulatory pores and gonopores located laterally. The genital aperture of the males is paired and located ventrally (Boxshall & Halsey 2004). Kiefer (1929) grouped the family Oithonidae into two subfamilies: Limnoithoninae Kiefer 1928, and Oithoninae Kiefer, 1928 and two generas: Oithona Baird, 1843 and Paraoithona Farran, 1908. Kiefer (1935) separated a new genus *Dioithona* from *Oithona* Baird.

Though genetic markers have widely been used for species identification in marine calanoid copepods, paucity of the same on cyclopoid copepods still persists (Jungbluth, 2013). Application of molecular techniques for the studies on population structure, phylogeography and phylogeny of copepods is very relevant (Ryuji *et al*.,2002).DNA barcoding has recently been recommended as a quick method useful for species discovery and biodiversity assessment as it provides unambiguous taxonomic discrimination (Bucklin and Wiebe 1998; Lee and Frost 2002; Eyun *et al*.,2007; Soh *et al*.,2012).The use of mtCOI gene sequence for the DNA barcoding of copepod species have now been edifying and widely accepted (Bucklin *et al*., 1999, 2010a, b; Costa *et al*., 2007; Ortman *et al*., 2010).

This chapter comprises DNA barcodes of selected species of Family Oitnonidae and Family Oncaedae. Results include two sections wherein the first section includes morphology and molecular analysis of *D.rigida* and its discussion. These results have been published in the international peer reviewed journal *Mitochondrial DNA Part A*, 2016, Taylor and Francis (publishers), doi.org/10.1080/ 24701394.2016.1202941. The second section includes DNA barcoding of *Oncaea venusta* and *Oncaea media* and its discussion.

8.2 Morphological and molecular identification of marine copepod *Dioithona rigida* Giesbrecht, 1896

The status of the genus *Dioithona* has been widely discussed amongst taxonomists. Even though Kiefer (1935) classified *Dioithona* as a separate genus, Vervoort (1964) and Wellershaus (1970) considered it only as a subgenus of *Oithona*. However this genus was not recognized by Nishida (1985), but Boxshall

and Halsey (2004) did recognize it, mainly on the basis of Abiahy (2000). Since its first description by Giesbrecht (1896), females of *D.rigida* have been described by Sewell (1947) from Arabian Sea; Mori (1964) from Japanese waters; Chen and Zhang (1974) from China seas and Shuvalov (1980) from Leningrad. Bottger and Schnack (1995) and Johan *et al* (2013) have reported the presence of *D.rigida* species from coastal waters of Bintulu-Sarawak, Malaysia and Red sea respectively.

When most of the taxonomic and molecular works got concentrated on other Oithonid species like *O.similis*, *O.atlandica* and *O.nana* (Georgina *et al*., 2012), little attention has been given to *D.rigida* and therefore, molecular studies on this species are rather limited. Contributions of Kasturirangan (1963) and Wellershaus (1970) on the taxonomy of this group along with other planktonic copepods of India are exceptions to this. However, taxonomic uncertainty still persists at the species level of the genus *Oithona and* genus *Dioithona*, particularly the coastal species, despite their importance in the world oceans (McKinnon, 2000). In view of the present scarcity of information on the classical and molecular taxonomic status of Dioithonids, we present the first molecular barcode of the species *Dioithona rigida* based on mitochondrial COI sequence, along with its morphological description.

8.3. Materials and Methods

8.3.1 DNA isolation

Genomic DNA was extracted from single adult female specimens of *D.rigida, O.venusta* and male specimens of *O.media* that had been alcohol preserved and were rehydrated in 500µl milliQ for 10-12hrs at room temperature (Bucklin *et al*., 1995, 1996a, b). Individual copepods, cut into pieces with a needle, were transferred to a 2ml tube. Total DNA extraction was performed with the DNeasy Blood and Tissue Kit (Qiagen) using spin column protocol and the isolates were stored at -20°C for further analysis. Mitochondrial DNA sequences of five specimens were determined for portions of the mitochondrial cytochrome *c* oxidase subunit I gene (mtCOI). PCR amplification was performed with 25µl samples using a gradient thermal cycler (BIO-RAD Model Number 621BR07085). The PCR reaction mixture (25µl) contained: 12.5 µl PCR Master mix (Takara

Clontech Emerald Amp® GT PCR Master Mix (Takara Bio,Otsu,Shiga Prefecture, Japan), 1µl LCO 1490,1 µl HCO 2198,4 µl template DNA and 6.5 µl milliQ.

8.3.2 Amplification and sequencing of mitochondrial cytochrome c-oxidase sub unit I (COI) gene

PCR primers were LCO-1490 (5-GGTCAACAAATCATAAAGATATTGG-3′) and HCO-2198 (5′-AAACTTCAGGGTGACCAAAAAATCA-3′). The PCR protocol started with preheating for polymerase activation at 94°C for 5 min followed by 40 cycles of 1min each at 94°C for denaturation, 37°C for 2min for annealing, extension of 72°C for 3min,a final extension for 10mn at 72°C.

8.3.3 Agarose gel Electrophoresis

For analysis of the PCR products, 1% agarose gel was prepared by pouring 0.3g agarose powder into microwave flask along with 30ml of 1xTAE buffer. It was then microwaved for 1min until the agarose is completely dissolved. After cooling, 1µl EDTA was added to this solution and was poured on to the gel tray and was allowed to solidify. The gel tray was submerged in 1xTBE buffer filled in a buffer tank. Approximately 4µl of each PCR product was mixed with 1µl loading dye and loaded into the well. Electrophoresis was carried out and the gel was visualized on a UV transilluminator.

8.3.4 Sequencing

The PCR products were sent to ScieGenom labs (ScieGenom labs Pvt, Ltd, Kerala, India) for purification and sequencing. All the sequences developed in this study and obtained sequences from NCBI were manually checked and aligned using the default parameters by Clustal X (Karanovic *et al*., 2014; Thompson *et al*., 1997).Phylogenetic and molecular evolutionary analyses were conducted using a Maximum Likelihood tree and intraspecific pair wise distance matrix was calculated using Kimura 2 parameter (K2P) model in MEGA5 (Tamura *et al*., 2011; Karanovic *et al*., 2014).

8.4 Results

8.4.1 Systematics of *D.rigida*

Phylum-Arthropoda
Class-Maxillopoda Dahl, 1956
Subclass-Copepoda Milne-Edwards, 1840
Order-Cyclopoida Burmeister, 1834
Family-Oithonidae Dana, 1853
Genus-*Dioithona* Kiefer, 1935
Species-*Dioithona rigida* female (Giesbrecht, 1896)

Female specimens were collected from Kavaratti (10°33′N-72°36′E) island, Lakshadweep sea in January 2014, postmonsoon [MBM/DBT/05/14]. Total length 0.68-0.8mm including CR (Figure.8.1.A).Prosome comprises cephalosome and 4 thoracic segments, maximum width at posterior part of cephalosome. Frontal margin arc shaped, laterally produced into single rostrum which is blunt. Urosome (Fig.8.1B) five segmented. Genital somite longest part of urosome; anterior swollen part bears P6 represented by a genital flap armed with setae. Distal margin ornamented with spines ventrolaterally. Anal somite rectangle shaped; distal margin bears spines ventrolaterally.

Caudal rami armed with six setae. Antennule (A1) (Fig.8.1C) long, symmetrical, extending to 3rd pedigerous somite dorsally; 12 segmented. Armature formula or setation pattern 2,5,8,5,1,2,2,1,1+ae,1,2+ae,6+1ae.P1-P4 (Fig.8.2 and 3A-D) biramus, with 3 segmented exopods and endopods. Exopods longer than endopods. The inner margin of proximal segment of the exopod ramus in P1-P4 bears compact dagger like setae and engorged portions of P1 basis bears a setae. P5 represented by an exopod armed with two naked setae (Fig.8.3.E). Armature formula is given in Table.8.1.

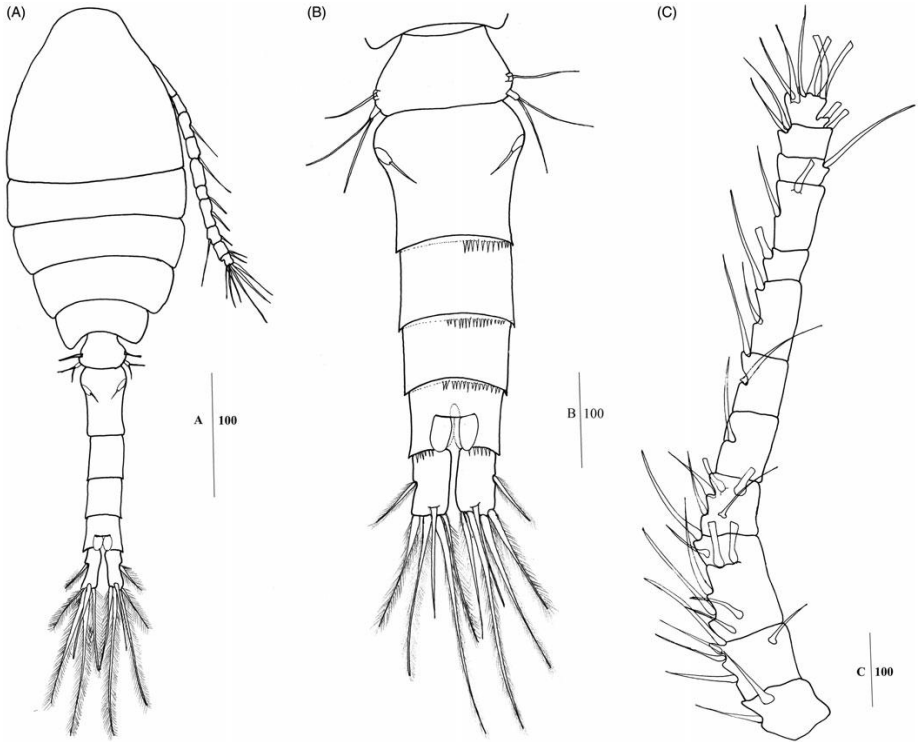


Fig.8.1. *Dioithona rigida* female. (A) Habitus (dorsal); (B) urosome (dorsal view); (C) antennule (A1). Measurements expressed in µm

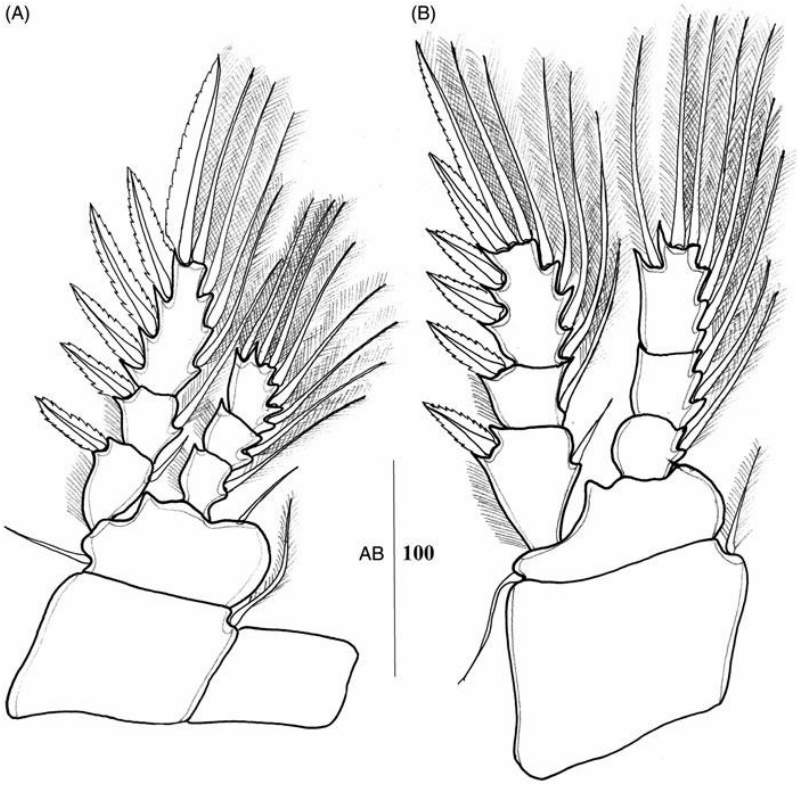


Fig. 8.2. *Dioithona rigida* female. (A) P1; (B) P2; Measurements expressed in µm

8.4.1.2 Phylogenetic analysis of *D.rigida* with other Oithonids (Molecular systematic analysis).

Mitochondrial DNA COI(mtCOI) sequences of *D.rigida* with average sequence length of 645 base pairs were obtained and were shown to comprise no indication of stop codons, ambiguities or insertions deletions indicative of nonfunctional copies of mtCOI.

Developed sequences were submitted to NCBI database and the following accession numbers were obtained KP972540, KP972541, KR528586, KR528587and KR528588.In order to construct the Maximum Likelihood tree (Fig.8.4), supplementary sequences of genus *Oithona* from NCBI database were also included (Table.8.2). The developed and obtained sequences were of copepod origin and were substantiated by BLAST analyses of Genbank. *Paracyclopina nana* (KP899609.1) represented a preferred outgroup.

The cladistic array of corresponding mtCOI gene sequences in Maximum Likelihood (ML) tree supported the morphological identification as well as speciation. *Oithona simplex* and *Oithona dissimilis* formed two clades each with high bootstrap value of 99-100% and appeared as the descendents of a common ancestor. Another relative assemblage according to speciation was exhibited by *O.similis* next to *O.dissimilis* with 100% bootstrap value. *O.attenuata* sequences converged into a single clade forming neighbor of *O.similis* with 100% bootstrap value. However, *D.rigida* sequences developed in the present study converged into a single clade exhibiting congruence with high bootstrap value of 98%. *Paracyclopina nana* (KP 899609.1) which was selected as an out-group showed a diverged array. Tree topology revealed a common ancestry of genus *Oithona and* genus *Dioithona,* as well as the divergence of *D. rigida* species into a separate entity.

Phylogenetic inference obtained from ML tree was scrutinized with distance matrix data. Persisting levels of intraspecific and interspecific divergence within the analyzed sequences are detailed in Table.8.3. As evidenced from distance matrix data, the sequences of *D.rigida* revealed 0-2% intraspecific divergence which established their genetic identity.

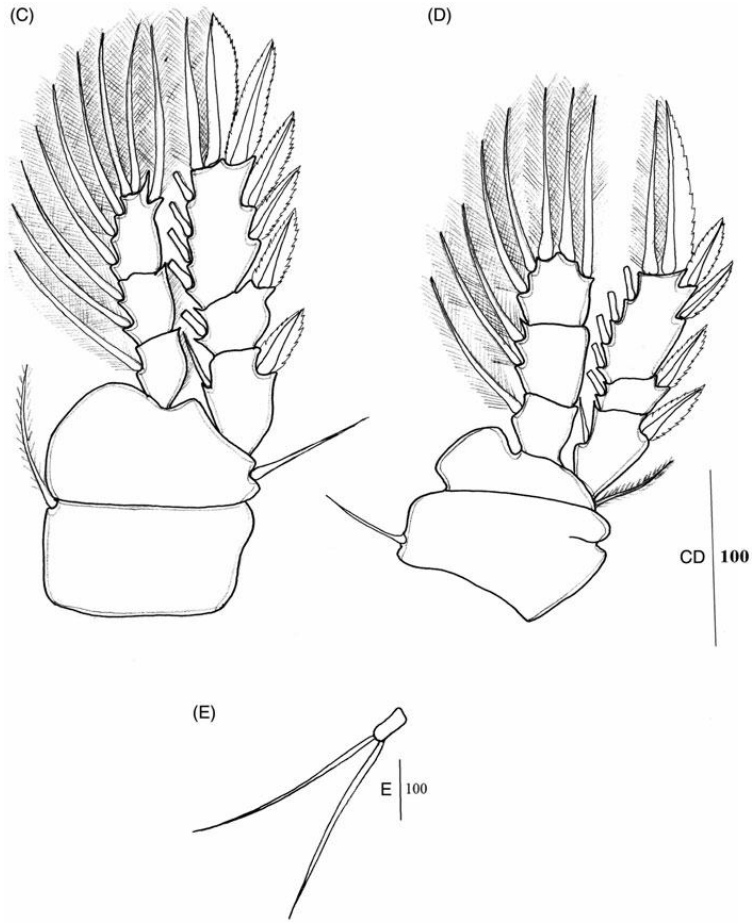


Fig.8.3. *Dioithona rigida* female. (C) P3; (D) P4; (E) P5. Measurements expressed in µm

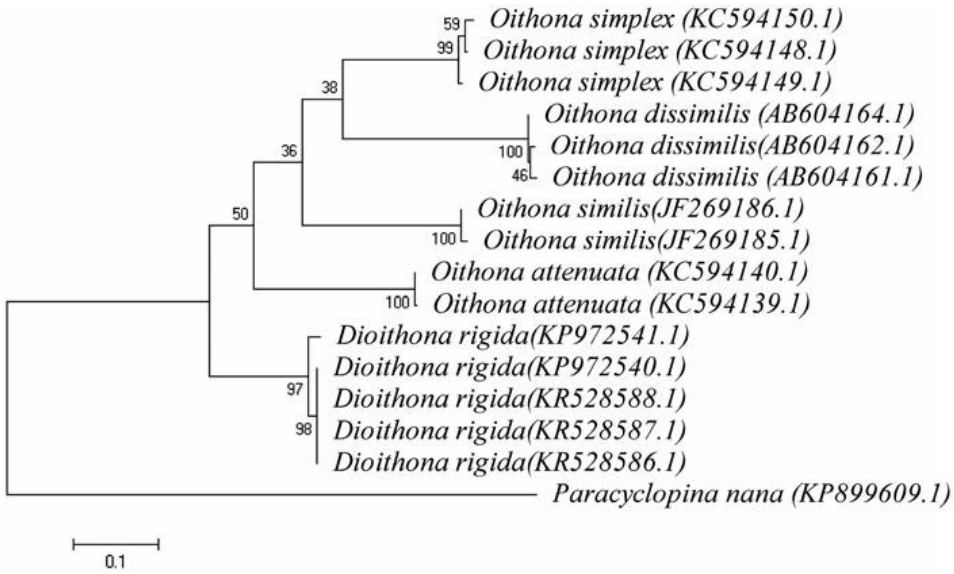


Fig.8.4 Maximum Likelihood tree (ML) tree of *D.rigida* based on 1000 pseudoreplicates. Paracyclopina nana is selected as an outgroup.

On the contrary, the higher interspecific divergence between *D.rigida* and *O.similis* (37%), *D.rigida* and *O.simplex* (40%), *D.rigida* and *O.attenuata* (35%), *D.rigida* and *O.dissimilis (*42%) displayed their diverged cladistic array in the dendrogram as two different species. *Oithona* species also showed interspecific divergence value ranging from 34-37%. As expected, *Paracyclopina* nana, the selected outgroup displayed maximum genetic distance. Agarose Gel Electrophoretogram of mtCOI region of species *D.rigida* is shown in Fig.8.6.

8.4.1.3. Discussion

Even though species of *Oithona* are highly abundant, ecologically important and widely distributed throughout the world oceans, routine identifications stay challenging due to their small size and subtle morphological diagnostic traits. Kiefer (1935) separated a new genus *Dioithona* from *Oithona* Baird, where the former is characterized by well-developed P5 that bears two setae, one terminal and the other median besides the basal seta. In contrast, the genus *Oithona* Baird includes those having very small P5 bearing only one seta (Wellershaus 1970). But Vervoort (1964) and Wellershaus (1970) reduced it only as a subgenus of *Oithona*. This genus could not be recognized by Nishida (1985), whereas Boxshall and Halsey (2004) did recognize it, which included *Oithona (Dioithona) minuta* Scott, 1894, *rigida* Giesbrecht, 1896, *oculata* Farran, 1913, *alia* Kiefer, 1935,*aurea* Lindberg, 1947, *propinqua* Herbst, 1964 and *horai* Sewell, 1934.

One of the important characters conventionally used to differentiate species within the family Oithonidae is the number of setae and spines on the exopod of swimming legs 1 to 4.The setal formulae of the exopod and endopod of *D.rigida* recorded previously by various authors are given in Table.8.4.It could be noted that the formula of exopod of P1to P4 of the present specimens conform closely to those recorded by previous authors.

A meticulous study on the previous records of *D.rigida* revealed little information on the morphological and molecular taxonomy. The specimens identified in the present study are very well characterized by the presence of the

salient features of *D.rigida.* The occurrence of *D.rigida* in Kavaratti lagoon as reported by Robin *et al* (2012) corroborates with the present report. The samples collected in the present study could be identified to *genus Dioithona* on the basis of well-developed P5 with two setae. Further, identification to species *rigida* was based on several characters like 12 segmented non-geniculate antennule (A1); 5 segmented urosome, swollen anterior part of the genital segment which is wider than that of other urosomal segments, presence of compact dagger like setae on the inner margin of proximal segment of exopod ramus in P1-P4 and presence of spine on the engorged portion of P1. All these characters agreed very well to the previous descriptions of *D.rigida* female (Sewell, 1947; Mori, 1964; Wellershaus, 1970; Cheng & Zhang, 1974; Shuvalov, 1980; Nishida, 1985). Identification of these specimens based on morphology exposed only the characters which were similar to the morphology of female *D.rigida* described earlier. During the present study of *D.rigida* specimens from Kavaratti, none of the characters were similar to that of a previously described male specimen of this particular species which, in turn, endorsed a unisexual collection.

When the morphological characters of Kavaratti specimen were evaluated, salient features like blunt rostrum, setation of free segment of P5 and segmentation of antennule, genital segment is shorter than the combined length of the following segments, setal formula of P1 to P4, proximal segment of exopod ramus in P1-P4 bearing compact dagger like setae on the inner margin were consistent with that employed by of Mori (1964), Nishida (1985), Sewell (1947) and Rosendorn (1917).

A scrupulous inquiry on the literature revealed a lack of molecular data on *D.rigida.* Molecular data based on mtCOI gene is limited to only very few species of genus *Oithona.* Ueda *et al* (2011), through molecular study, pointed out that *O.dissimilis* can be a species complex containing more than two cryptic species. Razouls *et al*(2015) opined that *Oithona brevicornis* Giesbrecht (1891) and *O. davisae* Ferrari and Orsi (1984) are coexisting close relatives in contrast to the findings of Nishida *et al* (1977) that they were different forms of the same species.

A comparative analysis using 28srDNA on the molecular systematics of *O.similis*, *O.atlandica* and *O.nana* has been reported by Georgina *et al* (2012). While Robin *et al* (2012) recently established the presence of *D.rigida* in Kavaratti waters; many others merely mentioned "*Oithona spp*." from Kavaratti atoll itself (Madhuprathap *et al*.,1991; Goswami and Usha goswami, 1990) owing to intricacy in identification due to their small size. The developed sequences of *D.rigida* in the present study were analyzed with *Oithonid* species available in the Genebank database and confirmed that *D.rigida* sequences was 37-42% divergent from other *Oithona* species which is evident from the tree topology and distance matrix data. Consequently, it could be outlined that, our developed mtCOI sequences for *D.rigida* represented the first molecular marker for the species. In addition, verification on the genetic congruence of *D.rigida* sequences revealed 0-2% intraspecific divergence value which very well confirms the threshold value of 0%-4% (Jungbluth, 2013) and by the assemblage within the ML tree forming a single clade with a bootstrap value of 98%. Therefore, the study provides the first molecular database as along with morphological authentication of *D.rigida* from Lakshadweep Sea, a part of Indian Ocean. It also establishes the interspecific and intraspecific patterns of variation of *D.rigida* with that of other *Oithona* species that resolves the taxonomic ambiguity of *D.rigida* species in marine waters.

8.4.2 DNA barcoding of selected species under Family *Oncaedae*

8.4.2.1 Phylogenetic analysis of *O.venusta* and *O.media*

mtCOI gene sequences of *O.venusta and O.media* with average sequence length of 645 base pairs were obtained. Developed sequences were submitted to NCBI database and the following accession numbers were obtained. In order to construct the ML tree, when searched in NCBI database, sequences of *O.venusta* and *O.media* based on mt Cytochrome 'b' gene were only available. Therefore those could not be included. So sequences of *Oithona* species ontained from NCBI database were included (Table.8.5). ML tree of *O.media* and *O.venusta* is shown in (Fig.8.5).

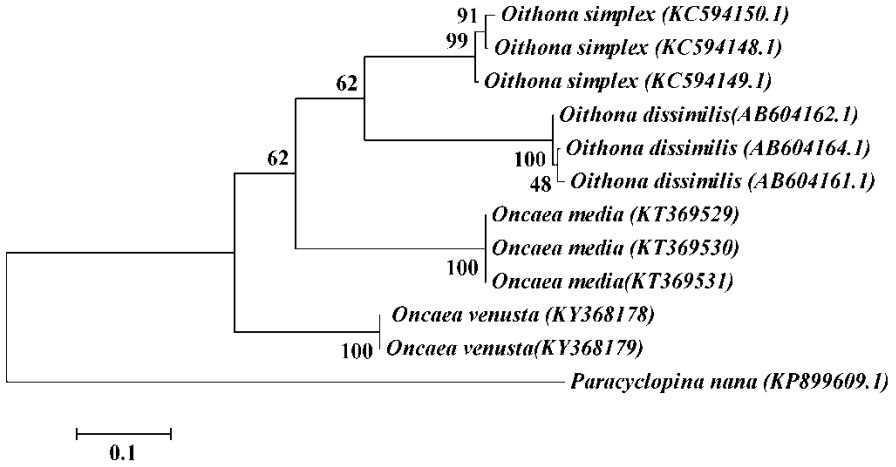


Fig.8.5 Maximum Likelihood tree (ML) tree of O*ncaea* species based on 1000 pseudoreplicates. Paracyclopina nana is selected as an outgroup.

In the tree topology, sequences of *O.media* and *O.venusta* converged into different clades each with a bootstrap value of 100% exhibiting their genetic identity and rooted a common ancestry. *Oithona simplex* and *O.diisimilis* sequences as expected assembled differently as sister clades. The selected outgroup exhibited a divergent array. In order to confirm the presumptions of dendrogram, pair wise distance matrix data was also scrutinized (Table.8.6). Distance matrix data replicated the phylogenetic inference since both the *Oncaea* species showed interspecific divergence of 38% confirming that they are two different species. Intraspecifc value was found to be 0% confirming their genetic identity. The interspecific divergence between *Oncea* and *Oithona* species was found to be 34-37%. Agarose Gel Electrophoretogram of mtCOI region of species *O.venusta* and *O.media* is shown in Fig.8.6.

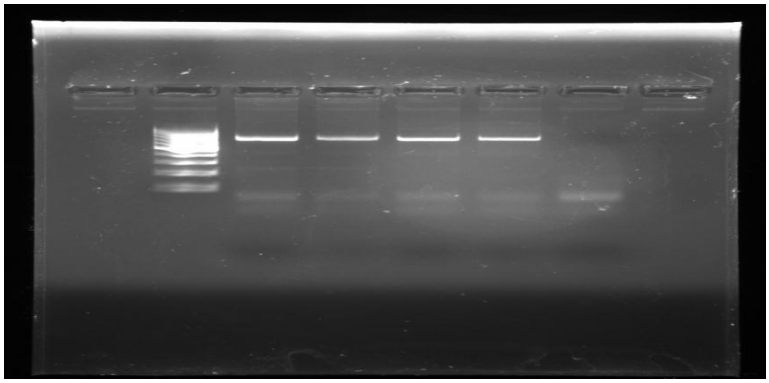


Fig.8.6 Agarose Gel Electrophoretogram of mtCOI region of species *D.rigida*, *O.venusta* and *O.media* Lane 1: Blank. Lane 2: 100bp ladder. Lane 7: Negative control

8.4.2.2 Discussion

Venusta and clevie are the two subgroups of genus Oncaea in which former is characterized by the absence of dorso-posterior projection on second pedigerous somite and latter by its presence. O.venusta and O.media come under the 'venusta' subgroup. Even though, the ecological importance of Oncaed copepods is largely implicated due to its high numerical abundance and species diversity; less has been spoken on its molecular characterization. Recently classical taxonomy works by Wi *et al* (2009) and Böttger-Schnack *et al* (2001) have been really useful for the identification of Oncaed species. Anyways, Heron and Bradford (1995) had already suggested on the co-occurrence of morphologically similar species and creation of new form or size due to mating between them. While Heron and Bradford opined on the inappropriateness of simple morphology to align size variants as distinct species, Bottger-Schnack and Huys (1997) also joined hand to hand to this opinion by recommending alternative methods such as breeding experiments or ribosomal RNA sequencing.

It's really very important to select an ideal barcode region pertinent to a selected taxon, since DNA barcoding relies on different DNA regions, the speed of sequence generation as well as maximum number of base pairs that could be accurately sequenced and therefore it varies among different taxa and even among different groups of the same taxa. There exists numerous report which support the benefits of DNA barcoding (Hebert and Gregory, 2005; Hebert *et al*., 2003a, b, 2004a, b; Rougerie *et al.,* 2012).

Sequencing of mtCyt b gene region of *O.venusta* and *O.media* by (Elvers et al., 2006) from Indian and Pacific Ocean could obtain only 310 bp which is not at all ample to barcode a particular species. On the contrary, mtCOI gene amplification of the above said same species (*O.venusta* and *O.media*) from Lakshadweep sea ,a part of Indian Ocean could obtain a sequence 534- 640bp accurately demarcating these two species. In this context, molecularly characterized or barcoded two Oncaed species, *O.media* and *O.venusta* based on mtCOI gene sequences have been presented here which represents the primary barcodes.

Table.8. 1 Armature formula of P1 to P4 of *Dioithona rigida* female (present study)

			Exopod			Endopod		
Leg	**Coxa**	**Basis**	**Proximal**	**Distal**	**Terminal**	**Proximal**	**Distal**	**Terminal**
P1	0-1	1-1	I,(1)	I,1	III,I,4	0,1	0,1	1,2,3
P2	0-1	1-0	I,(1)	I,1	III,I,5	0,1	0,2	1,2,3
P3	0-1	1-0	I,(1)	I,1	III,I,5	0,1	0,2	1,2,3
P4	0-1	1-0	I,(1)	I,1	II,I,5	0,1	0,2	1,2,2

Roman numerals (I,II,III) indicate spine, arabic numerals (1–4) indicate setae; (in brackets: reduced, dagger like).

Table 8.2 List of accession numbers used for constructing maximum likelihood tree.

Sl.No	Species	Accession numbers	Remarks
1	*Dioithona rigida*	KP972540.1,KP972541.1,KR528586.1, KR528587.1, KR528588.1	Developed
2	*Oithona simplex*	KC594148.1,KC594149.1,KC594150.1	Obtained
3	*Oithona dissimilis*	AB604161.1, AB604162.1,AB604164.1	Obtained
4	*Oithona similis*	JF269185.1, JF269186.1,	Obtained
5	*Oithona attenuata*	KC594139.1,KC594140.1	Obtained
6	*Paracyclopina nana*	KP899609.1	Obtained

Table 8.3 Average pairwise distance matrix among mtCOI sequences between and within species

Species	Dr1	Dr2	Dr3	Dr4	Dr5	Os1	Os2	Osp1	Osp2	Osp3	Oa1	Oa2	Od1	Od2	Od3	Pn
D.rigida(Dr1)																
D.rigida(Dr2)	0.00															
D.rigida(Dr3)	0.02	0.02														
D.rigida(Dr4)	0.00	0.00	0.02													
D.rigida(Dr5)	0.00	0.00	0.02	0.00												
O.similis(Os1)	0.36	0.36	0.34	0.36	0.36											
O.similis(Os2)	0.37	0.37	0.35	0.37	0.37	0.01										
O.simplex(Osp1)	0.40	0.40	0.39	0.40	0.40	0.33	0.34									
O.simplex(Osp2)	0.38	0.38	0.38	0.38	0.38	0.34	0.35	0.02								
O.simplex(Osp3)	0.39	0.39	0.39	0.39	0.39	0.34	0.35	0.01	0.01							
O.attenuata(Oa1)	0.35	0.35	0.35	0.35	0.35	0.41	0.41	0.36	0.35	0.35						
O.attenuata(Oa2)	0.34	0.34	0.35	0.34	0.34	0.41	0.41	0.36	0.35	0.35	0.00					
O.dissimilis(Od1)	0.42	0.42	0.41	0.42	0.42	0.40	0.40	0.34	0.34	0.35	0.36	0.37				
O.dissimilis(Od2)	0.42	0.42	0.41	0.42	0.42	0.40	0.40	0.34	0.34	0.35	0.37	0.37	0.01			
O.dissimilis(Od3)	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.34	0.34	0.35	0.36	0.37	0.01	0.01		
P.nana(Pn)	0.98	0.98	1.00	0.98	0.98	1.33	1.33	1.07	1.07	1.07	1.14	1.13	1.02	1.04	1.04	

Table 8.4 Setal formula of the exopod (outer and inner margins) and endopod of the four legs (P1 to P4) of female *Dioithona rigida* female recorded by previous authors

P1			P2			P3			P4			References
Exopod		Endopod	Exopod		Endopod	Exopod		Endopod	Exopod		Endopod	
Spines	Setae	Setae	Spines	Setae	Setae	Spines	Setae	Setae	Spines	Setae	Setae	
I,I,III	1,1,5	-	I,I,III	1,1,5	-	I,I,III	1,1,5	-	I,I,II	1,1,5	-	Rosendorn,1917
I,I,III	1,1,4	1,1,6	I,I,III	1,1,5	1,2,6	I,I,III	1,1,5	1,2,6	I,I,II	1,1,5	1,2,5	Sewell,1947
I,I,III	1,1,4	-	I,I,III	1,1,5	-	I,I,III	1,1,5	-	I,I,II	1,1,5	-	Mori,1964
I,I,III	1,1,4	1,1,6	I,I,III	1,1,5	1,2,6	I,I,III	1,1,5	1,2,6	I,I,II	1,1,5	1,2,5	Wellershaus,1970
I,I,III	1,1,4	1,1,6	I,I,III	1,1,5	1,2,6	I,I,III	1,1,5	1,2,6	I,I,II	1,1,5	1,2,5	Nishida,1985
I,I,III	1,1,4	1,1,6	I,I,III	1,1,5	1,2,6	I,I,III	1,1,5	1,2,6	I,I,II	1,1,5	1,2,5	Present Study

Table 8.5 List of accession numbers used for constructing maximum likelihood tree of Oncaea species

Sl.No	Species	Accession numbers	Remarks
1	*Oncaea media*	KT369529.1,KT369530.1,KT369531.1	Developed
2	*Oncaea venusta*	KY368178.1,KY368179.1	Developed
3	*Oithona dissimilis*	AB604161.1, AB604162.1,AB604164.1	Obtained
4	*Oithona simplex*	KC594148.1,KC594149.1,KC594150.1	Obtained
5	*Paracyclopina nana*	KP899609.1	Obtained

Table 8.6 Average pairwise distance matrix among mtCOI sequences between and within species of *O.media* and *O.venusta*

	Species	1	2	3	4	5	6	7	8	9	10	11	12
1	*O.media1*												
2	*O.media2*	0.00											
3	*O.media3*	0.00	0.00										
4	*O.venusta 1*	0.38	0.38	0.38									
5	*O.venusta 2*	0.38	0.38	0.38	0.00								
6	*O.simplex*	0.36	0.36	0.36	0.37	0.37							
7	*O.simplex*	0.34	0.34	0.34	0.36	0.36	0.02						
8	*O.simplex*	0.35	0.35	0.35	0.36	0.36	0.01	0.02					
9	*O.dissimilis1*	0.41	0.41	0.41	0.41	0.41	0.31	0.31	0.32				
10	*O.dissimilis2*	0.41	0.41	0.41	0.41	0.41	0.31	0.31	0.32	0.01			
11	*O.dissimilis3*	0.41	0.41	0.41	0.41	0.41	0.31	0.30	0.32	0.01	0.01		
12	*P.nana*	1.17	1.17	1.17	0.97	0.97	0.99	0.99	0.99	1.06	1.05	1.05	

Chapter 9

Genetic characterization of selected species of Family *Sapphirinidae*

Contents

9.1 Introduction

Copepod communities in lagoons and embayment of tropical islands in the Indian Ocean are geographically isolated from other populations along continents and other islands. However, even if recent taxonomic identifications imply the cosmopolitan nature of certain species, isolated existence of certain species in open ocean waters of islands to that of lagoon, also persists. Most of the tropical embayment, which are often associated with coral reef communities, are highly productive environments that are economically important, supporting fisheries and recreational activities. Not only, as these habitats and its nearby offshore waters are under threat from global warming, pollution, invasive species and overfishing (Smith *et al*., 1981,2010) but also includes the larval stages of most invertebrates, vertebrates and holoplankton. Thus significance of taxonomic and molecular identification of dominating species exists. Holoplankton, typically dominated by copepods (McKinnon *et al*.,2005) are important food source for other zooplankton including itchyoplankton, planktivorous reef fishes and reef invertebrates (Kimmerer, 1984 ; Hamner *et al*.,1988).

The Sapphirinid copepods (family *Sapphirinidae*) are distributed widely in the tropical and subtropical waters of the world oceans (Lehnhofer, 1926,1929; Sewell, 1947).They are common inhabitants of Eastern Indian Ocean, the South China sea and the tropical and subtropical Western Pacific where they predominate in the epipelagic zone mainly in the upper 200m.Their unique characteristic, the iridescence of male and scanning eyes have attracted the

attention of many biologists (Gregory *et al.,*1964; Elofsson 1969; Moray,1972; Land, 1981,1984).The genus *Sapphirina* J.Thompson,1829*,* are characterized by its semi-transparent, ovate or subovate depressed body, comparatively short lamelliform furcal joints, and the presence of a pair of eye-lenses on frontal margin of the cephalic segment (Scott, 1909; Chae & Nishida, 1995;Razouls *et al*.,2017).Owing to morphological variations, Lehnhofer (1929) attempted grouping of the species under this genus. Recently, Boxshall and Halsey (2004) reduced the number of species under this genus from 20 to 15 valid species.

When compared to other cyclopoid copepods where identification seems to be really difficult due to their small size; Sapphirinids were auspiciously large in size but due similar morphological characters of closely related species, accurate identification seemed to be tedious. Therefore, DNA barcoding has recently been recommended as a quick method useful for species discovery and biodiversity assessment as it provides unambiguous taxonomic discrimination (Bucklin and Wiebe 1998; Lee and Frost 2002; Eyun *et al*., 2007; Soh *et al*., 2012) of cyclopoids (Radhika *et al*., 2016). And subsequently application of molecular techniques for the studies on population structure, phylogeography and phylogeny of copepods is very relevant (Ryuji *et al.,* 2002).

Species under genus *Copilia* are large transparent copepods in which females are relatively smaller with distinct rectangular shaped prosome with anterior large cuticular lenses. Anyhow, males resemble *Sapphirina* species with only difference in the long and slender CR and absence of cuticular lenses. However, only seven *Copilia* species have been taxonomically identified till now of which genotyping attempted species are only *C.mirabilis*. In this context of a dearth of information on molecular part of this particular species, the present study on the DNA barcoding of *Copilia* species become significant.

Copepod communities associated with open oceans waters of Minicoy Island were mainly dominated by species under the family Sapphirinidae ie genus *Sapphirina* and *Copilia* in the present study. When Oncaeds, Oithonids ,Corycaids

were inhabitants of both lagoon as well as open ocean copepod community, the *Sapphirina* and *Copilia* species existed only in the open ocean waters of Minicoy.

A thorough scrutiny revealed that no attempt has so far been taken to explicate the phylogenetic relationships among species under the genus *Sappphirina* and genus *Copila*. This chapter, thus provides the first DNA barcode for six species under family Sapphirinidae ie. *S.auronitens*,*S.vorax*, *S.stellata*, *S.vorax*, *C.hendorffi* and *C.quadrata* collected from open ocean zones of Minicoy Island, Lakshadweep archipelago, a part of Indian Ocean.

9.2 Materials and Methods

9.2.1 Material examined

Specimens were collected from offshore(open ocean) waters of Minicoy Island (8°15′N and 73°52′E), Lakshadweep Archipelago, in April 2015 on board FORV Sagar Sampada Cruise# 338.The salinity was recorded as 33.5 to 34 PSU and temperature was in the range of 28 °C to 30 °C.

9.2.2 DNA isolation

Genomic DNA was extracted from single adult specimens of *S.auronitens*, *S.vorax*, *S.stellata*, *S.vorax*, *C.hendorffi*,*C.mirabilis* and *C.quadrata* that had been alcohol preserved and were rehydrated in 500µl milliQ for 10-12hrs at room temperature (Bucklin *et al*., 1995, 1996a, b). Individual copepods, cut into pieces with a needle, were transferred to a 2ml tube. Total DNA extraction was performed with the DNeasy Blood and Tissue Kit (Qiagen) using spin column protocol and the isolates were stored at -20°C for further analysis. Mitochondrial DNA sequences of five specimens were determined for portions of the mitochondrial cytochrome *c* oxidase subunit I gene (mtCOI). PCR amplification was performed with 25µl samples using a gradient thermal cycler (BIO-RAD Model Number 621BR07085). The PCR reaction mixture (25µl) contained: 12.5 µl PCR Master mix (Takara Clontech Emerald Amp® GT PCR Master Mix (Takara Bio,Otsu,Shiga Prefecture, Japan), 1µl LCO 1490,1 µl HCO 2198,4 µl template DNA and 6.5 µl milliQ.

9.2.3 Amplification and sequencing of mitochondrial cytochrome c-oxidase sub unit I (COI) gene

PCR primers were LCO-1490 (5-GGTCAACAAATCATAAAGATATTGG-3′) and HCO-2198 (5′-AAACTTCAGGGTGACCAAAAAATCA-3′). The PCR protocol started with preheating for polymerase activation at 94°C for 5 min followed by 40 cycles of 1min each at 94°C for denaturation, 37°C for 2min for annealing, extension of 72°C for 3min,a final extension for 10mn at 72°C.

9.2.4 Agarose gel Electrophoresis

For analysis of the PCR products, 1% agarose gel was prepared by pouring 0.3g agarose powder into microwave flask along with 30ml of 1xTAE buffer. It was then microwaved for 1min until the agarose is completely dissolved. After cooling, 1µl EDTA was added to this solution and was poured on to the gel tray and was allowed to solidify. The gel tray was submerged in 1xTBE buffer filled in a buffer tank. Approximately 4µl of each PCR product was mixed with 1µl loading dye and loaded into the well. Electrophoresis was carried out and the gel was visualized on a UV transilluminator.

9.2.5 Sequencing

The PCR products were sent to ScieGenom labs (ScieGenom labs Pvt, Ltd, Kerala, India) for purification and sequencing. All the sequences developed in this study and obtained sequences from NCBI were manually checked and aligned using the default parameters by Clustal X (Karanovic *et al*., 2014; Thompson *et al*., 1997).Phylogenetic and molecular evolutionary analyses were conducted using a Maximum Likelihood tree and intraspecific pair wise distance matrix was calculated using Kimura 2 parameter (K2P) model in MEGA5 (Tamura *et al*., 2011; Karanovic *et al*., 2014).

9.3 Results

9.3.1 DNA barcoding of *Sapphirina* species

Phylum: Arthropoda

Class: Maxillopoda Dahl, 1956

Subclass: Copepoda Milne-Edwards, 1840

Order: Cyclopoida Thompson 1829 syn.Poecilistomatoida

Family: *Sapphirinidae*

Genus: *Sapphirina*

The species *S.auronitens*, *S.metallina* ,*S.opalina*, *S.angusta*, *S.scarlata*, *S.stellata* and *S.vorax* that were described on the morphotaxonomy in Chapter 5 were confirmed by molecular analysis as distinct species.

9.3.1.2 Intra/Inter specific phylogeny of *Sapphirina* species.

Mitochondrial DNA COI sequences of *S.auronitens, S.opalina , S.metallina*, *S.angusta*, *S.scarlata*, *S.stellata*, *S.vorax* and *Sapphirina sp*. with average sequence length of 622 base pairs were obtained which comprised no indication of stop codons, ambiguities or insertions deletions. Developed sequences were submitted to NCBI database and accession numbers were obtained. In order to construct the Maximum Likelihood tree supplementary sequences of genus *Sapphirina* obtained from NCBI database were also included (Table.9.1).

The developed and obtained sequences were of copepod origin only and were substantiated by BLAST analyses of Genbank. Sequence of *Paracyclopina nana* (KP899609.1) was also included as a preferred out-group.The cladistic array of corresponding mtCOI gene sequences in Maximum Likelihood tree (Fig.9.1) supported the morphological identification as well as speciation. Sequences of *S.auronitens* and *S,angusta* exhibited congruence each with a high bootstrap value of 99-100% and diverged into sister clades with only 36 % identity. A similar pattern was displayed by another couple of sequences, *S.opalina* and *S.darwinii* in which *S.oplaina* formed a clade with 100% bootstrap value whereas it showed only 32% identity with *S.darwinii.* Another relative assemblage was exhibited by *S,stellata*. The sequences developed as *Sapphirina* sp. showed similarity to *S.stellata* with 99% bootstrap value.

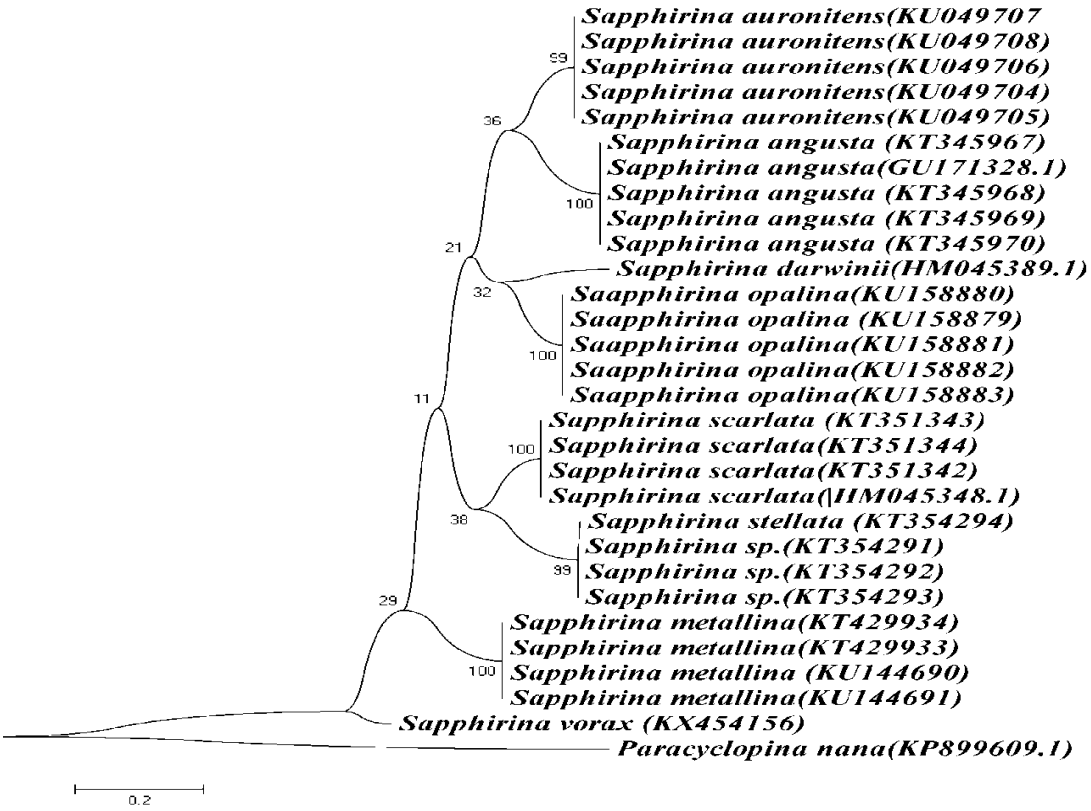


Fig.9.1 Maximum Likelihood tree (ML) tree of genus *Sapphirina* based on 1000 pseudoreplicates

Next to *S.stellata*, *S.metallina* converged into a single clade with 100% bootstrap value exhibiting genetic congruence and a single sequence of *S.vorax* assembled with only 29% similarity to its neighbor, *S.metallina.* Tree topology demonstrated a common ancestry of *Sapphirina* species and close relationships relative to others within the genus *Sapphirina.* Therefore it may be concluded that all the individuals of the genus *Sapphirina* showed considerable intra/interspecific divergence with respect to speciation.

Paracyclopina nana which was selected as an out-group showed a diverged array. Phylogenetic inference obtained from Maximum Likelihood tree was scrutinized with distance matrix data. Persisting levels of intraspecific and interspecific divergence within the analyzed sequences are detailed in (Table.9.2). The sequences of *S.auronitens, S.opalina , S.metallina*, *S.angusta*, *S.scarlata*, *S.stellata*, *S.vorax* and *Sapphirina sp* revealed 0% intraspecific divergence as evidenced from the distance matrix data which established their genetic identity. On the contrary, the higher interspecific divergence between *S.auronitens* and

S.metallina (33%), *S.auronitens* and *S.opalina* (25%), *S.metallina* and *S.opalina* (31%), S.opalina and S.darwinii (27%), *S.scarlata* and *S.stellata* (25%), *S.auronitens* and *S.vorax* (30%), *S.angusta* and *S.auronitens* (24%) were displayed by their diverged cladistic array in the dendrogram. As expected, *Paracyclopina nana*, the selected outgroup displayed maximum genetic distance. Gel Electrophoretogram of mtCOI region of Sapphirina species is shown in Fig.9.2.

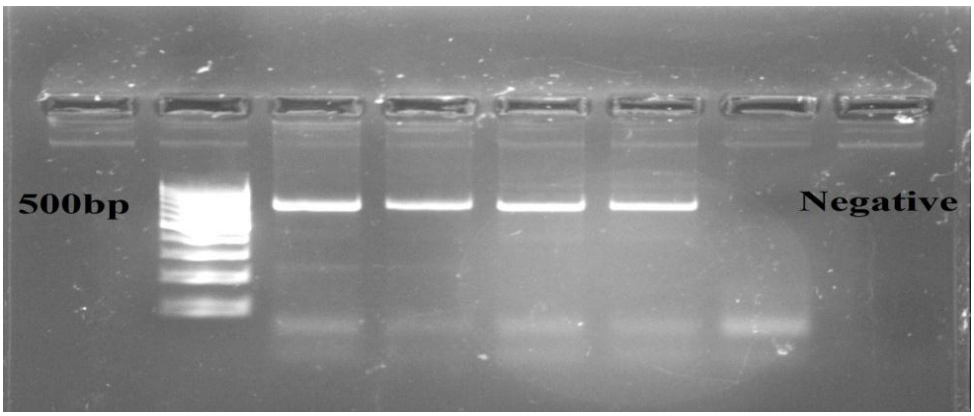


Fig.9.2 Agarose Gel Electrophoretogram of mtCOI region of species under *Sapphirina* species. Lane 1: Blank. Lane 2: 100bp ladder. Lane 7: Negative control

Table.9.1 List of accession numbers used for constructing maximum likelihood tree

Sl.No	Species	Accession numbers	Remarks
1	*S. auronitens*	KU049704.1,KU049705.1,KU049706.1, KU049707.1,KU049708.1	**Developed**
2	*S. opalina*	KU158879.1,KU158880.1,KU158881.1, KU158882.1,KU158883.1	**Developed**
	S.opalina	JX503000.1,JX503001.1,JX503002.1	Obtained
3	*S.metallina*	KU144691.1, KU200948.1, KU144690.1, KT429934.1, KT429933.1.	**Developed**
	S.metallina	KF985240.1,GU171329.1, GU171330.1	Obtained
4	*S.scarlata*	KT351342.1,KT351343.1,KT351344.1	**Devoloped**
	S.scarlata	HM045348.1	Obtained
5	*S.angusta*	KT345967.1,KT345968.1, KT345969.1, KT345970.1	**Developed**
	S.angusta	GU171328.1	Obtained
6	*S.darwinii*	HM045389.1	Obtained
7	*S.stellata*	KT354294.1	**Developed**
8	*Sapphirina sp.*	KT354291.1,KT354292.1, KT354293.1	**Developed**
9	*S.vorax*	KX454156.1	**Developed**
10	*C.hendorffi*	KY020448,KY020449	**Developed**
11	*C.mirabilis*	KT429931.1,KT429932.1	**Developed**
12	*C.quadrata*	KX470771.1, KX470772.1	**Developed**
13	*Paracyclopina nana*	KP899609.1	Obtained

9.3.2 DNA barcoding of *Copilia* species

Phylum: Arthropoda

Class: Maxillopoda Dahl, 1956

Subclass: Copepoda Milne-Edwards, 1840

Order: Cyclopoida Thompson 1829 syn.Poecilistomatoida

Family: *Sapphirinidae*

Genus: *Copilia*

Three species under the genus *Copilia- Copilia hendorffi, Copilia mirabilis* and *Copilia quadrata* that were morphologically described in Chapter 6 were confirmed as distinct species by molecular analysis.

9.3.2.1 Intra/Inter specific phylogeny of *Copilia* species

Two single individuals each of species identified as *C.hendorffi*, *C.mirabilis* and *C.quadrata* morphologically were sequenced and translated into similar amino acid sequences. When ML tree was constructed, each of the species diverged into single clades well according to speciation with high bootstrap value of 99-100% (Fig.9.3).*C.hendorffi* and *C.mirabilis* formed sister clades sharing a common ancestry with minor divergence. *C.quadrata* exhibited another relative assemblage next to *C.mirabilis.* Maximum Likelihood tree inference when examined with distance matrix data revealed persevered levels of intraspecific and interspecific divergence within the analyzed sequences are detailed in (Table.9.3). The sequences of *Copilia* species revealed 0% intraspecific divergence as evidenced from the distance matrix data which established their genetic identity. On the other hand, the higher interspecific divergence between *C.quadrata* and *C.hendorffi* (49%), *C.quadrata* and *C.mirabilis* (45-46%) and *C.hendroffi* and *C.mirabilis* (19%) confirmed their species distinctiveness. Agarose Gel Electrophoretogram of mtCOI region of species under *Copilia* species is shown in Fig.9.4

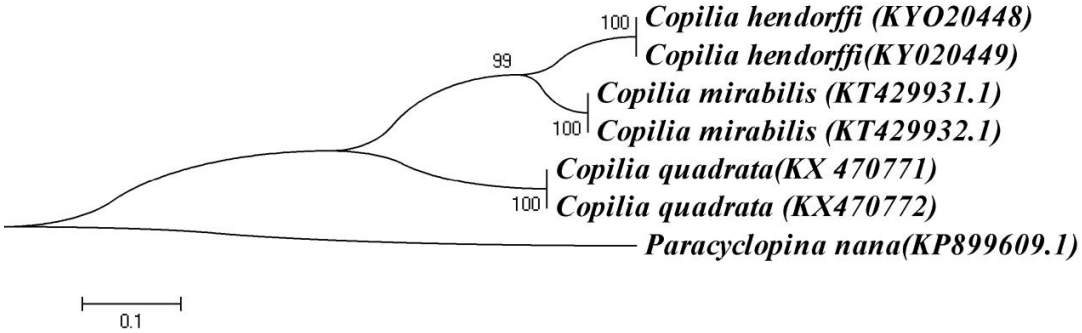


Fig.9.3 Maximum Likelihood tree (ML) tree of genus *Copilia* based on 1000 pseudoreplicates

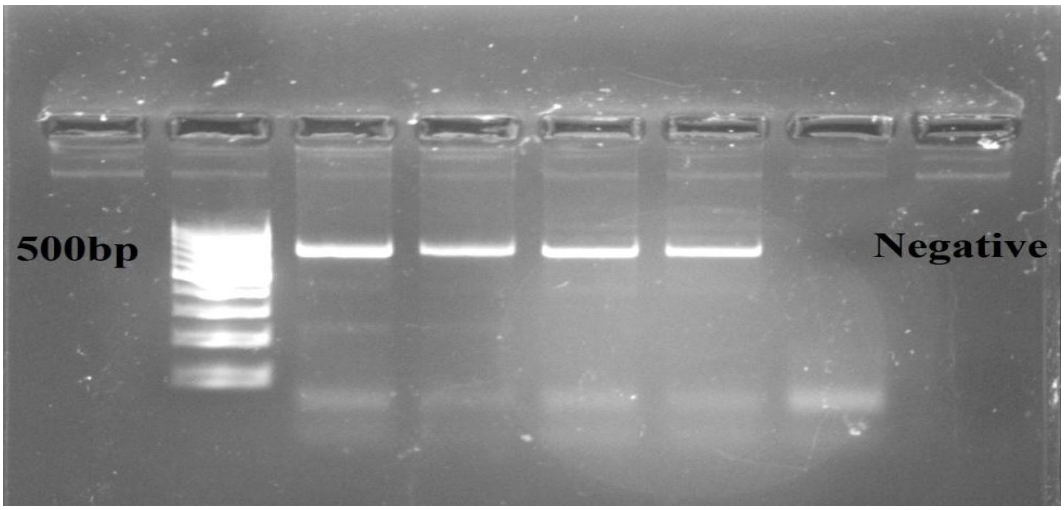


Fig.9.4 Agarose Gel Electrophoretogram of mtCOI region of species under *Copilia* species. Lane 1: Blank. Lane 2: 100bp ladder. Lane 7: Negative control

Table.9.3 Average pairwise distance matrix among mtCOI sequences between and within species

	Cq1	Cq2	Ch1	Ch2	Cm1	Cm2	Pn
Copilia quadrata (Cq1)	0.00						
Copilia quadrata (Cq2)	0.00	0.00					
Copilia hendorffi (Ch1)	0.49	0.49					
Copilia hendorffi (Ch2)	0.49	0.49	0.00				
Copilia mirabilis (Cm1)	0.46	0.46	0.19	0.19			
Copilia mirabilis (Cm2)	0.45	0.45	0.19	0.19	0.00		
Paracyclopina nana	1.13	1.13	1.25	1.25	1.09	1.09	

Table.9.4 *Sapphirina* and *Copilia* species listed in prior literature from Lakshadweep islands

Species	Island	Lagoon	Ocean	Reference
Sapphirina ovalolanceolata	Kavaratti	Absent	Present	Goswami,1973
Copilia mirabilis	Kavaratti	Present	Present	
Copilia quadrata	Kavaratti	Absent	Present	
Sapphirina spp.	Kavaratti	Absent	Present	Madhuprathap *et al*.,1977
	Agatti	Absent	Present	
	Suhelipar	Absent	_	
Copilia spp.	Kavaratti	Absent	Present	
	Agatti	Absent	Present	
	Suhelipar	Absent	_	
Sapphirina sp.	Kavaratti	_	Absent	Goswami and Usha Goswami,1990
	Minicoy	Absent	_	
Copilia sp.	Kavaratti	_	Absent	
	Minicoy	Present	_	

9.4 Discussion

Till date, molecular work has not been paired with morphological criteria to corroborate the identification of local species in any of the open ocean waters or lagoons of Lakshadweep islands. While most of the usage of genetic markers to confirm species identification focused on marine calanoid copepods, limited information is available for cyclopoid species from tropical islands.

Here, the study is being carried out in the open ocean waters surrounding the reef of Minicoy which is the southernmost and second largest atoll of the Lakshadweep archipelago. Open Ocean waters adjacent to the reefs are often characterized by high standing stocks of copepods (Bartholomew,1973; Hirota and Szyper, 1976; Hoover *et al*., 2006).The zooplanktivorous predators sheltered by the reef removes large amount of copepods from the water column as the water flows over or around them.

The species under the genus *Sapphirina* analyzed here, *S.auronitens*, *S.metallina* ,*S.opalina*, *S.angusta*, *S.scarlata*, *S.stellata*, *S.vorax* were characterized by morphological taxonomic analysis and were confirmed by molecular analysis as distinct species. When the morphological characters of *S.auronitens* described in the present study were evaluated, salient features in both sexes like cephalosome wider than long; dorsally visible cuticular lenses; ovate caudal rami; five segmented antennule; longer second segment of A1 than three following segments together and presence of a hook like process on the last endopod segment of P2, the last segment of A2 more than twice longer than terminal claw in males; fully agreed to the descriptions employed by Scott(1909); Mori (1964); Crisafi and Mazza (1966); Giesbrecht (1892); Wilson (1932). Simultaneously, the specimens of *S.metallina* described here also exhibited full agreement to previous descriptions (Scott,1909; Mori, 1964; Crusafi and Mazza,1966; Giesbrecht, 1892; Zheng *et al*.,1982) which included the presence of two spines on the first segment of antenna; quadrangular shaped caudal rami with two foliaceous terminal setae; endopod of P2 ending in 3 foliaceous spines and 6 segmented antennule; in both sexes. Morphological features of *S.opalina* male species like wider anterior round cephalosome; five segmented urosome and three segmented antennule and 4th segment of A2 longer than the terminal claw; in both sexes also exhibited close morphological proximity to *S.opalina* described previously (Scott, 1909; Mori, 1964; Crusafi and Mazza,1966; Giesbrecht, 1892; Zheng *et al*.,1982).Similar was with the case of each species under genus Sapphirina evaluated in the present study.

The caudal rami of these three species are significantly different from each other in that *S.metallina* possesses a characteristic quadrangular CR whereas *S.auronitens* has oval leaf like and *S.opalina* having an oval and wide furcal joints. *S.metallina* can be easily identified by the presence of two spines on the coxobasis as well as the quadrangular shape of CR of both sexes. *S.opalina* Dana ,1849 may be easily mistaken for *S.darwinii* Haeckel (1864).The morphology of antenna, segmentation in antennule ,maxillule and body pattern in males are similar to those of *S.darwinii*. But *S.opalina* is distinguishable from *S.darwinii* by the presence of five segmented urosome, anterior round cephalosome and longer antenna than antennule. Lahnhofer (1929) held that *S.opalina* and *S.darwinii* corresponds to

varieties of the same species. In contrast, Boxshall and Halsey (2004) did hold the taxonomic status of *S.opalina* (Razouls *et al*., 2017).The present study demonstrates the distinctiveness of these two species and it is evident that *S.opalina* and *S.darwinii* shared a common ancestry with a interspecific distance value of 29%.In addition, verification on the genetic congruence of *S.opalina* sequences revealed 0% intraspecific divergence value which very well confirms the threshold value of 0%-4% (Jungbluth, 2013).

Sapphirina and *Copilia* species listed in prior literature from Lakshadweep islands is shown in (Table.8.4) for an overview. Despite the earlier reports on the prevalence of *Sapphirina* species in Kavaratti and Agatti sea (Madhuprathap *et al.,* 1977) and in Kavaratti sea (Goswami, 1973), little is known on the morphology and molecular taxonomy of the same. Rajaram and Krishnaswamy (1981) has proposed *S.auoronitens, S.metallina and S.opalina* as frequently occurring species in the North western Indian Ocean with size ranging from 1.40mm-3.39mm in males and 1.20-3.59 mm in females. It was assumed that some dwarf forms existed in the populations might have led to misidentification of the species.

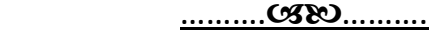
Correspondingly, distinct features of female specimen of *S.vorax* like urosome twice as long as wide, 1st metasomal segment as long as wide,5 segmented antennule confirmed its morphological identity. Lehnhofer, 1929 considered it as a variation of the species *Sapphirina auronitens- sinuicauda* . However this position was not approved by Crisafi & Mazza (1966).Even though Boxshall and Halsey (2004) did followed the position of Lehnofer and considered *S.vorax* as the single denomination of *Sapphirina auronitens,* the present study disagrees with that by confirming the uniqueness of these two species through a molecular study and is apparent that *S.vorax* and *S.auronitens* exhibited an interspecific distance value of 30% along with sharing a common ancestry.

A scrupulous inquiry on the literature revealed a lack of morphological and molecular data on *Sapphirina* species from Indian Ocean. Such taxonomic ambiguity can be resolved by DNA barcodes which provide an alternative approach to accurate identification of known species and can pace up their routine analysis. In this context, the relevance of this work becomes significant which describes the

molecular data of genus *Sapphirina* along with the first barcode of *S.auronitens* ,*S.stellata* and *S.vorax* from Lakshadweep islands, a part of Indian Ocean.

Among the three *Copilia* species described during the present study, *C.mirabilis* and *C.quadrata* was reported in Kavaratti waters by Goswami (1973). Later reports by Madhuprathap *et al* (1977) and Goswami and Usha Goswami (1990) just mentioned only *Copilia* sp. from Kavaratti Sea and Minicoy lagoon respectively.

The species under genus *Copilia* analyzed here *C.hendorffi*, *C.mirabilis* and *C.quadrata* were characterized by morphological taxonomic analysis. Female specimens of *C.mirabilis* easily distinguished by 1) rectangular shape of PR ;2) Ornamentation of A2; 3) Space between the cuticular lenses almost twice the diameter of the lenses; 3) AS longer than rest of the urosomal segments; 4) CR elongated wider at the distal end. The males of *C.mirabilis* are characterized by rounded prosome and slender A2. *C.hendorffi* male species was also distinguished by the flipping of the urosome upwards and protuberation of the last metasomal segment into a notch. The lateral margins of the metasomal segments as well as the proximal margins of the urosomal segments is festooned with minute spines. *Copilia quadrata* males could also be distinguished from other species by the presence of dark diagonal patch in the middle of the first urosomal segment .Distal middle margin of second and third urosomal segments bear small spines. However, a thorough scrutiny showed a lack of morphological and molecular data on *Copilia* species from Indian Ocean. This paucity was accomplished from the present study which confirmed their taxonomic identities through DNA barcoding.The present work provided patterns of mtCOI sequence variation between each of the studied species. Our results confirmed COI barcoding as an effective taxonomic tool and the robustness of universal primers for COI gene for identification of cyclopoids from Indian Ocean.



Chapter 10

Conclusion and recommendations

Oceans covering approximately 71% of the earth's surface are well connected forming one "World Ocean". Indian Ocean, the smallest of the three major oceans, is enormous with its unique weather patterns and extraordinary wealth and variety of life. Island ecosystem which primarily includes coastal ecosystems also fulfill many ecological roles, ranging from shoreline protection to buffer zones, from land-based activities and pollution to feeding, breeding and nursery grounds to many marine species. Among the oceanic islands, coral reefs which form a specialized ecosystem command the greatest importance by virtue of their very high productivity, maximum diversity of fauna representing all animal phyla, complexity of trophic organization and finally the resources that are of direct economic importance to mankind (Qasim, 1998). Lakshadweep (coral) islands in the South Eastern part of Arabian Sea forms the world's most spectacular tropical island ecosystem with extreme diverse geomorphologic and climatic variations. Lagoon ecosystem favours primary producers by means of their comparatively low flushing rate and often exchanges or mixes up with that of the ocean which upholds primary productivity, sequentially fostering secondary productivity. Diatoms and dinoflagellates, the largest primary producers form the basis of classic grazing food chain in oceans. These phytoplankton cells are consumed by the herbivorous grazers especially the copepods, a crucial component of zooplankton crustaceans. Copepods measuring 1-2mm in length, using their tiny mouth appendages, filter the phytoplankton. These zooplankton are then consumed by small to large fishes and then by larger predatory organisms. The huge mass of faecal pellets (poop) produced by zooplankton, the dead and decaying phytoplankton as well as zooplankton constituting the particulate organic matter (POM) forms the detritus food chain. Some POM is also consumed by zooplankton which gets recycled to grazing food chain. Among the copepods, cyclopoids are raptorial carnivores which often feeds on larger prey including fish larvae, while calanoids are both omnivorous particle grazers and

opportunistic predators on micro zooplankton whereas harpacticoids are grazers or browsers of benthic microflora and fauna (William and Dennis,2012).

Thus, understanding the grazing as well as detritus food chain in oceans requires knowledge on the zooplankton and the dominant role of copepods in partitioning the trophic elements as well as the physico-chemical attributes influencing their community structure patterns. In this context, even though isolated studies on zooplankton from different regions of the Arabian Sea (Lakshadweep) have been reported, specific works on their ecological variabilities and taxonomic characteristics are not well understood from the region. Therefore this work chronicles the mesozooplankton ecology and copepod (cyclopoid) community diversity of the Lakshadweep Sea and lagoons of the South Eastern Arabian Sea. The physico-chemical factors influencing the distribution of the organisms along with the detailed morphotaxonomy and molecular status of copepods (cyclopoids) have been discussed here.

Chapter 1 details the physical, chemical and biological character of the ocean systems. The island ecosystem and their role in sustaining the oceanic productivity is also discussed. The Indian Ocean, the Arabian Sea in particular, in the context of plankton productivity and energy transfer is elaborated. The specific orientation of the work on the role of copepods among zooplankton in delineating the trophic level changes, productivity pattern and their species wise taxonomic information is discussed in this chapter. This chapter also highlights the significance and objectives of the study.

Chapter 2 documents the international, national and regional information on different aspects of mesozooplankton and copepod abundance pattern, biomass, community structure, morphological variations and environmental patterns influencing the organisms.

Chapter 3 comprises description of the study area and transects selected, the general materials and methods employed for the collection and analysis of mesozooplankton, the hydrography of the area, morphotaxonomic and molecular analysis of cyclopoid copepods and the statistical treatment of the data. Field sampling were conducted by hired boats in different Lakshadweep islands (lagoon

stations of Kavaratti, Kalpeni, Minicoy, Agatti and Bangaram) from 2013 to 2016 during premonsoon (spring intermonsoon), monsoon (fall inter monsoon) and postmonsoon (winter monsoon) seasons for the collection of mesozooplankton and water samples for hydrographic analysis .The lagoon area of Kavaratti, Agatti and Bangaram was divided into three transects, code named T1 (coral area), T2 (inner lagoon), T3 (boat channel) and that of Kalpeni and Minicoy into two transects, T1 (coral area) and T2 (inner lagoon). Inorder to have a comparison of the zooplankton, copepod fauna and its biophysical characteristics, sampling from open ocean zones in Minicoy island was also undertaken during premonsoon (spring intermonsoon) on board the Fisheries and Oceanographic Research Vessel (FORV) Sagar Sampada (Cruise #338) in April 2015. The data collected from eighteen hydrographic stations occupied during the cruise (located between 8°12'-8°24'N and 72°54'-73°12'E) have been presented and discussed.

Chapter 4 details seasonal analysis of the hydrography from Lakshadweep lagoons (Kavaratti (Kvt), Kalpeni (Klp), Minicoy (Mcy), Agatti (Agt) and Bangaram (Bang) and open sea stations. In addition, seasonal reversal of ocean currents around the Lakshadweep islands is also discussed.

The average seasonal rainfall during 2013-14 in Lakshadweep islands ranged from 53.6±6.2mm (premonsoon), 273.2±25.9mm (monsoon) and 59.3±10.2mm (postmonsoon). Whereas during 2014-15, the average seasonal range was found to be 28.3±23.4mm (PreMon), 209.9±53mm (Mon) and 78.5±13.2mm (PoMon).During the first year (2013-14) premonsoon season of Kavaratti showed the highest average SST value (29.86°C±0.213) and also Kavaratti (Mon)(28.13°C±0.163) having the lowest values. But in the second year (2014-15), Bangaram (PreMon) showed the highest mean SST value (29.77°C±0.310) and Agatti, the lowest value (29.43°C±0.012). ANOVA of SST showed significant variation between seasons at 1% level ($p \leq 0.001$) ($F=63.247$).Mean salinity (SSS) values was highest during Kavaratti (PoMon) (36.09‰±0.445) and lowest in Kavaratti (Mon) (35.19‰±0.140) during the first year. In the second year, Bangaram (PreMon) showed the highest mean SSS values (34.98‰±0.520) and Agatti (PreMon) the lowest mean SSS values (34.88‰±0.438). ANOVA of SSS showed significant variation between seasons at

1% level (p≤0.001) (F=32.416). During the first year, mean pH values ranged between 8.75±0.004 (Kvt-PoMon) to 7.02±0.007 (Klp-Mon) whereas in the second year Kvt (8.613±0.003) showed the highest value and Bangaram the lowest value (8.44±0.016). ANOVA of pH showed significant variation between seasons and between seasons and locations at 1% level (p≤0.001) (F=32.54).Mean DO values during first year revealed Kavaratti (PoMon) (6.89±0.07mg/L) showing the highest values and Kalpeni (Mon) showing the lowest value (3.74 ±0.282mg/L), whereas in the second year Bangaram (PreMon) showed the highest mean DO value (6.07±0.05mg/L) and Agatti (PreMon) the lowest value (3.44±0.095 mg/L). Kalpeni (Mon) showed the highest mean nitrite value (0.625±0.007µM/L) and Kavaratti (PreMon) exhibited the lowest value (0.43±0.005µM/L)during the first year. But during the second year, Agatti (PreMon) (0.48±0.01µM/L) exhibited the highest value and Kvt(PreMon) (0.42±0.01µM/L) the lowest value. Minicoy (PoMon) witnessed the highest nitrate value (2.59±0.042µM/L) and Kavaratti (Premon) the lowest value (2.35±0.30µM/L) during the first year. But during the second year, Agatti (PreMon) (3.15±0.030 mg/L) displayed the highest nitrate value and Kavaratti (2.35±0.005 mg/L) the lowest. Average phosphate value was highest in Kalpeni (PoMon)(0.38±0.01µM/L) and the lowest in Kavaratti(PreMon) (0.34±0.005µM/L) during 2013-14 while Agatti(PreMon) showed the highest value (0.441±0.01µM/L) and lowest in Kavaratti(PreMon)(0.355±0.001µM/L) in the second year (2014-15).Mean silicate values were highest in Kavaratti (PreMon) (0.455±0.001µM/L) and lowest in Kavaratti(Mon) (0.31±0.01µM/L) during the first year. However, Kavaratti (PreMon) (0.516±0.01µM/L) witnessed the highest value in the second year and Bangaram (PreMon) (0.46±0.01 µM/L) being the lowest. During 2013-14, Minicoy (PoMon) showed the highest average ammonia value (0.425±0.01µM/L) and Kalpeni (Mon) the lowest value (0.42±0.01µM/L) whereas Bangaram (PreMon) had the highest (0.39±0.01µM/L) and Agatti (PreMon) the lowest mean ammonia value (0.38±0.01µM/L).

Chlorophyll a values of Kavaratti fluctuated between 0.49-0.52mg/m^3 (av.0.51±0.01) in premonsoon, 0.45-0.46mg/m^3 (av.0.456±0.005) in monsoon and 0.52-0.55mg/m^3 (av.0.533±0.015) in postmon soon 2013-14. But in Kalpeni, chlorophyll a values ranged from 0.67-0.68mg/m^3 (av.0.675±0.007) in monsoon

season and 0.15-0.16mg/m^3 (av.0.155±0.0075) in postmonsoon period. In Minicoy chlorophyll a values fluctuated between 0.21-0.23mg/m^3 (av.0.22±0.004) in monsoon and 0.18-0.19mg/m^3 (av.0.185±0.007) in postmonsoon. However, during pre-monsoon season 2014-15, Kavaratti showed chlorophyll a values of 0.14-0.15mg/m^3 (av.0.146±0.005) Agatti showed 0.25-0.47mg/m^3 (av.0.333±0.119) and Bangaram showed 0.19-0.21mg/m^3 (av.0.196±0.011). Kavaratti lagoon showed the minimum value and a maximum at Agatti lagoon. In the present study, chlorophyll a showed significant ($p \leq 0.01$) positive correlation with inorganic nutrients and negative correlation with inorganic phosphate in Kalpeni lagoon. While in Minicoy lagoon, chlorophyll a exhibited a significant ($p \leq 0.01$) positive correlation with nitrate, nitrite, silicate, phosphate and a significant ($p \leq 0.01$) negative correlation with SST, SSS, pH, DO and Ammonia. While in Kavaratti lagoon, Chlorophyll a showed a significant ($p \leq 0.05$) correlation with nitrite.

However, average sea surface temperatures in the open ocean waters (Minicoy) was found to be 30.42 ±0.19°C which slightly lowered with increasing depth from 10m to 300m. SSS were found to be 33.76±0.85psu that depicted a gradual increase with increasing depth. Average DO value was found to be 4.32±0.06 ml/L and average density of surface water was 20.28±0.16Kg/m^3. Average SST values of all the lagoons of selected islands displayed a considerable demarcation in the premonsoon season (30.04 to 30.38) than that in monsoon (27.97 to 28.31) and post monsoon (28.53 to 29.01) in the first year. Salinity exhibited a general decrease in all islands during premonsoon season. SSS (Sea surface salinity) distribution in general showed a peculiar pattern in which coastal region (lagoon stations) witnessed comparatively higher saline waters (35.53-36.13) and pockets of low saline waters in the open ocean stations (33.76 -34.88). Warmer and low saline water with a shallow MLD (Mixed Layer Depth) of 20m was observed in the open ocean waters of Minicoy during the present study. Principal Component Analysis (PCA) analysis also confirmed the strong correlation of environmental parameters that existed in different island systems.

Chapter 5 details seasonal analysis of mesozooplankton biomass and abundance pattern (with special reference to copepods) and cyclopoid community

structure from Lakshadweep lagoons (Kavaratti (Kvt), Kalpeni (Klp), Minicoy (Mcy), Agatti (Agt) and Bangaram (Bang) and open sea stations.

During the first year(2013-14), Kavaratti(PoMon) witnessed the highest mean mesozooplankton biomass (0.08±0.06ml/m^3) and abundance (111200±32579No/100m^3) and Kalpeni(Mon) witnessed the lowest biomass (0.01ml/m^3) and abundance (777±54No/100m^3).In the second year (2014-15), Bangaram (PreMon) witnessed the highest mean biomass (0.07±0.02ml/m^3) and abundance (967±935No/100m^3) whereas Kavaratti (PreMon) had the lowest biomass (0.01±0.01ml/m^3) and abundance (1893±490No/100m^3).Highest mean cyclopoid abundance was recorded in Kvt(PoMon) (30633±16990 No/100m^3)in the first year while it ranged from 301±253 No/100m^3 (Kvt-PreMon) to 617±368 No/100m^3 (Bang-PreMon) in the second year. Inter-island comparison established that Kavaratti was the most abundant and Kalpeni the least during the first year on the basis of mesozooplankton abundance whereas Bangaram contributed to the peak abundance of fauna and the least for Kavaratti island. The most dominant cyclopoid genera from the lagoon stations were *Farranula, Onychocorycaeus, Corycaeus, Ditrichocorycaeus, Oithona, Oncaea, Urochorycaeus* and *Dioithona* in three transects (T1, T2 and T3) of lagoons during different seasons. Genus *Saphhirina and Copilia* were totally absent in lagoon stations.

The average mesozooplankton abundance of Minicoy open ocean station was 8989±3866 No/100m^3 with the highest in Station 10 (15432 No/100m^3),whereas the mean biomass was 0.07±0.03ml/m^3 with highest biomass (0.11 ml/m^3)in Station 10.The cyclopoid abundance was highest in Station 18(1680 No/100m^3) and the lowest in Station 5 (310 No/100m^3). Fifty one cyclopoid species belonging to ten genera and four families were identified from eighteen stations of open ocean region in Minicoy Island. The dominant genus was *Sapphirina* and least dominant genus was *Urocorycaeus*. Inter-island comparison established that Kavaratti was the most abundant and Kalpeni the least during the first year on the basis of cyclopoid abundance whereas Bangaram contributed to the peak abundance of cyclopoids and the least in Kavaratti island. Similarity analyses based on mesozooplankton abundance showed that in Kavaratti stations, 13-14, PreMonT2, MonT1, PoMon T1 stood apart from other clusters. Transects of

both seasons showed more than 90% similarity in Kalpeni during first year. Whereas in Minicoy, transects of both seasons formed clusters with more than 85% similarity. While in Bangaram, BangT3 and BangT2 were clustered together with 86% similarity and that in AgtT2, Kvt T3, Bang T1 stood apart.

SIMPER analysis grouped stations based on species responsible for the clustering pattern of cyclopoids. In Kavaratti 13-14, average similarity of T1 (55.39%), T2 (55.29%), T3 (43.47%) was mainly contributed by 21species of which *Corycaeus crassiusculus* became the most discriminating species. In Kalpeni stations, 13-14, average similarity of T1(55.26%) was mainly contributed by 17 species of which, *Dioithona rigida* was the major contributor. While average similarity of T2 (62.66%) was mainly contributed by 13 species of which, *Ditrichocorycaeus dahli* was the major contributor. In Minicoy stations, 13-14 average similarity of T1 (39.96%) was mainly contributed by 23 species of which *Farranula gibbula* was the major contributor. While average similarity of T2 (38.98%) was mainly contributed by 26 species of which *Oithona plumifera* was the major contributor. In Agatti stations,14-15 during the second year, the average dissimilarity between T1 and T2(17.05%), between T1 and T3 (18.89%) was mainly contributed by *Onychocorycaeus giesbrechti* and that between T2 and T3 (23.36%) was contributed by *Corycaeus crassiusculus.* In Bangaram stations,14-15, the average dissimilarity of 13.5% between T1 and T2 was mainly contributed by *Oithona similis*, while *Corycaeus vitreus* contributed mainly to average dissimilarity of 39.55% between T1 and T3 and *Corycaeus crassiusculus* contributed mainly to average dissimilarity of 35.54% between T2 and T3.In Kavaratti stations,14-15, the average dissimilarity of 29.25% between T1 and T2 was mainly contributed by *Ditrichocorycaeus dahli*, while *Oncaea scottidicarloi* contributed mainly to average dissimilarity of 69.31% between T1 and T3 and *Onychocorycaeus agilis* contributed mainly to average dissimilarity of 50.39% between T2 and T3. In open ocean stations of Minicoy, the average dissimilarity between 18 stations were mainly contributed by *Sapphirina scarlata, Sapphirina nigromaculata, Oncaea scottodicarloi, Oncaea media, Farranula curta, Ditrichocoryceus andrewsi, Copilia mirabilis, Sapphirina stellate, Sapphrina vorax, Copilia hendorffi, Dioithona oculata, Farranula gracilis, Corycaeus vitreus, Sapphrina auronitens, Urocorycaeus lautus,*

Oithona simplex, Copilia mirabilis, Ditrichocoryceus dahlia, Sapphirina metallina and *Sapphirina siniuicauda.*

A total of thirty four cyclopoid species from lagoon stations of Kavaratti, twenty seven from Kalpeni, thirty eight from Minicoy, thirty six from Bangaram and fifty one species from Minicoy open ocean stations were identified. Cyclopoid species diversity showed a wide range of variation in which the species reported from the present study included eighteen species under the genus *Corycaeus*; five species from genus Farranula; eight species from genus *Oncaea*; five species from genus *Oithona*; two species from genus *Dioithona ;*ten species from genus *Sapphirina* and three species from genus *Copilia.* Among them, *Sapphirina* and *Copilia* species were found only from Minicoy open ocean stations and not from the lagoons. However species like *Oncaea conifera, Corycaeus pellucidus, C.longistylis, Oithona tropica, Oithona robusta* and *Sapphirina ovalolanceolata* were reported by Goswami(1973) but was absent during the present study.

In the first year, Minicoy represented the maximum value for Margalef species richness index (5.841),Shanon diversity index (3.408) and Simpson's dominance index (0.969) whereas Kalpeni registered maximum Pielou's evenness index(0.979).But Kavaratti represented the minimum value for Margalef species richness index (3.246),Shanon index (2.664), Simpson's index (0.797) and Pielou's index(0.827).However during the second year, Bangaram registered maximum value for Margalef index (6.862),Shanon index (3.445), Simpson's index (0.974) and Pielou's index(0.977) while Kavaratti represented the minimum values for Margalef index (6.437),Shanon index (3.245),Simpson's index (0.973) and Pielou's index (0.971).

However ABC plots established that during first year, Kalpeni (Mon)and Minicoy (PoMon) to be moderately disturbed community (abundance and biomass curve intersect) whereas Kavaratti (PreMon), Kavaratti (Mon), Kavaratti (PoMon), Kalpeni(PoMon) as undisturbed community (biomass curve above abundance curve). However in second year, Kavaratti (PreMon), Agatti (PreMon) and Bangaram (PreMon) were established to be undisturbed community.

In the first year, the 95% confidence funnel drawn for the variation in taxonomic distinctness values of Kavaratti showed that all the points fell outside the confidence level showing deviation from normal deviation. While in Kalpeni and Minicoy, for the 95% confidence funnel drawn for the variation in taxonomic distinctness values, all points fell within the confidence level showing no deviation from normal deviation. However in the second year, confidence funnel drawn for the variation in taxonomic distinctness values of Kavaratti, Agatti and Bangaram showed that all points clustered together within 95% confidence level. Confidence funnel drawn for the variation in taxonomic distinctness values of open ocean zones of Minicoy island revealed that all the points clustered within 95% confidence level showing no deviation from normal.

Species accumulation plots observed and predicted 40 cyclopoid spp.(Kvt), 37spp. (Klp), 39spp. (Mcy) and 38 spp. (Agt and Bang) thus signifying the accuracy of sampling intensity. Using multivariate analysis(MDS plots), it was possible to divide the transects into three groups in Kavaratti and Kalpeni based on cyclopoid abundance during the first year ,two groups in Kavaratti, Bangaram and Agatti during premonsoon season of second year and eight groups in Minicoy open ocean. Dendrogram and MDS plots based on mesozooplankton analysis of Minicoy open ocean stations revealed that S7 (Station7) stood apart forming three clusters. From the whole MDS analysis, it was confirmed that seasonal samplings are best for the interpretation of the faunal composition of Lakshadweep islands.

The results showed that the BEST correlation coefficient (Rho) for total cyclopoids from Minicoy open ocean was 0.015 for DO. In Kavaratti, pH and ammonia were the best correlating variables (σ=0.622) while in Kalpeni, SST, SSS, pH, nitrate, nitrite, phosphate, silicate (σ=0.600) formed the correlating parameters. But in Agatti, Bangaram and Minicoy all were found to be matching variables (σ=1.000).All these correlations were suggestive on the response and behavior of organisms to the fluctuations in hydrographic parameters.

Chapter 6 details the morphotaxonomic descriptions of the cyclopoid copepod species identified during the study .Fifty one species from four important families, ten genera have been identified and systematically reviewed based on

both taxonomic and molecular methods. For a precise taxonomic identification right from the family to species level, several features have been considered as unique, even if the same exhibit prominent variations. Four species from genus *Corycaeus*, six species from genus *Onychocorycaeus*, two species from genus *Urocorycaeus*, six species from genus *Ditrichocorycaeus,* five species from genus *Farranula,* eight species from genus *Oncaea ,*five species from genus *Oithona* and two species from genus *Dioithona*, ten species from genus *Sapphirina,* and three species from genus *Copilia* were identified. Out of this two were new reports to Indian Ocean. They are *Oncaea macilenta* and *C.vitreus.* In order to compare, the known cyclopoid copepod species and to document the phylogenetic affiliations among congeneric species, molecular analysis based on mtCOI gene sequences of some of the identified species were carried out. The morphotaxonomic ambiguity of some cyclopoid species documented during this study has also been resolved successfully by the DNA barcoding methods. Thus, DNA barcodes of nineteen cyclopoid species belonging to four families were developed out of which fourteen were primary barcodes. The accession numbers received from NCBI for the respective species are given in parenthesis. They are *Farranula gibbula* (KM114216.1, KP985538.1, KP972542.1),*Ditrichocorycaeus andrewsi* (KY321186, KY321187),*Onychocorycaeus catus* (KY368180,KY368181),*Corycaeus speciosus* (KR007641, KR816563),*Corycaeus crassiusculus* (KY923193, MF457915)*, Oncaea media*(KT369529,KT369530,KT369531) *,Oncaea venusta* (KY368178, KY368179)*, S.auronitens* (KU049704, KU049705, KU049706, KU049707, KU049708)*, S.stellata* (KT354294) *,Sapphirina sp.*(KT354291, KT354292, KT354293),*S.vorax* (KX454156), *C.hendorffi* (KY020448,KYO20449)*, C.quadrata*(KX470771, KX470772) *and Dioithona rigida* (KP972540,KP972541, KR528586,KR528587, KR528588)

Chapter 7 elaborates the redescription of female specimens of *Coryceus crassiusculus* and *Onychocorycaeus catus* from Kavaratti Island along with molecular characterization of five species under the family Corycaedae. Female specimens of *C.crassiusculus* and *O.catus* were redescribed based on ornamentation of the first endopodal segment of the antenna of *C.crassiusculus*, overlapping of genital segment on anal segment at the dorsal margin in *C.crassiusculus,* Distal margin of the genital and anal somite ornamented with spines ventrolaterally in

both and presence of four spines in the third exopodal segments of first, second and third swimming leg in *O.catus.* Therefore, the DNA barcode database of species described in this chapter under the Corycaedae family was lacking which has thus been documented. These results have been published in an international peer reviewed journal *Biosystematica*, 2014, ISSN: 0973-9955, Vol.8 (1&2).

Chapter 8 comprises DNA barcodes of selected species of Family Oitnonidae and Family Oncaedae. Results include two sections wherein the first section includes morphology and molecular analysis of *D.rigida* and the second section includes DNA barcoding of *Oncaea venusta* and *Oncaea media*. Morphological identification of the marine cyclopoid copepod *Dioithona rigida* in combination with sequencing a 645bp fragment of mtCOI gene, collected from offshore waters of Kavaratti Island, Lakshadweep Sea is presented. The main distinguishing characters like presence of well-developed P5 with 2 setae; 5 segmented urosome; 12 segmented antennule; compact dagger like setae on the inner margin of proximal segment of exopod ramus in P1-P4 and engorged portion of P1 bearing a spine; confirmed their morphology to *D.rigida.* Maximum likelihood Tree analysis exhibited the clustering of *D.rigida* sequences into a single clade (NCBI accession numbers KP972540.1-KR528588.1) which in contrast, was 37-42% divergent from other *Oithona* species. Therefore, the study provides the first molecular database along with morphological authentication of *D.rigida* from Lakshadweep Sea, a part of Indian Ocean and also establishes the interspecific and intraspecific patterns of variation of *D.rigida* with that of other *Oithona* species that resolves the taxonomic ambiguity of *D.rigida* species in marine waters. These results have been published in the international peer reviewed journal *Mitochondrial DNA Part A*, 2016, Taylor and Francis (publishers), doi.org/10.1080/ 24701394.2016.1202941.

Sequencing of mtCyt b gene region of *O.venusta* and *O.media* by Elvers *et al* (2006) from Indian and Pacific Ocean could obtain only 310 bp which is not at all ample to barcode a particular species. On the contrary, mtCOI gene amplification of the above said same species from Lakshadweep sea obtained a sequence 534 to 640bp accurately demarcating these two species. Therefore, primary barcodes of

two Oncaed species, *O.media* and *O.venusta* have been presented in the second section of this chapter

Chapter 9 comprises intra/inter specific phylogeny of *Sapphirina* and *Copilia species*. The primary DNA barcodes for six species under family ie. *S.auronitens*, *S.vorax, S.stellata, C.hendorffi* and *C.quadrata* collected from open ocean waters of Minicoy Island are presented. These species that were described on the morphotaxonomy in Chapter 5 were confirmed by molecular analysis as distinct species. The present study also demonstrates the distinctiveness of *S.opalina* and *S.darwinii* through molecular analysis thus resolving persisting taxonomic ambiguity that was evident through Maximum Likelihood tree and distance matrix data that *S.opalina* and *S.darwinii* shared a common ancestry with a interspecific distance value of 29%. Similarly distinctiveness of *S.vorax* and *S.auronitens* was also confirmed through ML tree and distance matrix data analysis by which an interspecific divergence value of 30% existed between the two species. The paucity of molecular data of *Copilia* species (*C.hendorffi*, *C.mirabilis* and *C.quadrata*) from Indian Ocean was accomplished from the present study which confirmed their taxonomic identities through DNA barcoding.

Inspite of extensive studies from IIOE, even though awareness on the taxonomy and distribution of planktonic copepods has enhanced our knowledge in Indian Ocean consequent to the International Indian Ocean Expedition (IIOE, 1962-65),information on planktonic crustaceans especially copepods, from South Eastern Arabian Sea (mainly coral habitats), a biodiversity hot spot, was least accounted. Thus the overall contribution of the study presents the major outcome on the diversity and distribution of pelagic copepods (cyclopoids) and their phylogenetic status in South Eastern Arabian Sea (Lakshadweep archipelago-Agatti, Bangaram, Kalpeni, Kavaratti and Minicoy) from 2013-16 period. The study fulfills the goals enshrined in UN convention in Biodiversity (CBD) where India is a signatory under the Aichi Biodiversity Targets (2011-2020) that stresses the need for reducing biodiversity loss, strengthen capacity building (taxonomists) and make available scientific data and knowledge on biodiversity and its application. Therefore based on the study, the following recommendations are put forth:

- Biodiversity studies pertaining to the distribution, diversity and community structure and taxonomy of various communities from marine ecosystems have been reported by several authors. However, many a times the morpho taxonomy of these organisms lacks clarity mainly due to the ambiguities in the proper taxonomic characterization of the species. So, the use of molecular tools in the identification helps in the effective understanding of the species and their ecological characteristics. So, this thesis as a pioneering effort and approach has effectively blended the use of the conventional taxonomic and molecular methods in documenting fifty one species of cyclopoid copepod species from the Lakshadweep lagoons of the eastern Arabian Sea.
- Lakshadweep islands are one of the biodiversity hotspots in the South West Indian Ocean. The study has laid a basic framework on the taxonomic richness and biodiversity status of the copepod species from the south west Arabian sea including the Lakshadweep islands. There are still, possibly many species to be taxonomically established by morphological and molecular methods, tracing their phylogenetic status, genetic variability and related evolutionary linkage.
- It is evident that mesozooplankton community in the study area was more susceptible to variation on temporal scale rather than spatial scale and the number of cyclopoid species were higher in the oceanic stations than the lagoon area. So effective steps are to be taken to carry out relevant studies for long term data sets with sufficient field sampling (both lagoon and open ocean area) on seasonal/monthly basis for understanding the ecobiological alterations in the ecosystem.
- Anthropogenic activities are leading to global climate change at an unprecedented rate. Understanding the mechanisms of how coral reef fauna and flora cope with environmental shifts is imperative to understand their fate in a marine system. In addition, the physical forcings with signatures of climate change is looming large in the Arabian Sea and the Indian Ocean, which also has direct and indirect effects on the genetic and morphological variations in the species that also needs to be thoroughly investigated.

- The relevance of the present study is in resonance with the three values of Convention on Biological diversity (CBD) ie. the conservation of biodiversity by understanding morphotaxonomy of the relevant species and its sustainable development by profiling it into aquaculture field and equitable sharing of benefits arising from genetic resources by providing DNA barcodes. Proper initiatives should be taken by the government through various funding agencies for fullfilling this objective by appropriate studies in various marine ecosystems.
- Education of the local population about the importance of corals and its associated flora and fauna need to be initiated since direct and indirect human impacts on these may lead to increase in velocity of waves, thus accelerating coastal erosion. This in turn may portent the very existence of islands and also tourism industry.
- Since tourism activity is on the rise in Lakshadweep islands, urgent action is required to restrict various pressures associated with this on the islands and its resources. Proper measures are to be developed to protect these ecosystems from further modification.
- Accessibility from the mainland to each island on a regular basis is limited due to several rules and regulations along with non-availability of ships. Further, inadequate lab facilities is also restraining proper and time bound analyses of water samples collected that would upset precise interpretation of the results. Therefore it is high time to take necessary initiatives in this direction.
- By segregating the habitat water through various physico-chemical and/or biotic factors and/or food resources pooled with mtCOI gene sequence variation of the existing species, a two dimensional habitat of their neustonic life from different island ecosystems of the Indian Ocean need to be articled.
- This work confirms the molecular and morphological methods, that is considered complementary but when applied in combination, constitute a powerful DNA Barcoding of cyclopoid copepods from the South Eastern Arabian Sea, for identification not only of copepods but also other

zooplankton with minimal errors. The results of the study is the first step in building databases of sequences and updating morphological identification keys of pelagic copepods. As zooplankton forms a vital link in the trophic chain of aquatic ecosystems, effective steps are to be initiated for exploring several of our hitherto unknown biotic structure from the lagoons and deep oceans.

- The morphological-genetic match would lead to a startup of barcode library of copepods from such marine habitats of south west coast of India that would surely help to ascertain the taxonomic significance of intraspecific genetic separation discovering cryptic species especially sibling species that have been discriminated only with few or subtle morphological characters.

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Annexure 1 Correlations between SST, SSS and pH with rainfall

Pearson Correlation			
Parameters	**SST**	**SSS**	**pH**
Rainfall	-.885**	.510	-.871**

***. Correlation is significant at the 5% level (2-tailed).**
****. Correlation is significant at the 1% level (2-tailed).**

Annexure 2 Correlations between environmental parametersin Kavaratti lagoon

Pearson Correlation										
Parameters	**SST**	**SSS**	**pH**	**DO**	**Nitrate**	**Nitrite**	**Silicate**	**Ammonia**	**Phosphate**	**Chlorophyll a**
SST	1									
SSS	-.699	1								
pH	.828	-.179	1							
DO	-.257	.871	.329	1						
Nitrate	-.952	.885	-.617	.541	1					
Nitrite	-.963	.866	-.647	.508	**.999***	1				
Silicate	.891	-.948	.483	-.668	-.987	-.980	1			
Ammonia	.425	.350	.859	.766	-.127	-.165	-.033	1		
Phosphate	-.989	.795	-.738	.394	.986	.992	-.947	-.289	1	
Chlorophyll a	.620	.127	.953	.599	-.350	-.386	.196	.974	-.500	1

***. Correlation is significant at the 5% level (2-tailed).**

****.Correlation is significant at the 1% level (2-tailed)**

Annexure 3 Correlations between environmental parameters in Minicoy lagoon

Pearson Correlation										
Parameters	**SST**	**SSS**	**pH**	**DO**	**Nitrate**	**Nitrite**	**Silicate**	**Ammonia**	**Phosphate**	**Chlorophyll a**
SST	1									
SSS	1.000**	1								
pH	1.000**	1.000**	1							
DO	1.000**	1.000**	1.000**	1						
Nitrate	-1.000**	-1.000**	-1.000**	-1.000**	1					
Nitrite	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1				
Silicate	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1.000**	1			
Ammonia	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**	-1.000**	1		
Phosphate	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1.000**	1.000**	-1.000**	1	
Chlorophyll a	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1.000**	1.000**	-1.000**	1.000**	1

***. Correlation is significant at the 5% level (2-tailed).**
****.Correlation is significant at the 1% level (2-tailed)**

Annexure 4 Correlations between environmental parameters and abundance in Kalpeni

	Pearson Correlation									
Parameters	**SST**	**SSS**	**pH**	**DO**	**Nitrate**	**Nitrite**	**Silicate**	**Ammonia**	**Phosphate**	**Chlorophyll-a**
SST	1									
SSS	1.000**	1								
pH	1.000**	1.000**	1							
DO	1.000**	1.000**	1.000**	1						
Nitrate	-1.000**	-1.000**	-1.000**	-1.000**	1					
Nitrite	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1				
Silicate	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**	1			
Ammonia	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**	1.000**	1		
Phosphate	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1.000**	-1.000**	-1.000**	1	
Chlorophyll-a	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	-1.000**	1
Mesozooplankton abundance	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**	-1.000**	-1.000**	-1.000**	-1.000**
Cyclopoid abundance	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**

***. Correlation is significant at the 5% level (2-tailed).**
****. Correlation is significant at the 1% level (2-tailed)**

Annexure 5 Correlations between environmental parameters and abundance in Minicoy lagoon

	Pearson Correlation									
Parameters	**SST**	**SSS**	**pH**	**DO**	**Nitrate**	**Nitrite**	**Silicate**	**Ammonia**	**Phosphate**	**Chlorophyll-a**
Mesozooplankton abundance	1.000**	1.000**	1.000**	1.000**	-1.000**	1.000**	1.000**	-1.000**	1.000**	-1.000**
Cyclopoid abundance	1.000**	1.000**	1.000**	1.000**	-1.000**	-1.000**	-1.000**	1.000**	-1.000**	-1.000**
Chlorophyll-a	-1.000**	-1.000**	-1.000**	-1.000**	1.000**	1.000**	1.000**	-1.000**	1.000**	1

***. Correlation is significant at the 5% level (2-tailed).**
****.Correlation is significant at the 1% level (2-tailed)**

Nucleotide sequences of *Corycaeus spesiosus.*

KR816563.1

CACGCTTTCATTATAATTTTTTTTATGGTTATGCCTATTCTAATTGGGGGGTTTGGAAATTGACTTGTAC
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AGCTTTGATTATATTATTATCCAGGTCGTTGGTGGAAAGGGGAGCTGGAACGGGGTGAACGGTATATCCC
CCCCTGTCAAGAAATATTGCTCATGCAGGGGGCTCAGTCGATTTTGCTATTTTTTCTTTACATTTGGCCG
GGGTAAGATCAATTCTAGGGGCTGTTAATTTTATCAGAACTTTAGGTAATCTACGAGTGTTTGGTATAGT
TCTAGATCGAATACCTTTGTTTGCTTGATCCGTTTTAATTACAGCTGTTTTGTTATTACTTTCATTACCT
GTTCTAGCAGGCGCGATTACAATACTCTTAACCGACCGTAACTTTAA

KR007641.1

TTGATTGGAGATGATCAGATTTATAATGTAGTGGTTACAGCTCACGCTTTCATTATAATTTTTTTTATGG
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TCCGTTTTAATTACAGCTGTTTTGTTATTACTTTCATTACCTGTTCTAGCAGGCGCGATTACAATACTCT
TAACCGACCGTAACTTTAAACTCTTCGTTCTATGACAC

KR007640.1

GATGATCAGATTTATAATGTAGTGGTTACAGCTCACGCTTTCATTATAATTTTTTTTATGGTTATGCCTA
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AACTTTAGGTAATCTACGAGTGTTTGGTATAGTTCTAGATCGAATACCTTTGTTTGCTTGATCCGTTTTA
ATTACAGCTGTTTTGTTATTACTTTCATTACCTGTTCTAGCAGGCGCGATTACAATACTCTTAACCGACC
GTAACTTTAAACTCTTCGTTCTATGACAC

Nucleotide Sequences of *Farranula Gibbula*

KP972542.1

TACAATGTTGTCGTAACGGCCCACGCGTTTGTAATGATTTTTTTCATGGAGATACCAATTCTTATTGGAG
GATTTGGGAATTGATTAGTGCCTCTTATAATTGGCGCTCCTGATATGGCATTTCCCCGATTAAATAACAT
AAGATTTTGATTCTTGCTTCCTGCTCTAACTCTGCTACTTTCTAGAGGGCTTGTTGAGTCCGGCGCAGGG
ACAGGATGAACAGTTTACCCTCCCCTAAGTGGAAACCTTTCCCACTCAGGAGCTTCCGTAGACTACGCAA
TTTTCTCTCTTCACCTAGCAGGAGTTTCATCTTTGTTAGGAGCTGTGAATTTTATTAGCACTCTTAGAAA
TCTTCGAGTTTTTTGGGATAATGCTAGACCGCTTACCTCTATTCGCTTGAGCAGTTTTAGTTACTGCTATT
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CGTCTTTTTACGACCCAAGAGGGGAGGAGACCCGCTTCTTTACCAGCACTTTATT

KM114216.1

TACTTAATTTCTGGTGCTTGATCCGGCATAGTTGGAACAGGGCTTAGAATAATCATTCGTTTAGAGCTGG
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GATTTTTTTCATGGTGATACCAATTCTTATTGGAGGATTTGGGAATTGATTAGTGCCTCTTATAATTGGC
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CTCTATTCGCTTGAGCAGTTTTAGTTACTGCTATTTTACTTCTTCTTTCTTTACCAGTATTAGCTGGGGC
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KP985538.1

ATAATCATTCGTTTAGAGCTGGGGCAGGGGGGATCCTTAATAGGAGATGACCAAGTTTACAATGTTGTCG
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CCTAGCAGGAGTTTCATCTTTGTTAGGAGCTGTGAATTTTATTAGCACTCTTAGAAATCTTCGAGTTTTT
GGGATAATGCTAGACCGTTTACCTCTATTCGCTTGAGCAGTTTTAGTTACTGCTATTTTACTTCTTCTTT
CTTTACCAGTATTAGCTGGGGCTATTACTATGCTGCTCACTGACCGAAATTTTAATACGTCTTTTTACGA
CCCAAGAGGGGGAGGAGACCCGCTTCTTTACCAGCACTTATTT

Nucleotide sequences of *Ditrichocorycaeus andrewsi*

KY321186.1

TTAGGAGATGATCAATTGTATAATGTGGTAGTGACTGCCCATGCTTTTATTATGATTTTTTTCATAGTAA
TGCCTATTTTAATTGGCGGGTTTGGGAATTGACTGGTCCCGTTAATACTGGGGGCGCCAGATATGGCCTT
TCCACGTTTAAACAACATAAGTTTTTGGTTTTTACTGCCCGCTCTTATATTATTATTGGTCAGAAGTTTA
GTTGAAGCAGGGGCAGGGACAGGCTGGACAGTCTACCCGCCTTTGAGGAGAAATATCGCTCACGGGGGGG
CGTCCGTAGATTTTGCTATTTTTTCCCTTCACCTAGCAGGTGTGTCTTCACTACTGGGGGCAGTAAACTT
TATTAGAACCTTAAGTAATCTTCGGGCCATGGGTATACTGGCAGATCGAATACCCTTATTTCCTTGGGCC
GTGTTAGTTACTGCAATCTTGCTTTTGCTTTCCCTTCCGGTGCTGGCTGGTGCAATTACGATGCTACTAA
CAGACCGAAACTTTAACTCTTCATTTTATGATCCTAGAGGCGGAGGAGACCCTTTACTATACCAACACTT
ATTTTGATTTTTTGGTCACCCTGAAGTT

KY321187.1

ATAATTATTCGTTTGGAGCTAGGTCAAAGAGGGTCTTTATTAGGAGATGATCAATTGTATAATGTGGTAG
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ACTGGTCCCGTTAATACTGGGGGCGCCAGATATGGCCTTTCCACGTTTAAACAACATAAGTTTTTGGTTT
TTACTGCCCGCTCTTATATTATTATTGGTCAGAAGTTTAGTTGAAGCAGGGGCAGGGACAGGCTGGACAG
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GGTATACTGGCAGATCGAATACCCTTATTTCCTTGGGCCGTGTTAGTTACTGCAATCTTGCTTTTGCTTT
CCCTTCCGGTGCTGGCTGGTGCAATTACGATGCTACTAACAGACCGAAACTTTAACTCTTCATTTTATGA
TCCTAGAGGCGGAGGAGACCCTTTACTATACCAACACTTATTTTGATTTTTTGGTCAC

Nucleotide sequences of *Onychocorycaeus catus*

KY368180.1

AGCCTCCTTATTCGAGCCGAGCTAGGCCAGCCAGGCAACCTTCTAGGTAACGACCACATCTACAACGTTA
TCGTCACAGCCCATGCATTTGTAATAATCTTCTTCATAGTAATACCCATCATAATCGGAGGCTTTGGCAA
CTGACTAGTTCCCCTAATAATCGGTGCCCCCGATATGGCGTTTCCCCGCATAAACAACATAAGCTTCTGA
CTCTTACCTCCCTCTCTCCTACTCCTGCTCGCATCTGCTATAGTGGAGGCCGGAGCAGGAACAGGTTGAA
CAGTCTACCCTCCCTTAGCAGGGAACTACTCCCACCCTGGAGCCTCCGTAGACCTAACCATCTTCTCCTT
ACACCTAGCAGGTGTCTCCTCTATCTTAGGGGCCATCAATTTCATCACAACAATTATCAATATAAAACCC
CCTGCCATAACCCAATACCTTACGCACCTCTTCGCCTGATCCGTCCTAATCACAGCAGTCCTACTTCTCC
TATCTCTCCCAGTCCTAGCTGCTGGCATCACTATACTACTAACAGACCGCAACCTCAACACCACCTTCTT
CGACCCCGCCGGAGGAGGAGACCCCATTCTATACCAACACCTATTCTGATTTTTT

KY368181.1

ATTCGAGCCGAGCTAGGCCAGCCAGGCAACCTTCTAGGTAACGACCACATCTACAACGTTATCGTCACAG
CCCATGCATTTGTAATAATCTTCTTCATAGTAATACCCATCATAATCGGAGGCTTTGGCAACTGACTAGT
TCCCCTAATAATCGGTGCCCCCGATATGGCGTTTCCCCGCATAAACAACATAAGCTTCTGACTCTTACCT
CCCTCTCTCCTACTCCTGCTCGCATCTGCTATAGTGGAGGCCGGAGCAGGAACAGGTTGAACAGTCTACC
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AGGTGTCTCCTCTATCTTAGGGGCCATCAATTTCATCACAACAATTATCAATATAAAACCCCCTGCCATA
ACCCAATACCAAACGCCCCTCTTCGTCTGATCCGTCCTAATCACAGCAGTCCTACTTCTCCTATCTCTCC
CAGTCCTAGCTGCTGGCATCACTATACTACTAACAGACCGCAACCTCAACACCACCTTCTTCGACCCCGC
CGGAGGAGGAGACCCCATTCTATACCAACACCTATTCTGATTTTTTGGTCAC

Nucleotide sequences of *Corycaeus crassiusculus*

KY923193.1

CGACTGGAATTAGGGCAAGGGGGCTCTTTAATAGGTGATGATCAGGTTTATAATGTAGTAGTAACCGCAC
ACGCCTTTATTATAATTTTTTTTATAGTAATGCCAATTTTGATCGGGGGATTTGGTAATTGACTTGTACC
GCTTATACTAGGGGCTCCAGATATAGCCTTCCCGCGGCTTAATAATATGAGTTTATGGTTTCTAATTCCA
GCTTTAATCCTACTACTTTCTAGAGGGCTGGTTGAATCTGGAGCTGGGACGGGTTGAACGGTCTACCCCC
CTCTTAGAAGTAATATGTCTCATGCCGGAGCATCAGTAGATTTTGCTATTTTTTCTCTTCATCTGGCAGG
GATTTCATCTCTTTTGGGTGCCGTGAATTTTATTAGGACTTTAAGAAATCTCCGTACAATAGGTATGTTA
ATAGATCGTATA

MF457915.1

CGACTGGAATTAGGGCAAGGGGGCTCTTTAATAGGTGATGATCAGGTTTATAATGTAGTAGTAACCGCAC
ACGCCTTTATTATAATTTTTTTTATAGTAATGCCAATTTTGATCGGGGGATTTGGTAATTGACTTGTACC
GCTTATACTAGGGGCTCCAGATATAGCCTTCCCGCGGCTTAATAATATGAGTTTATGGTTTCTAATTCCA
GCTTTAATCCTACTACTTTCTAGAGGGCTGGTTGAATCTGGAGCTGGGACGGGTTGAACGGTCTACCCCC
CTCTTAGAAGTAATATGTCTCATGCCGGAGCATCAGTAGATTTTGCTATTTTTTCTCTTCATCTGGCAGG
GATTTCATCTCTTTTGGGTGCCGTGAATTTTATTAGGACTTTAAGAAATCTCCGTACAATAGGTATGTTA
ATAGATCGTATA

Nucleotide sequences of *Dioithona rigida*

KP972540.1

CTCTGTTTGATAACGAGCAGATTTATAACGTGGTCGTAACTGCCCACGCCTTTATTATAATTTTCTTTAT
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GCTTTCCCTCGTCTTAATAATATAAGGTTCTGGTTATTACCCCCCGCTTTGTTCCTTCTGTTAATAAGGT
CTTTGGTGGAGTCGGGAGCCGGAACCGGCTGAACAGTTTACCCTCCTCTGAGAACTCATCTATTTCATAG
TGGGGCGTCAGTGGATTTTGCTATTTTTAGTCTTCACTTGGCTGGGGTCTCTTCTCTCTTAGGAGCAGTT
AACTTCATTACCACGATCGTTAACCTCCGAGTACTGGGCATGTTCTTAGACCGGATGCCTTTGTTTCCCT
GGGCTGTTTTAGTGACGGCCATTCTACTTTTATTATCCCTCCCCGTCTTGGCAGGGGCAATTACAATGCT
ATTGACAGACCGTAATATTAACACTTCTTTTTATGACCCTATGGGGGGAGGTGATCCTGTCTTATATCAG
CACCTTTTCTGATTTTTTGGTCACCC

KP972541.1

CTCTGTTTGATAACGAGCAGATTTACAACGTGGTCGTAACTGCCCACGCTTTTATTATGATTTTCTTTAT
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GCTTTTCCTCGTCTTAATAATATAAGGTTCTGGTTATTACCCCCTGCTTTGTTCCTTCTGTTAATAAGGT
CTTTGGTGGAATCGGGAGCCGGAACCGGCTGAACAGTTTATCCTCCCCTGAGAACTCATCTATTTCATAG
TGGGGCGTCAGTGGATTTTGCTATTTTTAGTCTTCACTTGGCTGGGGTCTCTTCTCTCTTAGGAGCAGTT
AACTTCATTACCACGATCGTTAACCTGCGAGTACTGGGCATGTTCTTAGACCGAATGCCTTTGTTTCCTT
GGGCTGTTTTAGTGACGGCCATTCTACTTTTATTATCCCTCCCCGTCTTGGCAGGGGCAATTACAATGCT
ATTGACAGACCGTAATATCAACACTTC

KR528586.1

CTCTGTTTGATAACGAGCAGATTTATAACGTGGTCGTAACTGCCCACGCCTTTATTATAATTTTCTTTAT
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GCTTTCCCTCGTCTTAATAATATAAGGTTCTGGTTATTACCCCCCGCTTTGTTCCTTCTGTTAATAAGGT
CTTTGGTGGAGTCGGGAGCCGGAACCGGCTGAACAGTTTACCCTCCTCTGAGAACTCATCTATTTCATAG
TGGGGCGTCAGTGGATTTTGCTATTTTTAGTCTTCACTTGGCTGGGGTCTCTTCTCTCTTAGGAGCAGTT
AACTTCATTACCACGATCGTTAACCTCCGAGTACTGGGCATGTTCTTAGACCGGATGCCTTTGTTTCCCT
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CACCTTTTCTGATTTTTT

KR528587.1

GGTAACTGGCTAGTACCTTTAATACTTGGGTCTCCTGACATGGCTTTCCCTCGTCTTAATAATATAAGGT
TCTGGTTATTACCCCCCGCTTTGTTCCTTCTGTTAATAAGGTCTTTGGTGGAGTCGGGAGCCGGAACCGG
CTGAACAGTTTACCCTCCTCTGAGAACTCATCTATTTCATAGTGGGGCGTCAGTGGATTTTGCTATTTTT
AGTCTTCACTTGGCTGGGGTCTCTTCTCTCTTAGGAGCAGTTAACTTCATTACCACGATCGTTAACCTCC
GAGTACTGGGCATGTTCTTAGACCGGATGCCTTTGTTTCCCTGGGCTGTTTTAGTGACGGCCATTCTACT
TTTATTATCCCTCCCCGTCTTGGCAGGGGCAATTACAATGCTATTGACAGACCGTAATATTAACACTTCT
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KR528588.1

ACTGCCCACGCCTTTATTATAATTTTCTTTATAGTCATGCCAATTCTTATTGGCTGCTTCGGTAACTGGC
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TGGCTGGGGTCTCTTCTCTCTTAGGAGCAGTTAACTTCATTACCACGATCGTTAACCTCCGAGTACTGGG
CATGTTCTTAGACCGGATGCCTTTGTTTCCCTGGGCTGTTTTAGTGACGGCCATTCTACTTTTATTATCC
CTCCCCGTCTTGGCAGGGGCAATTACAATGCTATTGACAGACCGTAATATTAACACTTCTTTTTATGACC
CTATGGGGGGAGGTGATCCTGTCTTATAT

Nucleotide sequences of *Oncaea media*

KT369529.1

TTTTTCATAGTTATGCCATTTTTAATCGGAGGTTTTGGGAGTTGGCTATTACCCCTTATACTGGGTGCCC
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TAGAAGAGCTCTTGTTGAATCAGGGGCAGGAACCGGATGAACAGTTTACCCGCCGTTAAGAAACAATTTA
GCTCATTCAGGCCCTTCAGTCGATTTTGCTATTTTTGCACTCCATTTGGCCGGCGTTTCTTCACTGTTGG
GGGCTGTAAATTTTATTAGAACTTTTTCCAATCTCCGGAGATTGGGAATACTTTTGGAGCGGGTACCCCT
CTTTGGGTGAGCTGTTTTAATTACTACTATCTTATTATTACTATCCCTTCCCGTATTAGCAGGCGCTATT
ACTATACTTCTCACTGATCGAAATTTAAACACAGCTTTTTATGATTCAAATGGAGGAGGTGACCCAATTT
TGTACCAACACTTATTTTGATT

KT369530.1

TAAGAATACTTATTCGTATAGAGCTAGGAAAGCCAGGGTCATTATTAGGAAATGATCATTTATATAATGT
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AGTTGGCTATTACCCCTTATACTGGGTGCCCCAGATATAGCTTTTCCACGACTTAACAATATGAGATTTT
GAATACTTCTACCAGCTTTAGTGATATTAACTAGAAGAGCTCTTGTTGAATCAGGGGCAGGAACCGGATG
AACAGTTTACCCGCCGTTAAGAAACAATTTAGCTCATTCAGGCCCTTCAGTCGATTTTGCTATTTTTGCA
CTCCATTTGGCCGGCGTTTCTTCACTGTTGGGGGGCTGTAAATTTTATTAGAACTTTTTCCAATCTCCGGA
GATTGGGAATACTTTTGGAGCGGGTACCCCTCTTTGGGTGAGCTGTTTTAATTACTACTATCTTATTATT
ACTATCCCTTCCCGTATTAGCAGGCGCTATTACTATACTTCTCACTGATCGAAATTTAAACACAGCTTTT
TATGATTCAAATGGAGGAGGTGACCCAATTTTGTACCAACACTTATTTTGATT

KT369531.1

CTTAACAATATGAGATTTTGAATACTTCTACCAGCTTTAGTGATATTAACTAGAAGAGCTCTTGTTGAAT
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CGATTTTGCTATTTTTGCACTCCATTTGGCCGGCGTTTCTTCACTGTTGGGGGCTGTAAATTTTATTAGA
ACTTTTTCCAATCTCCGGAGATTGGGAATACTTTTGGAGCGGGTACCCCTCTTTGGGTGAGCTGTTTTAA
TTACTACTATCTTATTATTACTATCCCTTCCCGTATTAGCAGGCGCTATTACTATACTTCTCACTGATCG
AAATTTAAACACAGCTTTTTATGATTCAAATGGAGGAGGTGACCCAATTTTGTACCAACACTTATTTTGA
TT

Nucleotide sequences of *Oncaea venusta*

KY368178.1

AATGTAATTGTAACAGCTCATGCATTTATTATAATTTTCTTTATAGTAATGCCAATTATAATTGGAGGAT
TTGGAAATTGATTAGTTCCTTTAATATTAGGAGCCCCTGATATAGCTTTCCCTCGAATGAATAATATAAG
TTTTTGAATACTACCTCCTTCATTGACTCTTCTATTATCAAGCTCAATAGTAGAAAATGGGGCAGGAACA
GGGTGAACAGTTTATCCTCCTCTCTCTTCAGGAACAGCTCATGCTGGAGCTTCTGTTGATTTAGCTATTT
TTTCTCTTCATTTAGCTGGAATTTCCTCAATTTTAGGGGCAGTAAATTTTATTACAACTGTGATTAATAT
GCGATCGTCAGGGATTACTTTAGATCGACTACCCTTATTTGTTTGATCTGTAGTTATTACAGCTATCTTA
TTACTTCTTTCTCTTCCTGTTTTAGCTGGAGCTATTACTATATTATTAACAGACCGAAACTTAAATACAT
CTTTCTTTGATCCAATCGGAGGGGGAGACCCTATTTTATACCAACACTTATTTTGATTTTTT

KY368179.1

AATGTAATTGTAACAGCTCATGCATTTATTATAATTTTCTTTATAGTAATGCCAATTATAATTGGAGGAT
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GCGATCGTCAGGGATTACTTTAGATCGACTACCCTTATTTGTTTGATCTGTAGTTATTACAGCTATCTTA
TTACTTCTTTCTCTTCCTGTTTTAGCTGGAGCTATTACTATATTATTAACAGACCGAAACTTAAATACAT
CTTTCTTTGATCCAATCGGAGGGGGAGACCCTATTTTATACCAACACTTATTTTGATTTTTT

Nucleotide sequences of *Sapphirina auronitens*

KU049707.1

GGAGGGTCTTTAATTGGCGACGATCAGATTTACAACGTTGTTGTGACAGCTCATGCTTTTATTATAATTT
TCTTTATAGTTATGCCTGTTTTAATTGGAGGGTTTGGCAATTGGCTAGTTCCTCTAATATTAGGGTCGCC
AGACATAGCATTTCCCCGTTTAAACAATTTAAGATTTTGGTTTTTAGTCCCGGCGCTAACGCTTCTTTTA
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CCCACGCAGGAGCGTCTGTGGACTTTGCCATTTTCTCTCTTCATCTGGCCGGGGTCTCTTCCTTAATAGG
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KU049708.1

GGAGGGTCTTTAATTGGCGACGATCAGATTTACAACGTTGTTGTGACAGCTCATGCTTTTATTATAATTT
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AGACATAGCATTTCCCCGTTTAAACAATTTAAGATTTTGGTTTTTAGTCCCGGCGCTAACGCTTCTTTTA
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CCCACGCAGGAGCGTCTGTGGACTTTGCCATTTTCTCTCTTCATCTGGCCGGGGTCTCTTCCTTAATAGG
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KU049706.1

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KU049705.1

GGAGGGTCTTTAATTGGCGACGATCAGATTTACAACGTTGTTGTGACAGCTCATGCTTTTATTATAATTT
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KU049704.1

GGAGGGTCTTTAATTGGCGACGATCAGATTTACAACGTTGTTGTGACAGCTCATGCTTTTATTATAATTT
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AGACATAGCATTTCCCCGTTTAAACAATTTAAGATTTTGGTTTTTAGTCCCGGCGCTAACGCTTCTTTTA
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CCCACGCAGGAGCGTCTGTGGACTTTGCCATTTTCTCTCTTCATCTGGCCGGGGTCTCTTCCTTAATAGG
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CAATGCTTCTTACAGACCGAAACTTCAACACATCTTTCTATGACCCTAGGGGAGGCGGAGACCCCTTGCT
ATATCAACACCTGTTTTGATTTTTTGGTCACCCT

Nucleotide sequences of *Sapphirina angusta*

KT345968.1

GGGACAGGCCTTAGTATGTTAATTCGTCTGGAGTTAGGCCAAGCAGGGTCTTTAATTGGAGACGACCAAA
TCTACAATGTGGTGGTTACAGCACATGCATTTATCATAATTTTTTTTATAGTTATGCCGGTTCTTATCGG
GGGCTTTGGAAACTGGCTGGTTCCGCTAATGTTAGGATCCCCTGATATAGCGTTTCCTCGATTAAACAAT
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GAACAGGTTGAACAGTCTACCCTCCGCTTAGGGGCAACTTGGCCCATTCTGGCGCCTCCGTTGATTTTGC
TATTTTTTCTCTTCACCTTGCTGGGGTCTCATCCTTGATAGGGGCAGTCAATTTTATTAGCACGCTTGGA
AATCTACGGGCTATGGGGATGCTTATAGATCGCGTCCCTTTATTTGCGTGGTCGGTGCTAGTAACTGCAA
TTTTATTACTGCTATCCTTACCTGTTTTGGCTGGGGCTATCACCATACTTCTTACCGATCGAAATTTTAA
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CACCCTGAAGTTTTA

KT345967.1

GGCCTTAGTATGTTAATTCGTCTGGAGTTAGGCCAAGCAGGGTCTTTAATTGGAGACGACCAAATCTACA
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TTTTGGTTTTTAGTCCCTGCGTTAACCCTGCTCCTCTCAAGGGCGCTAGTGGAATCTGGGGCAGGAACAG
GTTGAACAGTCTACCCTCCGCTTAGGGGCAACTTGGCCCATTCTGGCGCCTCCGTTGATTTTGCTATTTT
TTCTCTTCACCTTGCTGGGGTCTCATCCTTGATAGGGGCAGTCAATTTTATTAGCACGCTTGGAAATCTA
CGGGCTATGGGGATGCTTATAGATCGCGTCCCTTTATTTGCGTGGTCGGTGCTAGTAACTGCAATTTTAT
TACTGCTATCCTTACCTGTTTTGGCTGGGGCTATCACCATACTTCTTACCGATCGAAATTTTAACACTTC
ATTTTATGATCCTAGAGGAGGAGGGGACCCCTTACTATACCAGCACTTGTTTTGATTTTTTGGTCACCCT
GAAGTT

KT345969.1

GCAGGGTCTTTAATTGGAGACGACCAAATCTACAATGTGGTGGTTACAGCACATGCATTTATCATAATTT
TTTTTATAGTTATGCCGGTTCTTATCGGGGGCTTTGGAAACTGGCTGGTTCCGCTAATGTTAGGATCCCC
TGATATAGCGTTTCCTCGATTAAACAATTTAAGGTTTTGGTTTTTAGTCCCTGCGTTAACCCTGCTCCTC
TCAAGGGCGCTAGTGGAATCTGGGGCAGGAACAGGTTGAACAGTCTACCCTCCGCTTAGGGGCAACTTGG
CCCATTCTGGCGCCTCCGTTGATTTTGCTATTTTTTCTCTTCACCTTGCTGGGGTCTCATCCTTGATAGG
GGCAGTCAATTTTATTAGCACGCTTGGAAATCTACGGGCTATGGGGATGCTTATAGATCGCGTCCCTTTA
TTTGCGTGGTCGGTGCTAGTAACTGCAATTTTATTACTGCTATCCTTACCTGTTTTGGCTGGGGCTATCA
CCATACTTCTTACCGATCGAAATTTTAACACTTCATTTTATGATCCTAGAGGAGGAGGGGACCCCTTACT
ATACCAGCACTTGTTTTGATTTTTTGGTCAC

KT345970.1

ATCTACAATGTGGTGGTTACAGCACATGCATTTATCATAATTTTTTTTATAGTTATGCCGGTTCTTATCG
GGGGCTTTGGAAACTGGCTGGTTCCGCTAATGTTAGGATCCCCTGATATAGCGTTTCCTCGATTAAACAA
TTTAAGGTTTTGGTTTTTAGTCCCTGCGTTAACCCTGCTCCTCTCAAGGGCGCTAGTGGAATCTGGGGCA
GGAACAGGTTGAACAGTCTACCCTCCGCTTAGGGGCAACTTGGCCCATTCTGGCGCCTCCGTTGATTTTG
CTATTTTTTCTCTTCACCTTGCTGGGGTCTCATCCTTGATAGGGGCAGTCAATTTTATTAGCACGCTTGG
AAATCTACGGGCTATGGGGATGCTTATAGATCGCGTCCCTTTATTTGCGTGGTCGGTGCTAGTAACTGCA
ATTTTATTACTGCTATCCTTACCTGTTTTGGCTGGGGCTATCACCATACTTCTTACCGATCGAAATTTTA
ACACTTCATTTTATGATCCTAGAGGAGGAGGGGACCCCTTACTATACCAGCACTTGTTTTGATTTTTT

Nucleotide sequences of *Sapphirina opalina*

KU158881.1

GGCATAATCGGAACCGGACTAAGGATACTAATTCGCCTTGAGCTAGGGCAGGGAGGAGCATTAATTGGAG
ACGACCAAATTTATAATGTAGTAGTTACTGCTCACGCCTTTATCATGATTTTTTTTATGGTTATACCTGT
CTTGATTGGAGGGTTTGGAAACTGGCTCGTTCCCCTGATACTAGGTGCCCCTGACATAGCGTTCCCTCGC
TTGAATAATTTAAGATTTTGATTTTTAATGCCTGCCCTCACACTGCTTCTCTCAAGGGCCTTAGTCGAGT
CCGGAGCGGGGACAGGGTGGACAGTATACCCTCCACTAAGAGGGAACCTATCTCACGCAGGGGGGTCAGT
GGACTTTGCAATCTTCTCTCTTCACCTGGCAGGGGTTTCTTCTCTTATAGGGGCAGTAAACTTTATTAGA
ACACTAGGCAATCTTCGGGTGATAGGGCTCCTAATAGACCGAATGCCTCTATTTGCCTGATCTGTGCTGG
TGACTGCTATTTTGCTTTTACTCTCCCTCCCCGTTCTGGCGGGAGCAATTACCATATTGCTAACAGACCG
CAACTTTAACACCTCTTTTTACGACCCCAGCGGGGGAGGCGACCCTTTACTATACCAGCACCTTTTCTGG
TTTTTTGGTCACCCTGGAAGT

KU158880.1

GGCATAATCGGAACCGGACTAAGGATACTAATTCGCCTTGAGCTAGGGCAGGGAGGAGCATTAATTGGAG
ACGACCAAATTTATAATGTAGTAGTTACTGCTCACGCCTTTATCATGATTTTTTTTATGGTTATACCTGT
CTTGATTGGAGGGTTTGGAAACTGGCTCGTTCCCCTGATACTAGGTGCCCCTGACATAGCGTTCCCTCGC
TTGAATAATTTAAGATTTTGATTTTTAATGCCTGCCCTCACACTGCTTCTCTCAAGGGCCTTAGTCGAGT
CCGGAGCGGGGACAGGGTGGACAGTATACCCTCCACTAAGAGGGAACCTATCTCACGCAGGGGGGTCAGT
GGACTTTGCAATCTTCTCTCTTCACCTGGCAGGGGTTTCTTCTCTTATAGGGGCAGTAAACTTTATTAGA
ACACTAGGCAATCTTCGGGTGATAGGGCTCCTAATAGACCGAATGCCTCTATTTGCCTGATCTGTGCTGG
TGACTGCTATTTTGCTTTTACTCTCCCTCCCCGTTCTGGCGGGAGCAATTACCATATTGCTAACAGACCG
CAACTTTAACACCTCTTTTTACGACCCCAGCGGGGGAGGCGACCCTTTACTATACCAGCACCTTTTCTGG
TTTTTT

KU158879.1

GGCATAATCGGAACCGGACTAAGGATACTAATTCGCCTTGAGCTAGGGCAGGGAGGAGCATTAATTGGAG
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CTTGATTGGAGGGTTTGGAAACTGGCTCGTTCCCCTGATACTAGGTGCCCCTGACATAGCGTTCCCTCGC
TTGAATAATTTAAGATTTTGATTTTTAATGCCTGCCCTCACACTGCTTCTCTCAAGGGCCTTAGTCGAGT
CCGGAGCGGGGACAGGGTGGACAGTATACCCTCCACTAAGAGGGAACCTATCTCACGCAGGGGGGTCAGT
GGACTTTGCAATCTTCTCTCTTCACCTGGCAGGGGTTTCTTCTCTTATAGGGGCAGTAAACTTTATTAGA
ACACTAGGCAATCTTCGGGTGATAGGGCTCCTAATAGACCGAATGCCTCTATTTGCCTGATCTGTGCTGG
TGACTGCTATTTTGCTTTTACTCTCCCTCCCCGTTCTGGCGGGAGCAATTACCATATTGCTAACAGACCG
CAACTTTAACACCTCTTTTTACGACCCCAGCGGGGGAGGCGACCCTTTACTATACCAGCACCTTTTCTGG
TTTTTTGGGCACCCTGGAAGTTTA

Nucleotide sequences of *Sapphirina scarlata*

KT351344.1

TTAAGGATATTAATCCGGCTGGAATTACGTCAAAGAGGATCCTTAATTGGGGACGACCAAATTTATAATG
TGGTAGTTACTGCCCACGCTTTTATTATAATTTTCTTTATAGTTATACCTGTTTTAATTGGCGGGTTTGG
TAACTGGCTGATCCCTCTAATACTAGGCTCTCCTGATATGGCCTTCCCCCGCTTAAACAATTTAAGGTTT
TGATTTTTAGTTCCTGCCCTCATATTGTTACTATCAAGAGCATTAGTAGAATCCGGCGCAGGTACAGGTT
GAACCGTGTACCCTCCTCTTAGGGGGAACCTAGCTCATGCCGGAGCGTCCGTCGATTTCGCAATTTTTTC
CTTGCATTTAGCTGGCGTTTCTTCTTTAATAGGGGCAGTTAACTTTATTAGGACCTTAGGTAACTTGCGG
GCCATGGGTATACTAATAGATCGCATACCCTTATTTGCTTGATCTGTTTTAGTAACAGCAGTTCTTCTTT
TACTTTCTCTGCCTGTATTAGCTGGAGCAATTACAATACTGTTGACAGATCGGAACTTTAACACTTCTTT
CTATGATCCTAGTGGGGGTGGGGATCCTCTTTTATATCAACATCTATTTTGATTTTTTGGACACCCAGA

KT351342.1

GGAACAGGATTAAGGATATTAATCCGGCTGGAATTACGTCAAAGAGGATCCTTAATTGGGGACGACCAAA
TTTATAATGTGGTAGTTACTGCCCACGCTTTTATTATAATTTTCTTTATAGTTATACCTGTTTTAATTGG
CGGGTTTGGTAACTGGCTGATCCCTCTAATACTAGGCTCTCCTGATATGGCCTTCCCCCGCTTAAACAAT
TTAAGGTTTTGATTTTTAGTTCCTGCCCTCATATTGTTACTATCAAGAGCATTAGTAGAATCCGGCGCAG
GTACAGGTTGAACCGTGTACCCTCCTCTTAGGGGGAACCTAGCTCATGCCGGAGCGTCCGTCGATTTCGC
AATTTTTTCCTTGCATTTAGCTGGCGTTTCTTCTTTAATAGGGGCAGTTAACTTTATTAGGACCTTAGGT
AACTTGCGGGCCATGGGTATACTAATAGATCGCATACCCTTATTTGCTTGATCTGTTTTAGTAACAGCAG
TTCTTCTTTTACTTTCTCTGCCTGTATTAGCTGGAGCAATTACAATACTGTTGACAGATCGGAACTTTAA
CACTTCTTTCTATGATCCTAGTGGGGGTGGGGATCCTCTTTTATATCAACATCTATTTTGATTTTTTGGA
CAC

KT351343.1

GGAACAGGATTAAGGATATTAATCCGGCTGGAATTACGTCAAAGAGGATCCTTAATTGGGGACGACCAAA
TTTATAATGTGGTAGTTACTGCCCACGCTTTTATTATAATTTTCTTTATAGTTATACCTGTTTTAATTGG
CGGGTTTGGTAACTGGCTGATCCCTCTAATACTAGGCTCTCCTGATATGGCCTTCCCCCGCTTAAACAAT
TTAAGGTTTTGATTTTTAGTTCCTGCCCTCATATTGTTACTATCAAGAGCATTAGTAGAATCCGGCGCAG
GTACAGGTTGAACCGTGTACCCTCCTCTTAGGGGGAACCTAGCTCATGCCGGAGCGTCCGTCGATTTCGC
AATTTTTTCCTTGCATTTAGCTGGCGTTTCTTCTTTAATAGGGGCAGTTAACTTTATTAGGACCTTAGGT
AACTTGCGGGCCATGGGTATACTAATAGATCGCATACCCTTATTTGCTTGATCTGTTTTAGTAACAGCAG
TTCTTCTTTTACTTTCTCTGCCTGTATTAGCTGGAGCAATTACAATACTGTTGACAGATCGGAACTTTAA
CACTTCTTTCTATGATCCTAGTGGGGGTGGGGATCCTCTTTTATATCAACATCTATTTTGATTTTTTGGA
CACCCAGAGGTGTAC

Nucleotide sequences of *Sapphirina stellata*

KT354294.1

GGGTTAAGGATGTTAATTCGCCTGGAGCTGGGCCAAGCCGGGTCATTAATTGGAGACGACCAAATTTACA
ATGTTGTAGTTACTGCCCATGCTTTCGTAATGATTTTTTTTATAGTTATACCTGTACTAATTGGGGGATT
CGGAAACTGACTTATCCCTCTTATACTAGGGTCTCCTGATATAGCCTTCCCTCGACTGAATAATTTGAGA
TTCTGGTTTTTGATCCCAGCTCTCATGCTCCTCTTGTCGAGGGCCTTAGTTGAGTCAGGAGCTGGTACTG
GGTGAACAGTGTACCCTCCACTCAGGGGAAATCTAGCCCACGCTGGGGCATCAGTGGATTTTGCGATCTT
CTCCTTACATCTAGCAGGAGTCTCATCTTTGATAGGAGCCGTCAACTTCATTAGGACATTAGGTAATCTC
CGAGCCATGGGTATGTTAATAGACCGAATACCTTTGTTCGCTTGATCAGTCTTAGTTACTGCTGTTCTCC
TTTTACTATCCCTCCCAGTTCTTGCCGGAGCTATTACAATACTGTTAACTGACCGAAACTTTAACACTTC
TTTCTACGACCCGAGAGGAGGAGGGGATCCACTCTTATATCAACATTTATTTTGATTTTTT

Nucleotide sequences of *Sapphirina sp*

KT354291.1

GGTACAGGGCTAAGGATGTTAATTCGCCTGGAGCTGGGCCAAGCCGGGTCATTAATTGGAGACGACCAAA
TTTACAATGTTGTAGTTACTGCCCATGCTTTCGTAATGATTTTTTTTATAGTTATACCTGTACTAATTGG
GGGATTCGGAAACTGACTTATCCCTCTTATACTAGGGTCTCCTGATATAGCCTTCCCTCGACTGAATAAT
TTGAGATTCTGGTTTTTGATCCCAGCTCTCATACTCCTCTTGTCGAGAGCCTTAGTTGAGTCAGGAGCTG
GTACTGGGTGAACAGTGTACCCTCCACTCAGGGGAAATCTAGCCCACGCTGGGGCATCAGTGGATTTTGC
GATCTTCTCCTTACATCTAGCAGGAGTCTCATCTTTGATAGGAGCCGTCAACTTCATTAGGACATTAGGT
AATCTCCGAGCCATGGGTATGTTAATAGACCGAATACCTTTGTTCGCTTGATCAGTCTTAGTTACTGCTG
TTCTCCTTTTACTATCCCTCCCAGTTCTTGCCGGAGCTATTACAATACTGTTAACTGACCGAAACTTTAA
CACTTCTTTCTACGACCCGAGAGGAGGAGGGGATCCACTCTTATATCAACATTTATTTTGATTTTTTGGT
CACCCTGAAGTT

KT354292.1

ACAGGGCTAAGGATGTTAATTCGCCTGGAGCTGGGCCAAGCCGGGTCATTAATTGGAGACGACCAAATTT
ACAATGTTGTAGTTACTGCCCATGCTTTCGTAATGATTTTTTTTATAGTTATACCTGTACTAATTGGGGG
ATTCGGAAACTGACTTATCCCTCTTATACTAGGGTCTCCTGATATAGCCTTCCCTCGACTGAATAATTTG
AGATTCTGGTTTTTGATCCCAGCTCTCATACTCCTCTTGTCGAGAGCCTTAGTTGAGTCAGGAGCTGGTA
CTGGGTGAACAGTGTACCCTCCACTCAGGGGAAATCTAGCCCACGCTGGGGCATCAGTGGATTTTGCGAT
CTTCTCCTTACATCTAGCAGGAGTCTCATCTTTGATAGGAGCCGTCAACTTCATTAGGACATTAGGTAAT
CTCCGAGCCATGGGTATGTTAATAGACCGAATACCTTTGTTCGCTTGATCAGTCTTAGTTACTGCTGTTC
TCCTTTTACTATCCCTCCCAGTTCTTGCCGGAGCTATTACAATACTGTTAACTGACCGAAACTTTAACAC
TTCTTTCTACGACCCGAGAGGAGGAGGGGATCCACTCTTATATCAACATTTATTTTGATTTTTTGGTCAC

KT354293.1

GGGTCATTAATTGGAGACGACCAAATTTACAATGTTGTAGTTACTGCCCATGCTTTCGTAATGATTTTTT
TTATAGTTATACCTGTACTAATTGGGGGATTCGGAAACTGACTTATCCCTCTTATACTAGGGTCTCCTGA
TATAGCCTTCCCTCGACTGAATAATTTGAGATTCTGGTTTTTGATCCCAGCTCTCATACTCCTCTTGTCG
AGAGCCTTAGTTGAGTCAGGAGCTGGTACTGGGTGAACAGTGTACCCTCCACTCAGGGGAAATCTAGCCC
ACGCTGGGGCATCAGTGGATTTTGCGATCTTCTCCTTACATCTAGCAGGAGTCTCATCTTTGATAGGAGC
CGTCAACTTCATTAGGACATTAGGTAATCTCCGAGCCATGGGTATGTTAATAGACCGAATACCTTTGTTC
GCTTGATCAGTCTTAGTTACTGCTGTTCTCCTTTTACTATCCCTCCCAGTTCTTGCCGGAGCTATTACAA
TACTGTTAACTGACCGAAACTTTAACACTTCTTTCTACGACCCGAGAGGAGGAGGGGATCCACTCTTATA
TCAACATTTATTTTGATTTTTTGGTCACCCTGAAGTT

Nucleotide sequences of *Sapphirina metallina*

KT429934.1

GTAATAATTTTTTTTATAGTTATACCGGTTTTAATTGGAGGCTTTGGAAATTGACTTGTTCCATTAATAC
TAGGCTCTCCAGATATGGCTTTCCCACGATTAAATAATCTAAGATTTTGATTTTTATTGCCTGCTTTTTC
ACTTCTTTTATCTAGAGCTTTAGTAGAGTCAGGAGCAGGGACAGGTTGAACAGTTTATCCTCCGTTAAGA
AGAAATGTCGCTCATTCAGGAAGATCCGTTGATTTTGCTATTTTTTCTCTTCATTTAGCAGGAGTTTCTT
CTTTAATAGGAGCAGTTAATTTTATTAGTACTTTAGGTAATTTACGAATAACAGGGATATATTTAGATAG
AGTCCCGCTATTTGCTTGATCGGTTCTAGTCACAGCAGTTTTATTATTGTTATCTCTCCCAGTTTTAGCT
GGTGCAATTACTATATTATTAACTGACCGTAACTTTAACACCTCTTTTTATGACTCAAGAGGGGGCGGGG
ACCCTCTTTTATACCAACATTTATTCTGATTTTTTGGTCATCCTGAA

KT429933.1

GCTTGGGCCGGAATAGTTGGTACTGGTTTAAGAATAATAATTCGGCTGGAACTTGGCCAAGCGGGCTCTT
TAATTGGAGATGATCAGATTTATAATGTAGTTGTTACTGCTCATGCTTTTGTAATAATTTTTTTTATAGT
TATACCGGTTTTAATTGGAGGCTTTGGAAATTGACTTGTTCCATTAATACTAGGCTCTCCAGATATGGCT
TTCCCACGATTAAATAATCTAAGATTTTGATTTTTATTGCCTGCTTTTTCACTTCTTTTATCTAGAGCTT
TAGTAGAGTCAGGAGCAGGGACAGGTTGAACAGTTTATCCTCCGTTAAGAAGAAATGTCGCTCATTCAGG
AAGATCCGTTGATTTTGCTATTTTTTCTCTTCATTTAGCAGGAGTTTCTTCTTTAATAGGAGCAGTTAAT
TTTATTAGTACTTTAGGTAATTTACGAATAACAGGGATATATTTAGATAGAGTCCCGCTATTTGCTTGAT
CGGTTCTAGTCACAGCAGTTTTATTATTGTTATCTCTCCCAGTTTTAGCTGGTGCAATTACTATATTATT
AACTGACCGTAACTTTAACACCTCTTTTTATGACTCAAGAGGGGGCGGGGACCCTCTTTTATACCAACAT
TTATTCTGATTTTTTGGTCATCCTGAA

KU200948.1

GGTACTGGTTTAAGAATAATAATTCGGCTGGAACTTGGCCAAGCGGGCTCTTTAATTGGAGATGATCAGA
TTTATAATGTAGTTGTTACTGCTCATGCTTTTGTAATAATTTTTTTTATAGTTATACCGGTTTTAATTGG
AGGCTTTGGAAATTGACTTGTTCCATTAATACTAGGCTCTCCAGATATGGCTTTCCCACGATTAAATAAT
CTAAGATTTTGATTTTTATTGCCTGCTTTTTCACTTCTTTTATCTAGAGCTTTAGTAGAGTCAGGAGCAG
GGACAGGTTGAACAGTTTATCCTCCGTTAAGAAGAAATGTCGCTCATTCAGGAAGATCCGTTGATTTTGC
TATTTTTTCTCTTCATTTAGCAGGAGTTTCTTCTTTAATAGGAGCAGTTAATTTTATTAGTACTTTAGGT
AATTTACGAATAACAGGGATATATTTAGATAGAGTCCCGCTATTTGCTTGATCGGTTCTAGTCACAGCAG
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CACCTCTTTTTATGACTCAAGAGGGGGCGGGGACCCTCTTTTATACCAACATTTATTCTGATTTTTTGGT
CATCCTGAAAGT

KU144691.1

GCTTGGGCCGGAATAGTTGGTACTGGTTTAAGAATAATAATTCGGCTGGAACTTGGCCAAGCGGGCTCTT
TAATTGGAGATGATCAGATTTATAATGTAGTTGTTACTGCTCATGCTTTTGTAATAATTTTTTTTATAGT
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TTCCCACGATTAAATAATCTAAGATTTTGATTTTTATTGCCTGCTTTTTCACTTCTTTTATCTAGAGCTT
TAGTAGAGTCAGGAGCAGGGACAGGTTGAACAGTTTATCCTCCGTTAAGAAGAAATGTCGCTCATTCAGG
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CGGTTCTAGTCACAGCAGTTTTATTATTGTTATCTCTCCCAGTTTTAGCTGGTGCAATTACTATATTATT
AACTGACCGTAACTTTAACACCTCTTTTTATGACTCAAGAGGGGGCGGGGACCCTCTTTTATACCAACAT
TTATTCTGATTTTTTGGTCATCCT

KU144690.1

GCTTGGGCCGGAATAGTTGGTACTGGTTTAAGAATAATAATTCGGCTGGAACTTGGCCAAGCGGGCTCTT
TAATTGGAGATGATCAGATTTATAATGTAGTTGTTACTGCTCATGCTTTTGTAATAATTTTTTTTATAGT
TATACCGGTTTTAATTGGAGGCTTTGGAAATTGACTTGTTCCATTAATACTAGGCTCTCCAGATATGGCT
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TAGTAGAGTCAGGAGCAGGGACAGGTTGAACAGTTTATCCTCCGTTAAGAAGAAATGTCGCTCATTCAGG
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TTTATTAGTACTTTAGGTAATTTACGAATAACAGGGATATATTTAGATAGAGTCCCGCTATTTGCTTGAT
CGGTTCTAGTCACAGCAGTTTTATTATTGTTATCTCTCCCAGTTTTAGCTGGTGCAATTACTATATTATT
AACTGACCGTAACTTTAACACCTCTTTTTATGACTCAAGAGGGGGCGGGGACCCTCTTTTATACCAACAT
TTATTCTGATTTTTTGGTCATCCTGAAAGTTTA

Nucleotide sequences of *Sapphirina vorax*

KX454156.1

ACGGGCCTTAGTATATTGATTCGTCTTGAGTTGGGCCAAGGAGGATCGCTAATTGGGGACGACCAAATCT
ACAACGTGGTGGTGACAGCCCATGCCTTTATCATAATTTTTTTTATGGTCATGCCCGTCTTGATTGGAGG
CTTTGGAAACTGGCTAGTACCCCTAATACTTGGTTCCCCTGACATGGCTTTCCCCCGCCTAAACAATCTC
AGCTTTTGGTTTCTTGTGCCTGCCCTGACCCTTTTGCTCTCAAGGGCTTTAGTCGAATCTGGTGCTGGAA
CCGGATGAACTGTTTACCCGCCTCTTAGGGGTAACCTCGCCCACGCTGGCGCCTCGGTTGACTTTGCTAT
TTTTTCGCTCCATTTGGCGGGAGTTTCTTCTCTGATAGGAGCAGTTAATTTTATTAGGACTCTGGGCAAC
TTGCGAACCATAGGAATAATCATGGACCGAATGCCGTTGTTTGCCTGGTCGGTTTTAGTGACCGCAATTT
TGCTGCTTCTTTCGTTACCGGTGTTAGCAGGTGCAATCACTATGCTTTTAACCGACCGTAACTTTAATAC
CTCTTTTTATGACCCAAGAGGTGGGGGGGACCCTCTTTTATACCAACACCTCTTTTGATTTTTTGGTCAC
CCTGAA

Nucleotide sequences of *Copilia hendorffi*

KY020448

GGAACGGGCC TAAGAATATT AATTCGTATA GAGTTAGGGC AAGCTGGGTC GCTTTTAGGG
GATGATCACC TATATAATGT GGTTGTTACA GCACACGCTT TTGTTATAAT TTTTTTCATA
GTGATGCCTA TTTTAATTGG GGGGTTTGGT AATTGACTTG TTCCACTAAT GCTTGGATCA
CCAGATATAG CATTCCCTCG ATTAAACAAT CTTAGATTTT GGTTTTTATT GCCTGCTCTA
TCGTTGCTCT TATCAAGATC GTTAGTTGAA TCGGGTGCTG GGACGGGATG AACAGTTTAT
CCCCCCCTTA GTGCAAACAT TGCTCATGCA GGGGCATCAG TAGATTTTGC AATTTTTTCT
TTACATTTAG CAGGAGTTTC TTCGTTGCTA GGTGCTGTAA ATTTTATTAC AACCTTGGCC
AACTTACGAG CAGTTGGAAT GGTAATAGAC CGCATATCGC TCTTCCCTTG GTCGGTATTT
GTCACTGCCA TTTTACTTCT TTTATCCCTC CCAGTTTTAG CAGGGGCTAT CACAATGCTT
TTAACAGACC GAAATTTCAA CACTTCATTC TATGACCCAA GAGGAGGGGG TGACCCCTTA
CTTTATCAGC ACTTGTTCTG ATTTTTTGGT CACCCTGGAA GT

KY020449

GGCCTAAGAA TATTAATTCG TATAGAGTTA GGGCAAGCTG GGTCGCTTTT AGGGGATGAT
CACCTATATA ATGTGGTTGT TACAGCACAC GCTTTTGTTA TAATTTTTTT CATAGTGATG
CCTATTTTAA TTGGGGGGTT TGGTAATTGA CTTGTTCCAC TAATGCTTGG ATCACCAGAT
ATAGCATTCC CTCGATTAAA CAATCTTAGA TTTTGGTTTT TATTGCCTGC TCTATCGTTG
CTCTTATCAA GATCGTTAGT TGAATCGGGT GCTGGGACGG GATGAACAGT TTATCCCCCC
CTTAGTGCAA ACATTGCTCA TGCAGGGGCA TCAGTAGATT TTGCAATTTT TTCTTTACAT
TTAGCAGGAG TTTCTTCGTT GCTAGGTGCT GTAAATTTTA TTACAACCTT GGCCAACTTA
CGAGCAGTTG GAATGGTAAT AGACCGCATA TCGCTCTTCC CTTGGTCGGT ATTTGTCACT
GCCATTTTAC TTCTTTTATC CCTCCCAGTT TTAGCAGGGG CTATCACAAT GCTTTTAACA
GACCGAAATT TCAACACTTC ATTCTATGAC CCAAGAGGAG GGGGTGACCC CTTACTTTAT
CAGCACTTGT TCTGATTTTT TGGTCACCCT

Nucleotide sequences of *Copilia mirabilis*

KT429931.1

ACAGGCTTAAGAATGTTAATTCGAATAGAGTTAGGGCAGGCGGGGTCTCTGCTGGGTGACGATCATTTGT
ATAATGTAGTTGTAACAGCTCATGCTTTTGTCATAATTTTTTTTATAGTAATACCTATTTTAATTGGTGG
GTTTGGCAACTGACTGGTGCCACTAATGCTTGGGTCCCCAGATATAGCGTTTCCTCGACTAAACAACCTC
AGATTTTGATTTCTCTTACCTGCTCTGTCACTACTCTTATCTAGATCTTTAGTAGAGTCAGGCGCCGGAA
CAGGGTGGACTGTTTACCCTCCTTTAAGTGCTAATATCGCTCATGCGGGAGCATCAGTAGATTTTGCAAT
TTTTTCTCTACATTTAGCAGGAGTGTCTTCTCTGCTAGGTGCTGTAAATTTCATTACTACCTTAGCAAAT
CTGCGAGCGGTGGGAATGGTTATGGACCGGATATCACTCTTTCCCTGATCAGTGTTTGTCACTGCCGTTT
TACTTCTTTTGTCTCTCCCGGTCTTAGCAGGAGCTATTACAATGCTTTTAACAGACCGAAATTTTAACAC
TTCTTTTTATGACCCAAGGGGAGGTGGTGACCCTTTGCTTTACCAACACTTATTCTGATTTTTTGGTCAC

KT429932.1

CTGGGTGACGATCATTTGTATAATGTAGTTGTAACAGCTCATGCTTTTGTCATAATTTTTTTTATAGTAA
TACCTATTTTAATTGGTGGGTTTGGCAACTGACTGGTGCCACTAATGCTTGGGTCCCCAGATATAGCGTT
TCCTCGACTAAACAACCTCAGATTTTGATTTCTCTTACCTGCTCTGTCACTACTCTTATCTAGATCTTTA
GTAGAGTCAGGCGCCGGAACAGGGTGGACTGTTTACCCTCCTTTAAGTGCTAATATCGCTCATGCGGGAG
CATCAGTAGATTTTGCAATTTTTTCTCTACATTTAGCAGGAGTGTCTTCTCTGCTAGGTGCTGTAAATTT
CATTACTACCTTAGCAAATCTGCGAGCGGTGGGAATGGTTATGGACCGGATATCACTCTTTCCCTGATCA
GTGTTTGTCACTGCCGTTTTACTTCTTTTGTCTCTCCCGGTCTTAGCAGGAGCTATTACAATGCTTTTAA
CAGACCGAAATTTTAACACTTCTTTTTATGACCCAAGGGGAGGTGGTGACCCTTTGCTTTACCAACACTT
ATTCTGATTT

Nucleotide sequences of *Copilia quadrata*

KX470771.1

AGCCTCCTTATTCGAGCCGAGCTAGGCCAGCCAGGCAACCTTCTAGGTAACGACCACATCTACAACGTTA
TCGTCACAGCCCATGCATTTGTAATAATCTTCTTCATAGTAATACCCATCATAATCGGAGGCTTTGGCAA
CTGACTAGTTCCCCTAATAATCGGTGCCCCCGATATGGCGTTTCCCCGCATAAACAACATAAGCTTCTGA
CTCTTACCTCCCTCTCTCCTACTCCTGCTCGCATCTGCTATAGTGGAGGCCGGAGCAGGAACAGGTTGAA
CAGTCTACCCTCCCTTAGCAGGGAACTACTCCCACCCTGGAGCCTCCGTAGACCTAACCATCTTCTCCTT
ACACCTAGCAGGTGTCTCCTCTATCTTAGGGGCCATCAATTTCATCACAACAATTATCAATATAAAACCC
CCTGCCATAACCCAATACCAAACGCCCCTCTTCGTCTGATCCGTCCTAATCACAGCAGTCCTACTTCTCC
TATCTCTCCCAGTCCTAGCTGCTGGCATCACTATACTACTAACAGACCGCAACCTCAACACCACCTTCTT
CGACCCCGCCGGAGGAGGAGACCCCATTCTATACCAACACCTATTCTGATTTTTTGGTCAC

KX470772.1

AGCCTCCTTATTCGAGCCGAGCTAGGCCAGCCAGGCAACCTTCTAGGTAACGACCACATCTACAACGTTA
TCGTCACAGCCCATGCATTTGTAATAATCTTCTTCATAGTAATACCCATCATAATCGGAGGCTTTGGCAA
CTGACTAGTTCCCCTAATAATCGGTGCCCCCGATATGGCGTTTCCCCGCATAAACAACATAAGCTTCTGA
CTCTTACCTCCCTCTCTCCTACTCCTGCTCGCATCTGCTATAGTGGAGGCCGGAGCAGGAACAGGTTGAA
CAGTCTACCCTCCCTTAGCAGGGAACTACTCCCACCCTGGAGCCTCCGTAGACCTAACCATCTTCTCCTT
ACACCTAGCAGGTGTCTCCTCTATCTTAGGGGCCATCAATTTCATCACAACAATTATCAATATAAAACCC
CCTGCCATAACCCAATACCAAACGCCCCTCTTCGTCTGATCCGTCCTAATCACAGCAGTCCTACTTCTCC
TATCTCTCCCAGTCCTAGCTGCTGGCATCACTATACTACTAACAGACCGCAACCTCAACACCACCTTCTT
CGACCCCGCCGGAGGAGGAGACCCCATTCTATACCAACACCTATTCTGATTTTTTGGTCAC

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LIST OF PUBLICATIONS

Research Papers Published

1) **Radhika. R**. ,Bijoy Nandan.S and Harikrishnan.M (2015). Morphological and molecular identification of marine copepod *Dioithona rigida* Giesbrecht, 1896 (Crustacea:Cyclopoida) based on mitochondrial COI gene sequences, from Lakshadweep sea, India. *Mitochondrial DNA.*
2) **R.Radhika**, S.Bijoynandan & M.Harikrishnan,*(*2014) "Rediscription of female specimens of *Corycaeus* (*Corycaeus) crassiusculus* Dana and *Corycaeus* (*Onychocorycaeus*) *catus* dahl *(Poicilostomatoida:* Corycaeidae) from Kavarathi Atoll, Lakshadweep Island, India*."*-***Biosystematica***,8(1&2)pp.31-43; ISSN: 0973-7871
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RESEARCH ARTICLE

Morphological and molecular identification of marine copepod *Dioithona rigida* Giesbrecht, 1896 (Crustacea:Cyclopoida) based on mitochondrial COI gene sequences, from Lakshadweep sea, India

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ABSTRACT

Morphological identification of the marine cyclopoid copepod *Dioithona rigida* in combination with sequencing a 645 bp fragment of mitochondrial cytochrome oxidase c subunit I (mtCOI) gene, collected from offshore waters of Kavarathi Island, Lakshadweep Sea, is presented in this study. Kiefer in 1935 classified *Dioithona* as a separate genus from *Oithona*. The main distinguishing characters observed in the collected samples, such as the presence of well-developed P5 with 2 setae, 5 segmented urosome, 12 segmented antennule, compact dagger-like setae on the inner margin of proximal segment of exopod ramus in P1–P4 and engorged portion of P1-bearing a spine, confirmed their morphology to *D. rigida*. A comparison of setal formulae of the exopod and endopod of *D. rigida* with those recorded previously by various authors are also presented here. Maximum likelihood Tree analysis exhibited the clustering of *D. rigida* sequences into a single clade (accession numbers KP972540.1-KR528588.1), which in contrast was 37–42% divergent from other *Oithona* species. Further intra-specific divergence values of 0–2% also confirmed the genetic identity of *D. rigida* species. *Paracyclopina nana* was selected as an out group displayed a diverged array. The present results distinctly differentiated *D. rigida* from other *Oithona* species.

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Dioithona rigida; DNA barcoding; Indian Ocean; Taxonomy; Lakshadweep Sea; Indian Ocean

Introduction

The status of the genus *Dioithona* has been widely discussed amongst taxonomists. Even though Kiefer (1935) classified *Dioithona* as a separate genus, Vervoort (1964) and Wellershaus (1970) considered it only as a subgenus of *Oithona*. However, this genus was not recognized by Nishida (1985), but Boxshall and Halsey (2004) did recognize it, mainly on the basis of Abiahy (2000). Since its first description in 1896 by Giesbrecht, females of *D. rigida* have been described by Sewell (1947) from Arabian Sea; Mori (1964) from Japanese waters; Chen et al. (1974) from China seas and Shuvalov (1980) from Leningrad. Böttger-Schnack (1995) and Johan et al. (2013) have reported the presence of *D. rigida* species from coastal waters of Bintulu-Sarawak, Malaysia and Red Sea, respectively.

When most of the taxonomic and molecular works got concentrated on other Oithonid species such as *O. similis*, *O. atlandica* and *O. nana* (Georgina et al. 2012), little attention has been given to *D. rigida* and therefore, molecular studies on this species are rather limited. Contributions by Kasturirangan (1963) and Wellershaus (1970) on the taxonomy of this group along with other planktonic copepods of India are exceptions to this. However, taxonomic uncertainty still persists at the species level of the genus *Oithona* and genus *Dioithona*, particularly the coastal species, despite their importance in the world oceans (McKinnon 2000). In view of the present scarcity of information on the classical and molecular taxonomic status of Dioithonids, we present the first molecular barcode of the species *D. rigida* based on mitochondrial COI sequence, along with its morphological description.

Materials and methods

Collection, preservation and morphological identification of samples

Dioithona rigida specimens were collected from Kavarathi (10°33′N and 72°36′E) island, Lakshadweep sea, a part of Indian Ocean (Figure 1) in January 2014, postmonsoon using a plankton net (mesh size 200 µm) having a mouth area of 0.28 m^2. Sub-surface horizontal tows at a fixed speed of ~1 Kn for 10 min were carried out with the net attached to a calibrated flow meter (General Oceanics model number – 2030 R, 2012). Immediately after sampling, copepods for DNA analysis were fixed in 95% ethyl alcohol and those for morphological examination were preserved in 4% buffered formalin. Morphological examination and dissection of specimens were done in glycerol distilled water mixture under Leica (Model DM 500) bright field compound microscope. The specimens were identified up to species level using standard keys (Kasturirangan 1963; Mori 1964; Wellershaus 1970; Nishida 1985). The alcohol was changed 24 h after collection.

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Redescription of female specimens of *Corycaeus* (*Corycaeus) crassiusculus* Dana and *Corycaeus* (*Onychocorycaeus*) *catus* Dahl (Poicilostomatoida: Corycaeidae) from Kavarathi Atoll, Lakshadweep island, India

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ABSTRACT - In 1929 and 1911, the female specimen of *Corycaeus crassiusculus* (Dana, 1848) and *Onychocorycaeus catus* (Dahl 1894) was first recorded in the Indian ocean by Farran and in the Arabian sea by Sewell in 1947. The two species are redescribed by a combination of morphological characteristics as follows in females (1) ornamentation of the first endopodal segment of the antenna of *C. crassiusculus* (2) overlapping of genital segment on anal segment at the dorsal margin in *C. crassiusculus* (3) distal margin of the genital and anal somite ornamented with spines ventrolaterally in both (4) presence of four spines in the third exopodal segments of first, second & third swimming leg in *O. catus* (5) length to width of 1st endopodal segment of the antenna (6) length ratio of coxal seta: 1st endopodal seta; (7) in P1 to P3 exp-3, length ratio of terminal spine to distal segment and to outer distal spine; (8) in P4 exp-3, length ratios of terminal spine to proximal spine and to distal segment. A comparison of the morphological variability with existing descriptions from other regions have also been provided.

KEYWORDS – Taxonomy, Corycaedae, Cyclopoida, Poicilostomatoida, Kavarathi, Arabian sea.

Introduction

The genus *Corycaeus* was established by Dana in 1846. The family Corycaeidae (Dana 1852) including two genera, *Corycaeus* Dana (1845) and *Farranula* (Wilson,1932) are marine pelagic copepods occurring typically in epipelagic zone of tropical to temperate seas (Motoda, 1963; Boxshall & Halsey, 2004; Wi *et al*., 2013) These groups of copepods are easily recognized by peculiar structure of their bodies and by their large paired eyes, and they are very useful indicator forms of warm ocean currents (Motoda, 1963; Mulyadi, 2003). The genus *Corycaeus* is widely distributed in the Mediterranean Sea (Wilson, 1942); the Indian and Pacific Oceans (Giesbrecht, 1891, 1892); Farran, 1911; Dahl, 1912; Sewell, 1947; Tanaka, (1957, 1960), the North Pacific Ocean (Motoda, 1963), the East China Sea and Yellow Sea (Chen *et al*.,1974; Zheng *et al*.,1982; Kang *et al.*,1990), and Japanese waters (Itoh, 1997). Seven subgenera have been recognized under a single genus *Corycaeus* by Dahl (1912), *Corycaeus* (*Agetus*) (Kröyer, 1849), *Corycaeus* (*Corycaeus*) (Dana, 1845), *Corycaeus* (*Ditrichocorycaeus*) (Dahl,1912), *Corycaeus* (*Monocorycaeus*) (Dahl,1912), *Corycaeus* (*Onychocorycaeus*) (Dahl,1912), *Corycaeus* (*Urocorycaeus*) (Dahl, 1912), and *Corycaeus* (*Corycella*) (Farran, 1911). The genus *Onychocorycaeus* (Dahl, 1912) includes seven species, *O. giesbrechti* (Dahl,1894), *O. agilis* (Dana, 1849), *O. catus* (Dahl, 1894), *O. latus* (Dana, 1849), *O. ovalis* (Claus, 1863), *O. pacificus* (Dahl, 1894), and *O. pumilus* (Dahl, 1912). In this article we provide a comparison of the morphological variability with existing descriptions from other regions and a detailed description on the female specimen of both the species coming under the order Poicilostomatoida from Kavarathi Island,

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RESEARCH ARTICLE

SPECIES ASSEMBLAGE AND COMMUNITY PATTERNS OF CYCLOPOID COPEPODS IN KAVARATHI ATOLL ALONG THE INDIAN COAST

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ABSTRACT

Despite the importance of cyclopoid copepod community in the global carbon cycle, diversity studies on copepods in Lakshadweep islands have usually been concentrated on calanoid group and little is known about the marine cyclopoid groups. The seasonal abundance, diversity and community structure of cyclopoid copepods in Kavarathi atoll, from April 2013 (premonsoon), September 2013 (monsoon) and January 2014, is presented. A total of 28 cyclopoids belonging to 4 subgenera, 4 genera and 3 families were identified of which 21 are new records to Kavarathi lagoon. They are *Corycaeus clausi, Corycaeus affinis, Corycaeus crassiusculus, Corycaeus speciosus, Corycaeus Agetus limbatus, Urocorycaeus furcifer, Onychocorycaeus catus, Onychocorycaeus agilis, Onychocorycaeus giesbrechti, Onychocorycaeus latus, Ditrichocorycaeus andrewsi, Ditrichocorycaeus asiaticus, Ditrichocorycaeus dahli, Ditrichocorycaeus tenius, Farranula concinna, Farranula gracilis, Farranula rostrata, Farranula curta, Oncaea clevei, Oncaea media and Oithona atlandica.* The cyclopoid taxa of Kavarathi lagoon appear to exhibit increase in abundance during the post monsoon; taxa dominance and evenness seemed to be higher during monsoon. The community structure of cyclopoid copepods were also analyzed broadly in accordance with abundance as criterion for different seasons.

INTRODUCTION

Copepods are supposed to be numerically the most abundant metazoans on earth and conservative estimations revealed that they likely outnumber the abundance of insects (Chang *et al.*, 2010; Schminke 2007; Hwang *et al.*, 2004; Javaid Ahmed *et al.*, 2013; Ka *et al.*, 2011) Like all wetland ecosystems, coral Islands in Lakshadweep, being unique in diversity and productivity are of great ecological and socio-economic importance (Bakus, 1993). The abundance, community structure and diversity of cyclopoid copepods has rarely been investigated in marine areas due to their small size and difficulties in taxonomic identification. Cyclopod copepods have shown to be recorded from previous studies held at Kavarathi as well as Minicoy atoll (Goswami and Usha, 1990; Madhuprathap *et al.*, 1977, 1991; Robin *et al.*, 2012) and are the main component of the zooplanktonic biomass. The aim of this work is to establish the species abundance, community structure and distribution of the Cyclopoid copepods from Kavarathi, Lakshadweep archipelago. Prior investigations were more concerned with the relative abundance of the total plankton or of major taxa rather than species composition, the same needs to be pointed out in this context as the present study includes an overwhelming data on cyclopoid copepod abundance and diversity as well as a baseline data about mesozooplankton in Kavarathi atoll.

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MATERIALS AND METHODS

Study area

Lakshadweep is an archipelago of twelve atolls, three reefs and five submerged banks located in the Arabian sea situated between 8 - 12°N latitude and 71°45 -73°45 E longitude .Kavarathi, located along latitude 10°33' N and longitude 72°36'E has its lagoon oriented in north to south direction which is approximately 4,500 m long and 1200 m wide with a maximum depth of 3.5m. Field sampling for the collection of mesozooplankton and various physico chemical parameters were conducted during April 2013 (premonsoon), September 2013 (monsoon) and January 2014 (postmonsoon).The exact sampling locations were fixed by Global Positioning System (GPS) (Magellan ® Triton 200/300). Samples were collected from three stations, one in the inner lagoon (T2) and the other two stations in the outer lagoon, in which one at the coral area (T1) and the other at boat channel (T3). T1 (coral area) was found to have more interactions with the island than other two stations (T2 and T3) as it was in close proximity to land

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Mesozooplankton Distribution in Kavaratti Atoll, Lakshadweep Archipelago, South West Coast of India with Special Reference to Calanoid Copepods

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Abstract: *Lakshadweep archipelago is a group of coral Islands on the West coast of the Arabian Sea. It is one among the unique coral atolls in India that are well known for several species of fishes and other biotic resources. Seasonal variation in mesozooplankton, particularly of copepod abundance and distribution in the inner and outer lagoon of Kavaratti atoll were studied during April 2013 (premonsoon), September 2013 (monsoon) and January 2014 (postmonsoon). Copepods were the most dominant taxa in all the stations and seasons, that accounted 44.15 to 85.97% of the total mesozooplankton abundance. Ostracoda (premonsoon), crustacean larvae (monsoon) and chaetognaths (postmonsoon) formed the abundant groups in the respective seasons. Mesozooplankton community in the study area exhibits temporal variation corresponding to the variation in abiotic parameters therefore can be used as potential indicators of water quality. Calanoid copepods formed the dominant taxa during monsoon and postmonsoon, while cyclopoid copepods dominated during premonsoon. Among the copepods, species of the family Candacidae, Calanidae, Pontellidae, Temoridae, Psuedodiaptomidae, Centropagidae and Oithonidae were predominant. The ten species of calanoids were previously not reported from Kavaratti atoll, in Lakshadweep.*

Keywords: *Calanoids, Copepods, Coral Atoll, Kavaratti, Mesozooplankton*

I. Introduction

Zooplankton plays an important role in structuring and regulating the coastal marine food web and also in the functioning of biological pump (Chiba et. al. 2006). As their community structure and function are highly susceptible to changes in the environmental conditions regular monitoring of their distribution as well as their interactions with various physico chemical parameters is inevitable for the sustainable management of the ecosystem (Kusum et. al. 2014). Of all the marine zooplankton groups, copepods particularly calanoid copepods are the dominant groups in marine subtropical and tropical waters and exhibit great diversity in morphology and habitats they occupy (Madhupratap, 1991; Cornils et. al. 2005). Further, copepods are significant in fisheries as it forms an important food item to the fishes, maintaining regenerated primary production and carbon flux (Madhupratap, 1997). Coral islands in Lakshadweep, endowed with unique diversity and productivity are of great ecological and socio-economic importance (Bakus, 1993). Kavaratti is a perfect atoll of the Lakshadweep archipelago and the Island is oriented along North-South axis with shallow lagoon enclosed by coral reef on the West. A constant flow of water from sea to lagoon is maintained by the action of surf which breaks across the reef and the coral reef beaches are exposed only during the low tide (Qasim and Sankaranarayanan, 1970).

Though there are a few studies reported on quantitative and qualitative distribution of mesozooplankton in Kavaratti (Qasim et. al.1972; Tranter and George, 1972; Goswami, 1973; 1979, Madhupratap et. al. 1977), they are based on short time observations.The present study is aimed to develop a baseline data on mesozooplankton abundance, distribution and seasonal variation in Kavaratti atoll in relation to various hydrographical parameters. The focus is on species diversity and distribution of calanoid copepods.

II. Materials and methods

Study area

The Union territory of Lakshadweep located in the Arabian sea comprises of a group of 11 inhabited islands, 25 uninhabited tiny islands and 3 coral reef environments situated between 8° - 12'N latitude and 71°45' -73°45' E longitude. The Kavaratti lagoon has a length of about 6 kilometer and an area of 4.96 square kilometers with an average depth of 2 meters. Field sampling for the collection of mesozooplankton and various physico chemical parameters were conducted during April 2013 (premonsoon), September 2013 (monsoon) and January 2014 (postmonsoon). The exact sampling locations were fixed by global positioning system (GPS) (Magellan ®Ttriton 200/300). Samples were collected from three stations, one in the inner lagoon (T2) and the

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COMMUNITY STRUCTURE AND SYSTEMATICS OF ARROW WORMS (PHYLUM: CHAETOGNATHA) FROM THE LAGOONS OF LAKSHADWEEP ARCHIPELAGO, INDIA

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Abstract

The Phylum Chaetognatha also known as arrow worm represents nearly 295 species that are mostly holoplanktonic. They perform an important role in the marine food web. Due to the geographical isolation of Lakshadweep islands, limited information on chaetognaths are available from this region. In this context, the present study on arrow worms (chaetognaths) in the coral lagoons of Lakshadweep is important and relevant. Eight species of chaetognaths were collected from the selected lagoons of Lakshadweep islands (Kavaratti, Kalpeni and Minicoy) they were Sagitta enflata, S.robusta, S. regularis, S.bedoti, S.madhupratapi, S.bipunctata, S.decepiens and Aidanosagitta neglecta. The present study emphasizes the importance of long term monitoring of this important holoplanktonic group for understanding the trophic condition of the lagoon ecosystem.

Keywords: Chaetognatha, Sagitta, Lakshadweep archipelago, Lagoon, Arrow worm

Introduction

The term chaetognath originated from two Greek words; *"Chaeto"* meaning bristle and *"gnathos"* meaning jaws. The Phylum Chaetognatha, also known as arrow worms, contains nearly 295 species [1] of mostly planktonic and 15 benthic, bilaterally symmetrical, coelomate, worm-like organisms (1 mm to 12 cm long). They are typically transparent, although some deepwater species may be orange in color, and some may be opaque, due to their musculature. Chaetognaths are hermaphroditic. Many species within this phylum are known to undergo a daily vertical migration, which provides protection from predators. Chaetognaths are often regarded as valuable indicators of water masses along different parts of the global ocean [2-4]. Chaetognaths are primary carnivores in the pelagic realm, except for the genera *Spadella*, *Bathyspadella* and *Krohnitella*. They feed on a number of crustacean (mainly copepods) and fish (mainly larvae) species, which they track through daily vertical migrations in the water column. Chaetognaths in turn form the important prey organisms. Thus they have a vital role in the marine ecosystem as an important mediator between primary consumers and organisms at higher trophic levels.

Materials and Methods

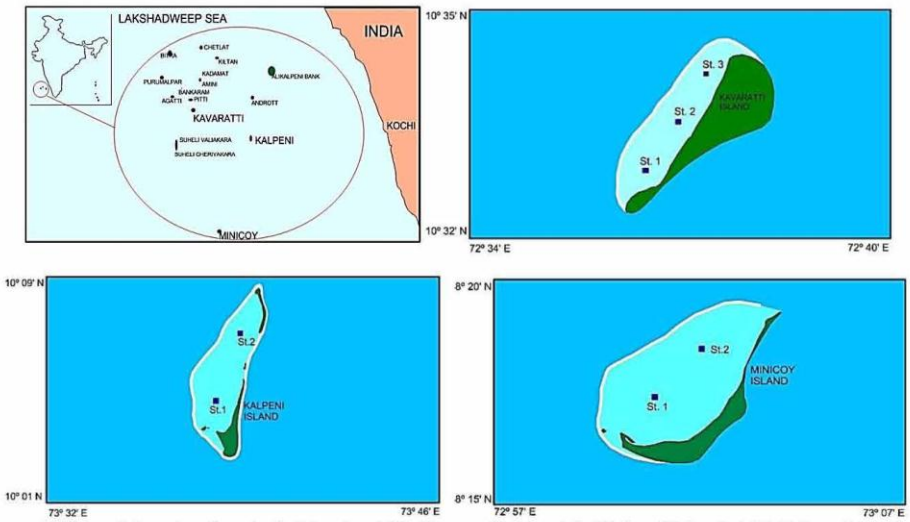

FIG.1a: Map showing study islands of (1b.Kavaratti Island 1c.Kalpeni Island, 1d.Minicoy Island) Lakshadweep archipelago, India

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Performance and emission analysis of 1.5 MW photovoltaic energy systems

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JK Laxmipat University, India

India has high solar insolation, making the place good for solar power initiatives. Thar Desert has been set aside for solar power projects, sufficient to generate 700 to 2,100 GW. India unveiled a $19 billion plan to produce 20 GW of solar power by 2020. India receives solar energy equivalent to over 5,000 trillion kWh/yr. The daily average solar energy incident varies from 4 -7 kWh/m2 depending upon the location. Many parts of the country do not have an electrical grid. The paper presents performance, sensitivity analysis and optimization studies are carried out for PV energy system proposed at Minambakkam. Energy model of 1.5 MW PV energy systems is simulated to judge its performance. Two configurations are analyzed one with battery and other without it battery for PV system, capital and replacement multipliers has been chosen as 0.8, and PV life 20 yr. Considering energy security, results with battery cash flow summary is illustrated in this paper.

Biography

Md. Fahim Ansari received PhD (Electrical Engineering) from NITTTR Chandigarh, Punjab University, Chandigarh MTech (Electrical Engineering) From Central University AMU Aligarh BTech (Electrical Engineering). He has published over twenty two research papers in international and national journals/conferences and supervised more than 13 MTech theses. His many research papers have been awarded by international and national committees/conference. He has chaired several national conferences. He has given expert lecture in various colleges like NITTTR Chandigarh. He has visited many countries for attending and presenting the research papers in the international conferences. Currently, he is supervising two PhD scholars and evaluated two PhD theses. He is the active reviewer of IEEE Journal, Taylor and Francis Elsevier and other various journals. He is member of BOG of BRCM CET Bahal.

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Diversity of Poecilostomatoida copepods including new records from Kavarathi, Lakshadweep Island, India

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Since 1972 many eminent scientists have been surveying zooplankton assemblages with special reference to copepods mainly on calanoid copepods and little on cyclopoid copepods. Copepod research in Kavarathi island of Lakshadweep archipelago started with Goswami (1973, 1979, and 1983) from National Institute of Oceanography, who reported 52 species from Kavarathi lagoon and sea among which only 16 species belonged to cyclopoid group, the rest being calanoids. Subsequent studies in this same region by Madhuprathap et al (1977) included 30 species out of which only 7 were under cyclopoids and the rest being majority of calanoids. Madhuprathap et al (1991) yielded only one cyclopoidand 14 species of calanoids from Kavarathi, Kadamat and Minicoy islands. Suresh and Mathw (1997), CMFRI, Cochin also reported copepods from Kavarathi. Six species of cyclopoids were only reported by Usha Goswami and Goswami (1990) from Kavarathi and Minicoy islands, the rest being 33 species of calanoids and 3 harpacticoids. Recent studies by Robin et.al (2012) reported only 3 cyclopoid species, 10 species of calanoids and 1 belonging to Harpacticoida. Taxonomic and diversity studies on copepods in Lakshadweep islands have usually been concentrated on calanoid group and little is known about the marine cyclopoid groups. The present study briefly outlines 16 species of Poecilostomatoid copepods identified from Kavarathi Island, Lakshadweep, of which 13 are new records from Kavarathi region.

Biography

R Radhika is a Junior Research Fellow perusing her PhD in the Department of Marine Biology, Cochin University of Science and Technology, under the supervision of Dr. S. Bijoy Nandan, under the Department of Biotechnology funder project "Taxonomy and genetic characterization of pelagic copepods from marine habitats along south west coast of India".

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ECOLOGY AND SYSTEMATICS OF PELAGIC COPEPODS (CRUSTACEA) FROM SOUTH WEST ARABIAN SEA

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Abstract

Of all the marine zooplankton groups, copepods particularly calanoid and cyclopoid copepods are the dominant groups in marine subtropical and tropical waters and exhibit great diversity in morphology and habitats they occupy (Sanu et. al. 2014).The present study is aimed to develop a baseline data on copepod abundance, distribution and seasonal variation in South West (SW) Arabian Sea (8°15'N 73°52'E to 10 °33'N 72°40' E). Seasonal sampling for mesozooplankton and physico chemical parameters from April 2013 to January 2014 from SW Arabian Sea (Lakshadweep islands) form basis of this paper. Forty one calanoids, 28 cyclopoids and 5 harpacticoids belonging to19 families were identified and developed MtCOI sequences of many copepod species were developed. The most dominant calanoid family observed is Pontellidae followed by Acartidae. Inter and intra island species- community structure and systematic variations were observed. Many species identified were first systematic accounts from the SW Arabian Sea. Mitochondrial COI sequences of *Acartia bispinosa, Labidocera madurae Labidocera kroyeri, Candacia catula, Labidocera minuta, Farranula gibbula* represented the first molecular barcode available in NCBI and these were important insights in marine biodiversity research.The species were found to occur in a salinity range of 33 to 37 PSU, pH of 7.72 to 8.76, and temperature range of 26.75 to 30.25 °C. Many species that were abundant in previous studies were not found to be occurring in the present study and were influenced remarkably by variations on temporal scale than spatial scale depending on the variation in temperature and salinity patterns.

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Eddy mediated nutrient pattern in the North Eastern Arabian Sea during spring intermonsoon

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A Cold Core Eddy (CCE) mediated nutrient pattern in the North Eastern Arabian Sea (NEAS) is explained based on in situ measurements during March 2013 onboard FORV SagarSampada, which was not reported earlier in the area. Samples for physical and chemical parameters were collected in 5 stations along the diameter of the eddy and following standard protocols. The core of the CCE is identified at 21°20.38'N; 66°30.68'E with a diameter of 120Km. Earlier studies explaining the process and the forcing mechanism of the particular eddy records that, the eddy is short term (1-3 months) and is regular during the season. Surface waters were well oxygenated (>4.8 ml L-1) in the core. Surface value of nutrients viz., Nitrate, Nitrite, Silicate and Phosphate in the core regions was 0.9µM, 0.01 µM, 0.5 µM and 0.7 µM respectively indicating upwelling in the core.

Spring intermonsoon (SIM) is generally termed as a transition period between the active winter and summer seasons and as per earlier studies, high biological production and the regularly occurring Noctiluca bloom is supported by the nutrient loading due to convective mixing during winter as well as regenerated production. However, present observations shows that, nutrient pumping due to the upwelling associated with the CCE also contributes for sustaining high biological production and are evident in the Chla and mesozooplanktonbiovolume which records values of 4.35mg/m3 and 1.09ml/m3 respectively in the core. An intense Noctiluca blooms observed in the western flank of the eddy (Chla 13.25 mg/m3; cell density 5.8×106 cells/litre), where Nitrate concentration records 1.04µM explains the role of such mesoscale processes in the sustenance of the HAB events. While eastern flank of the CCE showed typical open ocean condition of the season showing Nitrate 0.08µM; Chla 0.23mg/m3; and phytoplankton cell density as 421 cells/litre.

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A comparative study on mesozooplanktona bundance and diversity between selected coral lagoons of Lakshadweep, India

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Lakshadweep an important coral island on the west coast of India considered as a treasure house of biodiversity. Zooplankton is one of the major component in the food for coral reef community. The study was carried out to understand the variability in abundance and diversity of mesozooplanktonin selected coral lagoons. Seasonal variation in hydrographic parameters, mesozooplankton distribution, diversity and abundance in coral lagoons of Kavaratti, Kalpeni and Minicoy were studied during monsoon (September 2013) and postmonsoon (January 2014). Twenty eight, twenty two and nineteen functional groups of zooplankters formed the plankton population in Kavaratti, Kalpeni and Minicoy respectively. Copepods dominated all the selected lagoons whereas non copepod groups differed significantly between the lagoons. The dominant groups were Zoea (11.53%),Decapoda (6.94%), fish eggs (6.03%), Foraminifera (5.69%), Gastropoda (4.51%), fish larvae