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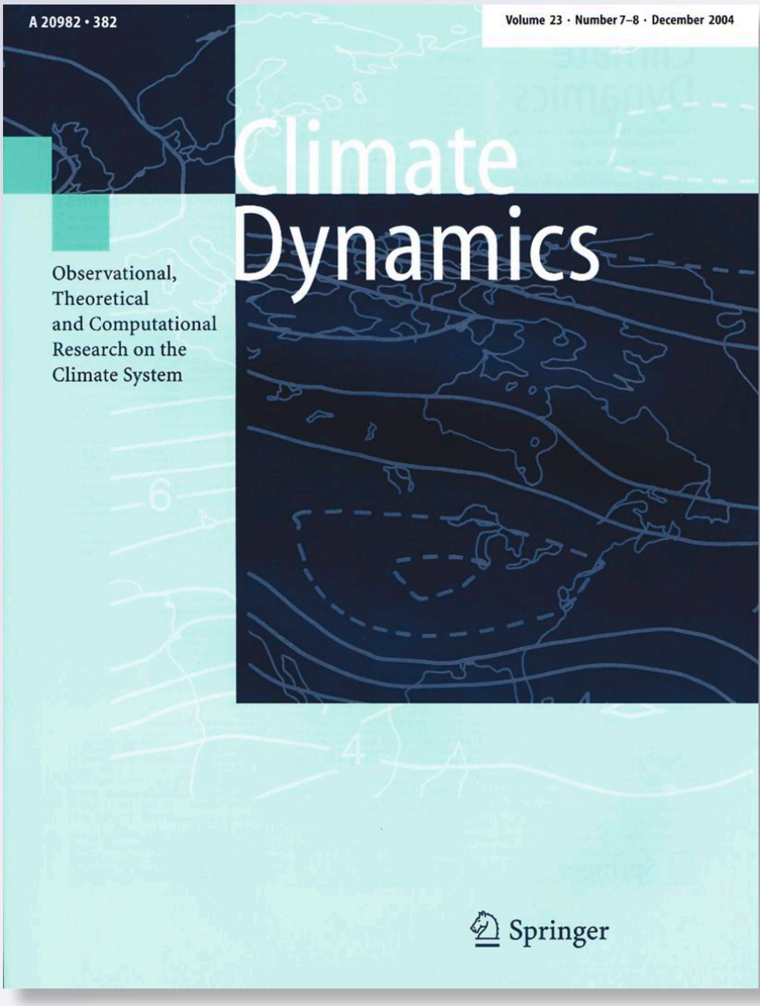

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Abstract Arabian Sea Mini Warm Pool (ASMWP) is a part of the Indian Ocean Warm Pool and formed in the eastern Arabian Sea prior to the onset of the summer monsoon season. This warm pool attained its maximum intensity during the pre-monsoon season and dissipated with the commencement of summer monsoon. The main focus of the present work was on the triggering of the dissipation of this warm pool and its relation to the onset of summer monsoon over Kerala. This phenomenon was studied utilizing NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric and Research) re-analysis data, TRMM Micro wave Imager (TMI) and observational data. To define the ASMWP, sea surface temperature exceeding 30.25°C was taken as the criteria. The warm pool attained its maximum dimension and intensity nearly 2 weeks prior to the onset of summer monsoon over Kerala. Interestingly, the warm pool started its dissipation immediately after attaining its maximum core temperature. This information can be included in the present numerical models to enhance the prediction capability. It was also found that the extent and intensity of the ASMWP varied depending on the type of monsoon i.e., excess, normal, and deficient monsoon. Maximum core temperature and wide coverage of the warm pool observed during the excess monsoon years compared to normal and deficient monsoon years. The study also revealed a strong relationship between the salinity in the eastern Arabian Sea and the nature of the monsoon.

Keywords Arabian Sea mini warm pool · Summer monsoon onset · Deficient, normal and excess monsoon years · Sea surface temperature

1 Introduction

Indian summer monsoon and its variability have been a major topic of study for the last few decades. An important conclusion emerging from these studies is that the variability in the Pacific Ocean is not isolated but linked with the Indian Ocean monsoon system. For example, the El-Nino Southern Oscillation phenomenon is mainly controlled by the sea surface temperature (SST) in the tropical Pacific and Indian Ocean. Here, the maximum temperature do occur and act as the main source of heat energy for the global atmosphere. The warm SST anomaly in the equatorial central Pacific Ocean causes delay in the shifting of convection from equatorial western Pacific to the North Indian Ocean, which in turn causes a delay in monsoon onset (Joseph et al. 1994).

Studies based on the SST climatology (Hastenrath and Lamb 1979; Bottomley et al. 1990; Shea et al. 1990; Rao et al. 1991) and thermal structure (Wyrtki 1971; Hastenrath and Greischar 1989; Levitus and Boyer 1994) in the western tropical Pacific Ocean, central and eastern Indian Ocean indicated a zone of warm water, where the SST was more than 28°C. This pool of warm water is generally known as Indo-Pacific warm pool; which migrates in the north–south direction in phase with the Sun. Even though the western Pacific Ocean warm pool has been studied

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extensively, the Indian Ocean warm pool, which is an extension of Pacific Ocean warm pool remained little explored.

Compared to the Indian Ocean warm pool, the western Pacific warm pool is more extensive and covers an area of about 33 × 10^6 km^2. Within this warm pool, the mean SST is around 29°C throughout the year in an area of 0.9 × 10^6 km^2. However, at the core of the Indian Ocean warm pool, the surface temperature is much higher than that observed in the Pacific Ocean (Vinayachandran and Shetye 1991).

Intensity and spatio-temporal variability of the Indian Ocean warm pool depends largely on the seasonally reversing monsoon (Vinayachandran and Shetye 1991). These strong winds force the ocean locally, and they excite propagating signals (Kelvin and Rossby waves) that travel long distances to affect the ocean remotely. Shenoi et al. (1999) has concluded that remote forcing plays a major role in the development of high SST in the Lakshadweep region, which is favourable for the genesis of the monsoon onset vortex. The coastally trapped Kelvin waves have an important role in bringing low salinity waters from the Bay of Bengal into the Arabian Sea during winter which eventually facilitates the building up of the mini warm pool in the Lakshadweep area. Durand et al. (2004) has noticed that temperature inversions that occur in this region contribute significantly to the warming in the south eastern Arabian Sea (SEAS) during the pre-monsoon period. Shankar et al. (2004) has provided observational evidence of the westward propagation of these temperature inversions which forms off the west coast of India and moving along with the downwelling Rossby waves that constitutes the Lakshadweep High.

Utilising the MONEX 79 data, Seetharamayya and Master (1984) showed that a pool of water with temperature in excess of 30.8°C occurred in the SEAS, well within the Indian Ocean warm pool, prior to the onset of summer monsoon. This zone, which is part of the Indian Ocean warm pool, is called as the Arabian Sea mini warm pool (ASMWP). Kershaw (1988) found that warm SST anomaly is essential for the development of onset vortex. Joseph (1990a) has reported that the onset vortex prior to the summer monsoon onset is formed in the warm pool area in the SEAS. Rao et al. (1994) studied the evolution of SST in the mini warm pool region (defined as the region where SST >30.25°C) and evaluated the relative importance of heat fluxes and entrainment in the building up of this mini warm pool. Rao and Sivakumar (1999) summarized the previous studies related to the warm pool and analysed various factors that involve in the formation of the ASMWP. Sanilkumar et al. (2004) conducted a cruise in the south-eastern Arabian Sea during May 2000, exclusively to study the characteristics of this mini warm pool. They defined mini warm pool as the region where the SST was in excess of 30.25°C. Recently, Hareesh Kumar et al. (2010) utilized the Princeton Ocean Model to study the role of heat flux and salinity in the evolution of this warm pool.

Several studies have been carried out to study the link between the SST in the Arabian Sea during pre-monsoon period and the monsoon activity over the Indian region (Shukla and Misra 1977; Weare 1979; Cadet and Diehl 1984; Rao and Goswami 1988). Anjaneyulu (1980) pointed out that higher the difference of maximum SST between the pre-monsoon and the monsoon seasons, greater the possibility for a good monsoon and vice versa. Joseph (1990b) found that warm SST anomaly in the north Indian Ocean or cold SST anomaly in the west Pacific Ocean is favourable for good monsoon rainfall over India. In spite of all these significance, not many studies have been carried out to understand the ASMWP in detail, primarily due to lack of sufficient data sets. With the availability of NCEP/NCAR (National Centre for Environmental Prediction/National Centre for Atmospheric and Research) Reanalysis data, sea truth measurements from ships of opportunities and satellite derived SST, a better attempt has been made to map the ASMWP. The primary objective of this work is to study the evolution of this mini warm pool during the pre-monsoon season and its dissipation associated with the monsoon onset. In this work, the mini warm pool is defined as the region where SST is more than 30°C, following Rao and Sivakumar (1999) and Sanilkumar et al. (2004). An attempt is also made to bring out its possible relationship with the nature of the forthcoming monsoon and to predict the onset of monsoon over Kerala from the characteristics of ASMWP.

2 Data and methodology

The study area extends from 40°E to 80°E and from 5°S to 25°N (Fig. 1). The characteristics of the mini warm pool has been studied mainly based on the NCEP/NCAR re-analysis SST data (Kalnay et al. 1996; herein after referred as NNR) for a period of 39 years (1960–1998). The onset dates of summer monsoon over Kerala from 1960 to 2010 are taken from India Meteorological Department (IMD). The average rainfall for the years from 1960 to 1994 and 1994–1998 is taken from Parthasarathy et al. (1994) and De et al. (1998) respectively. Pursuing their approach, each year has been classified as excess monsoon year, when rainfall of that year exceeds the long term mean (852.4 mm) rainfall by one standard deviation (σ), deficient monsoon year when the rainfall for that year is less than the mean rainfall by 1σ and normal otherwise. The evolution and dissipation of the ASMWP has been studied selecting typical years from NNR data representing

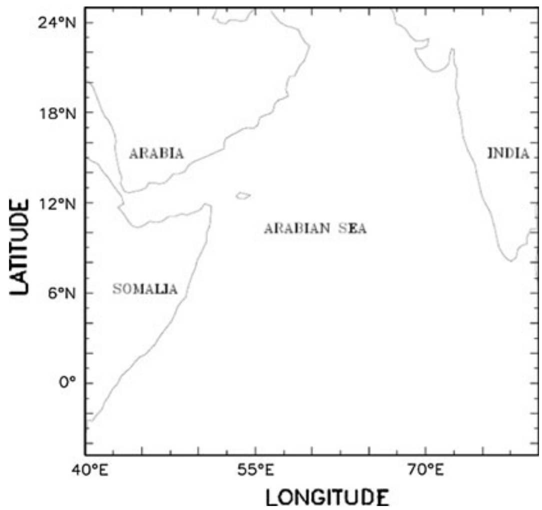


Fig. 1 Study region

excess, normal and deficient monsoon years. The results from the above analysis are further compared with the high resolution TRMM Micro wave Imager (TMI) SST (TMI SST) data (resolution of 0.25° latitude × 0.25° longitude) for the years from 1998 to 2009. Rajeevan et al. (2004) classified 2003, 2001 and 2002 as above normal, below normal and deficient monsoon years respectively. The TMI SST is further utilized to study the characteristics of the warm pool during excess, normal, and deficient monsoon years. In addition, all the available in situ salinity data in this region (1940–1998) obtained from various sources are also used to study the role of salinity in the corresponding excess, normal and deficient monsoon years after proper quality checks.

3 Results and discussion

3.1 Variability in the onset of summer monsoon and average rainfall

The onset date of the summer monsoon (1970–2010) is presented in Fig. 2. A noticeable observation is the variability in the onset dates with a periodicity of nearly 3 years.

3.2 Monthly evolution of sea surface temperature

To study the evolution of temperature in the upper layers of Arabian Sea, monthly averaged NNR SST (1960–1998) is presented (Fig. 3). The appearance of 28.5°C isotherm near the equator between December and May clearly indicates progressive warming in the surface layers. By May, temperature exceeds 29°C in the entire Arabian Sea, with maximum values concentrating in the SEAS. Here, a pool of water with core temperature in excess of 29.9°C is noticed. Various researchers (Seetharamayya and Master 1984; Joseph 1990a; Rao and Sivakumar 1999; Sanilkumar et al. 2004; Hareesh Kumar et al. 2010) also reported this pool of warm water prior to the onset of summer monsoon. The core temperature of 29.9°C observed in this study is slightly less than that reported by Rao and Sivakumar (1999). The difference may be due to the usage of different data sets, viz. data from Levitus and Boyer (1994) by Rao and Sivakumar (1999) and NNR Reanalysis data in this study. Even though, the core temperature is different, the warm pool is very prominent in both cases.

With the commencement of summer monsoon i.e. in June (Fig. 3), temperature in the warm pool region drops by more than 0.9°C compared to May (29.9°C in May to 29°C in June). During this period, decrease in SST is very prominent off Somalia, Arabia and southwest coast of India also. The cooling in the central and eastern Arabian is mostly manifested by the increased turbulent heat fluxes due to strengthened winds and decreased isolation under the monsoon cloud cover (Hastenrath and Lamb 1979; Hareesh Kumar and Mathew 1997). Studies by various researchers (Düing and Leetma 1980; Mathew 1981; Hareesh Kumar 1994; Hareesh Kumar and Mathew 1997) attributed this cooling to coastal upwelling. Düing and Leetma (1980) and Hareesh Kumar and Mathew (1997) estimated the summer cooling in the Arabian Sea due to various processes and stressed the importance of horizontal advection in the Arabian Sea cooling. The combined action of winds action, convective overturn due to buoyancy flux and coastal upwelling results in the dissipation of the warm pool. Vinayachandran and Shetye (1991) reported that the summer monsoon reduced the area of the warm pool by one third over a period of 5 months (24×10^6 km^2 in April to 8×10^6 km^2 in September).

3.3 Daily evolution of SST

Number of studies has suggested that there exists a relationship between SST anomalies in the Arabian Sea and anomalies in rainfall over India (Shukla and Misra 1977; Shukla 1975). Anjaneyulu (1980) indicated the dependency of monsoon on the SST of the pre-monsoon period. Joseph and Pillai (1984) also found positive correlation between pre-monsoon SST and the following monsoon rainfall. Joseph (1990b) has observed that warm SST anomaly in north Indian Ocean favoured good monsoon rainfall. Rao (1990) noticed large differences in the depletion of heat content in the topmost layers for two different types of monsoon years. All these studies prompted to understand the relationship between SST in the warm pool region and the monsoon characteristics.

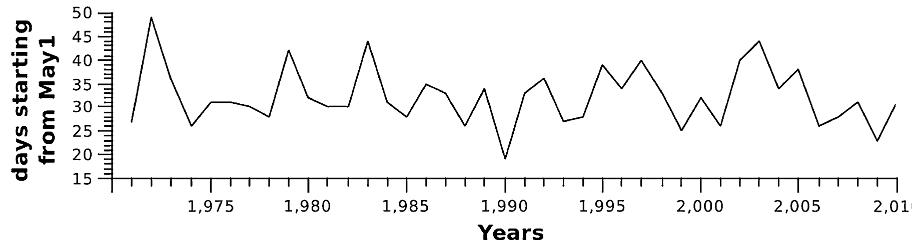


Fig. 2 Monsoon onset date (based on IMD) from 1970 to 2010

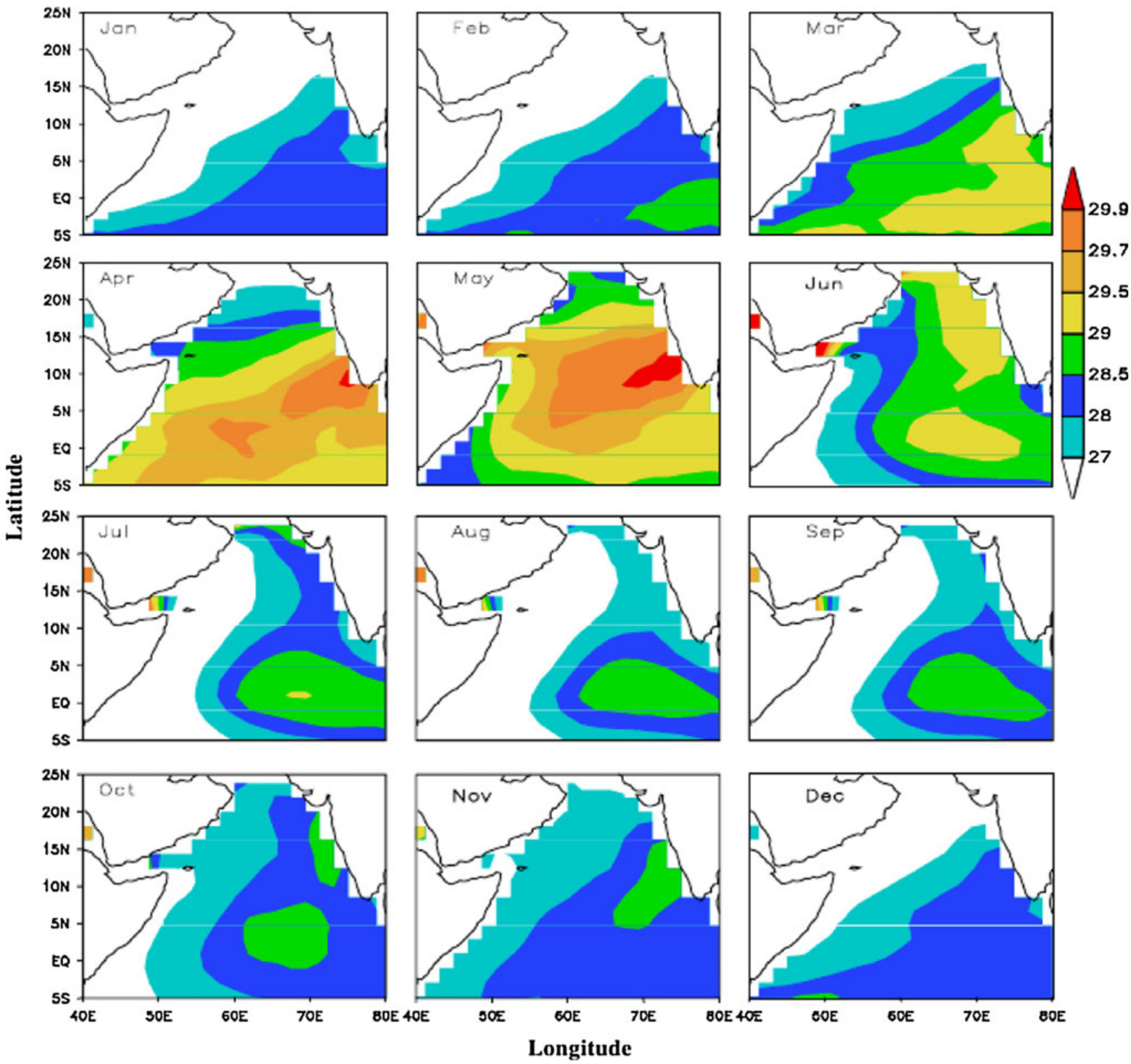


Fig. 3 Monthly evolution of NNR SST (°C)

The monthly evolution of SST (Fig. 3) in the Arabian Sea indicates the formation of a mini warm pool in the eastern Arabian Sea during May and dissipation after the onset of summer monsoon. To understand more about the evolution of this mini warm pool and its subsequent dissipation, the daily NNR SST from 1 May to 1 week after the onset for some typical year's corresponding to excess (1988), normal (1981) and deficient (1985) monsoon are presented (Fig. 4a, b, c). The results from these studies are further verified using the TMI data for the years 2001, 2002

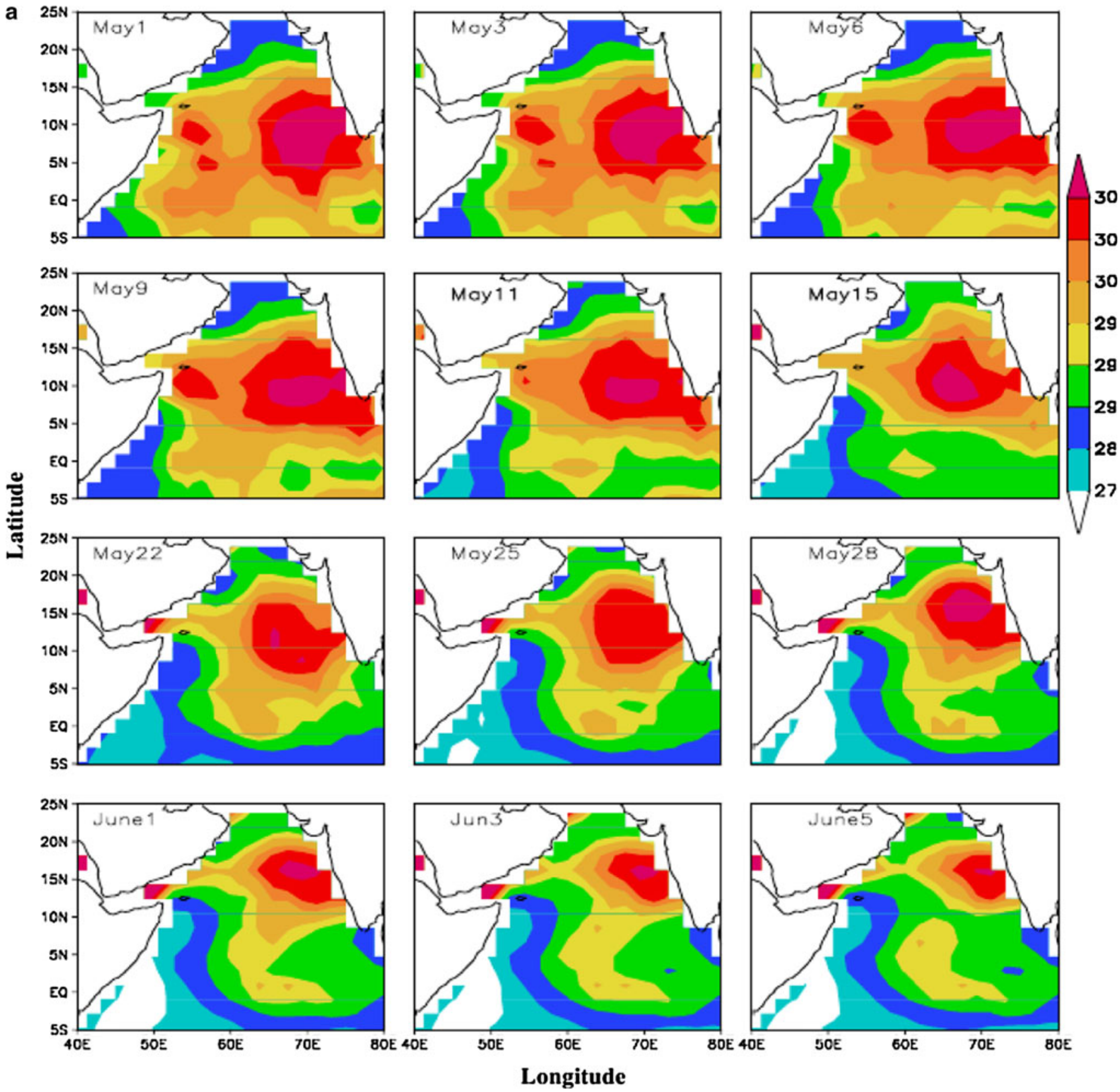


Fig. 4 **a** Daily evolution of SST (°C) representing some typical days of marked changes during May–June 1988. **b** Daily evolution of SST (°C) representing some typical days of marked changes during May-June 1981. **c** Daily evolution of SST (°C) representing some typical days of marked changes during May- June 1985. **d** Daily evolution of SST (°C) representing some typical days of marked changes during May- June 2002 (TMI). **e** Daily evolution of TMI SST (°C) for some typical days of marked changes during May- June 2003. **f** Daily evolution of TMI SST (°C) for some typical days of marked changes during May- June 2001

and 2003 (Fig. 4d, e, f), which are classified as normal, deficient and excess monsoon years respectively by Rajeevan et al. (2004).

3.3.1 Excess monsoon year

In general, during excess monsoon year (e.g. 1988), temperature is more than 29.5°C between 5°S–17°N and 50°–80°E during May (Fig. 4a). However, in the eastern Arabian Sea, a pool of water with temperature in excess of 30°C is noticed from 1 May onwards with core temperature of ~30.5°C. This pool attains its maximum lateral dimension, i.e. from 5°–15°N to 50°–75°E, on 6 May covering an area of more than 3,000,000 km^2. Here, the temperature increase got arrested after 6 May and slight decrease in SST is noticed from 11 May. However, IMD

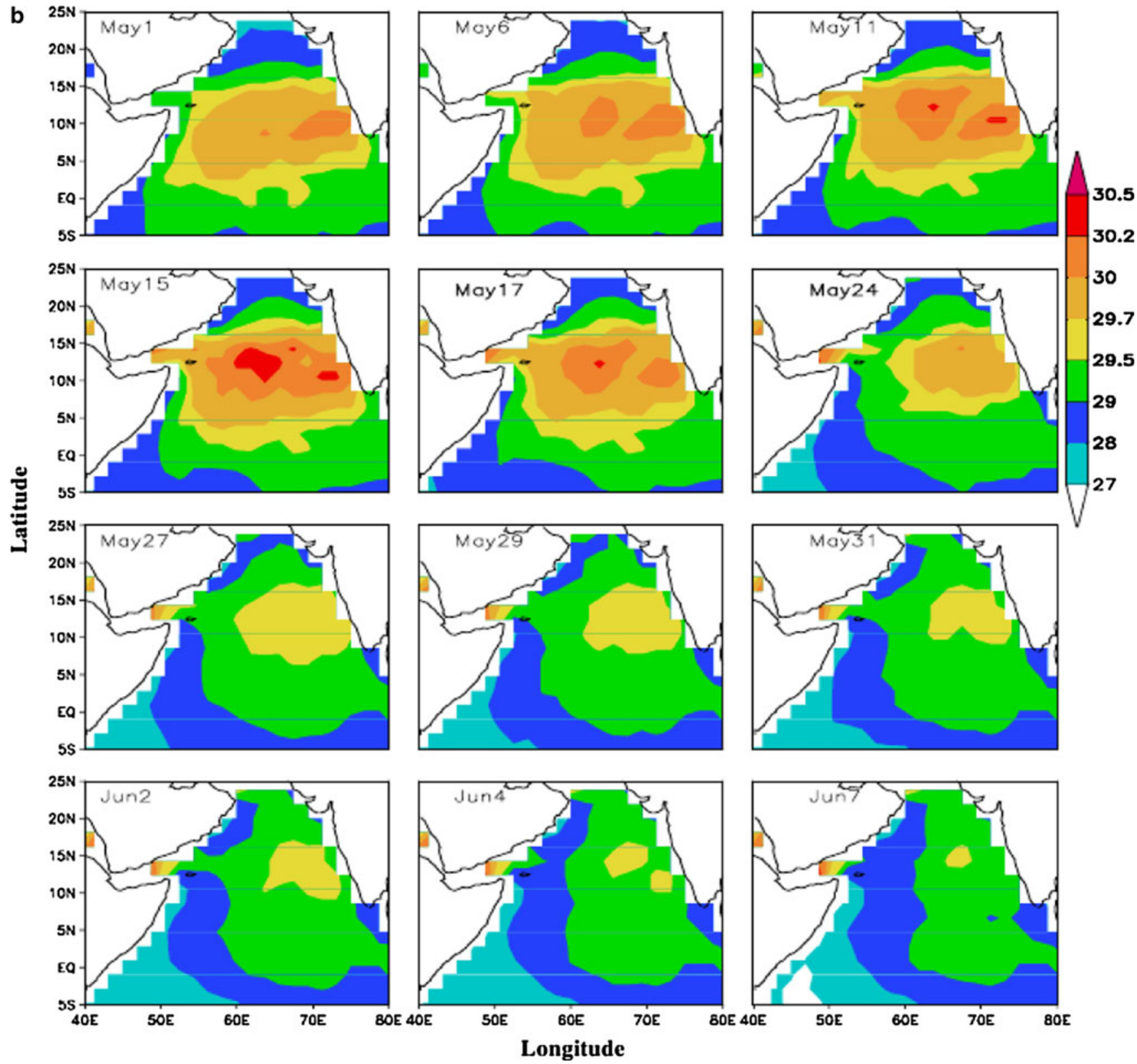


Fig. 4 continued

reported the onset of summer monsoon over Kerala on 26 May during 1988. This suggests that even before the onset of monsoon, the mini warm pool starts dissipating. The analysis of NNR wind at 850 mb (Figure not presented) revealed that the wind strengthens over the Arabian Sea from the second week of May itself, which in turn can trigger the dissipation of the warm pool. Between 6 May (when the warm pool attain maximum dimension) and 26 May, temperature at the core of the warm pool decreases by ~0.5°C (30.5–30°C) and it exceeds 1.5°C (30.5–29°C) by 1 June (average monsoon onset date). At the same time, intense cooling is observed off Somali (>2.5°C, 29.5° to <27°C) region and southwest coast of India (>1°C, 30°–29°C) for the corresponding period, due to coastal upwelling.

The year 2003 was classified as above normal monsoon year and the onset date was as 8 June (Fig. 4e). In this year, temperature in the eastern Arabian Sea exceeds 31.5°C even on 1 May. However, slight cooling is noticed till 9 May, probably associated with some convective system. Afterwards temperature again increases in this region and reaches its maximum (32°C) on 26 May. During this period the mini warm pool is observed between 0°–20°N and 52°–75°E (>5,500,000 km^2) with core temperature of 32°C.

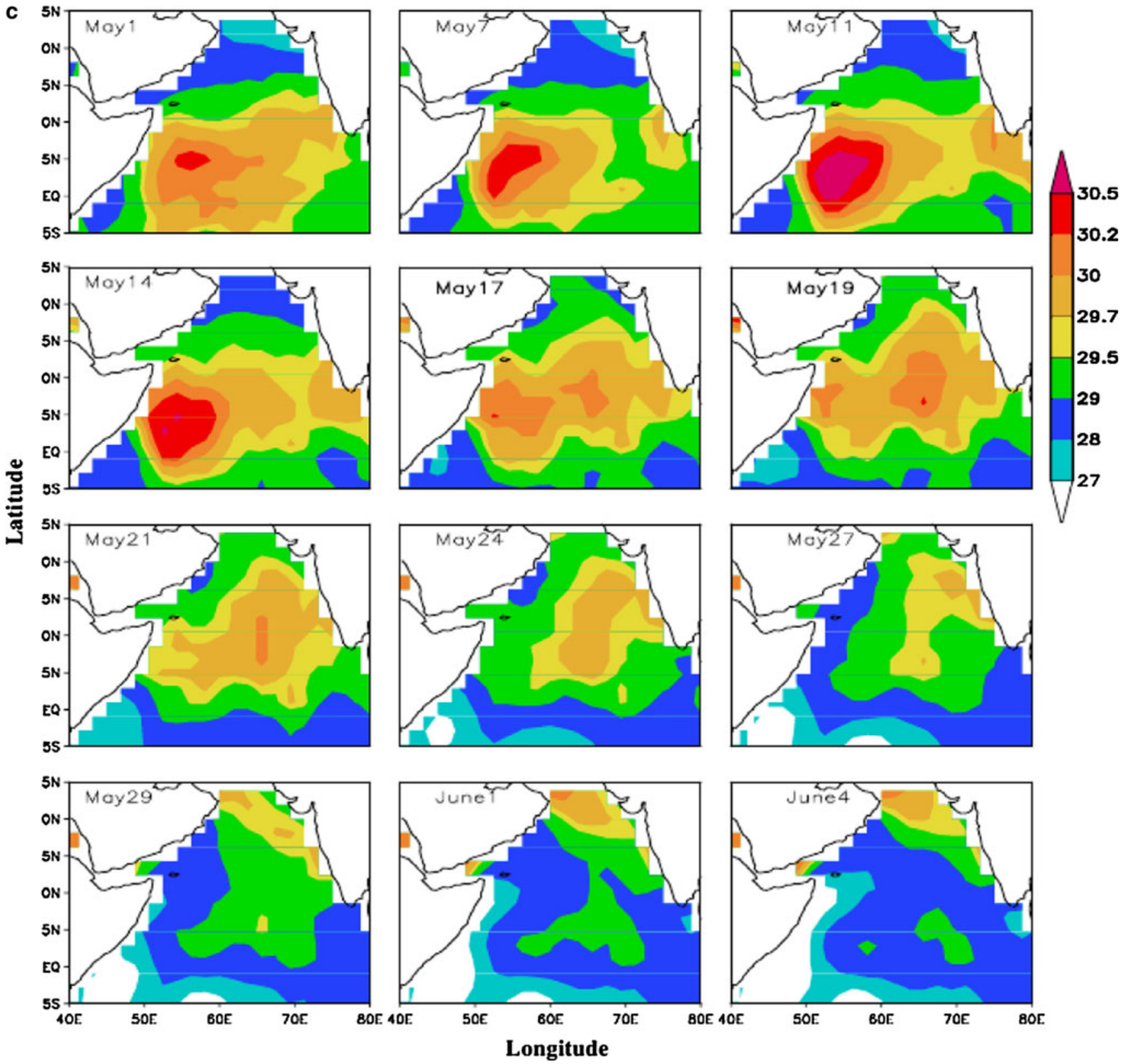
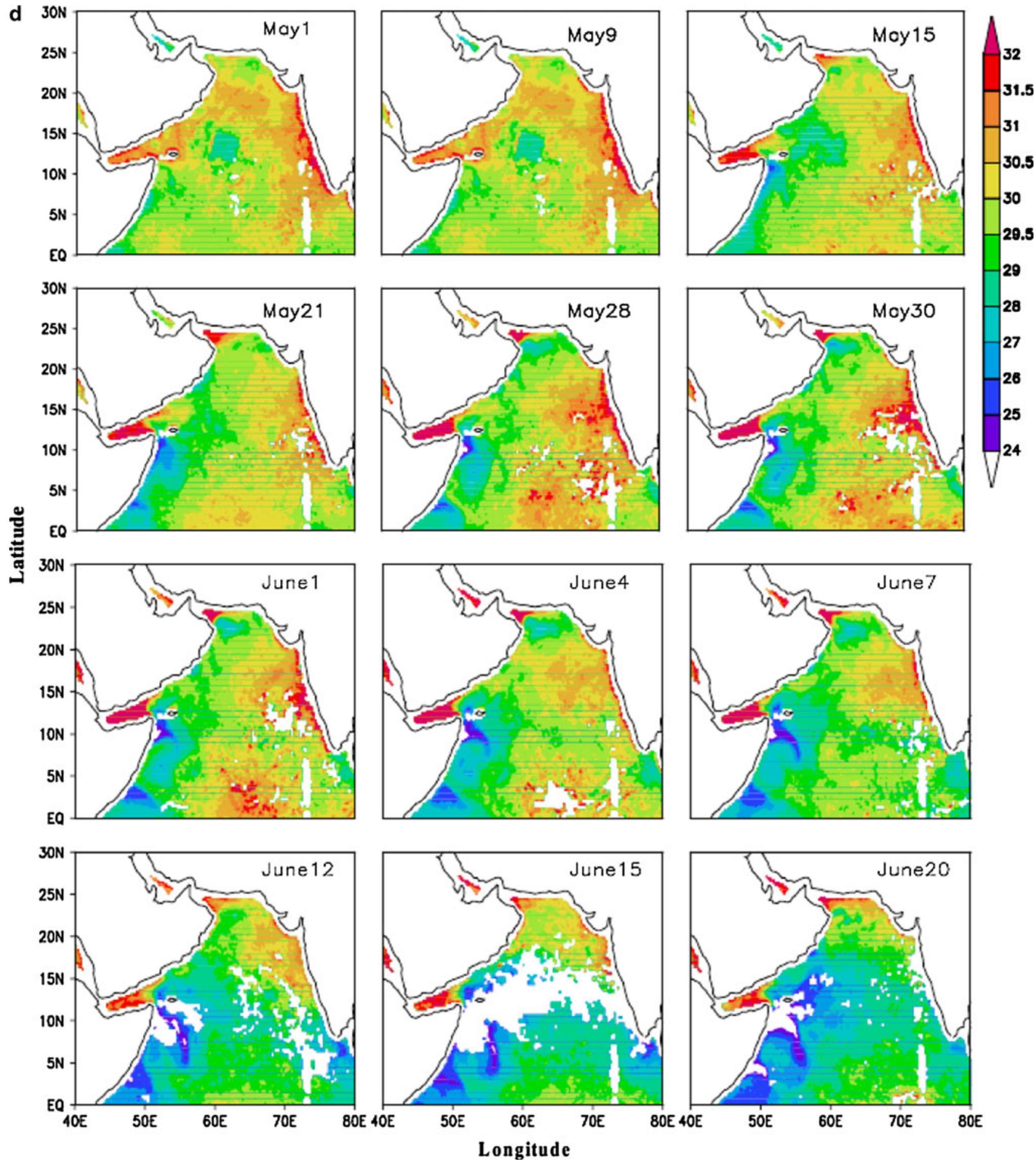


Fig. 4 continued

Noticeably, the region south of 8°N shows cooling from 28 May onwards. However, the core temperature (32°C) in the central Arabian Sea around 11°N remains the same till 4 June. Thus, in this case also cooling in the warm pool region starts approximately 11 days prior (i.e. from 28 May) to the normal onset date of 8 June. In the region south of 8°N, cooling exceeds 1.5°C between 26 May and 8 June (31.5 to <30°C), whereas in the central Arabian Sea the observed cooling for the same period is ~1°C (32°–31°C). By 17 June, cooling exceeds 2°C in the warm pool region (31.5°–29.5°C). In the upwelling regions off Somali and southwest coast of India, temperature drop is found to be more than 6°C (30.5°–24°C) and 1°C respectively.

3.3.2 Normal monsoon year

In the case of normal monsoon year (e.g. 1981), surface temperature in the basin on 1 May is ~29°C, except between 0°–15°N and 52°–75°E, where SST is found to be more than 29.5°C. In the warm pool region, the SST is 0.5°C less than that during the excess monsoon year (Fig. 4b). From 1 May, the mini warm pool has starts evolving in the eastern Arabian Sea and attains its maximum temperature on 15 May (30.2°C). During this year, the warm pool is noticed between 8°–15°N and 55°–75°E with coverage of more than 1,694,000 km^2. In this case, the core temperature (30.2°C) is found to be less compared



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to the excess monsoon year (30.5°C). Temperature increase in this zone arrests after 15 May and slight decrease is noticed from 17 May. The Indian Daily Weather Report (IDWR) reported the date of onset of monsoon over Kerala in this year as 30 May. However, from the second week of May, winds over the western Indian Ocean strengthens (from NNR wind at 850 mb, not presented here), thereby triggering the dissipation of the warm pool. So, in this case also, the dissipation of the mini warm pool starts even before the normal onset date

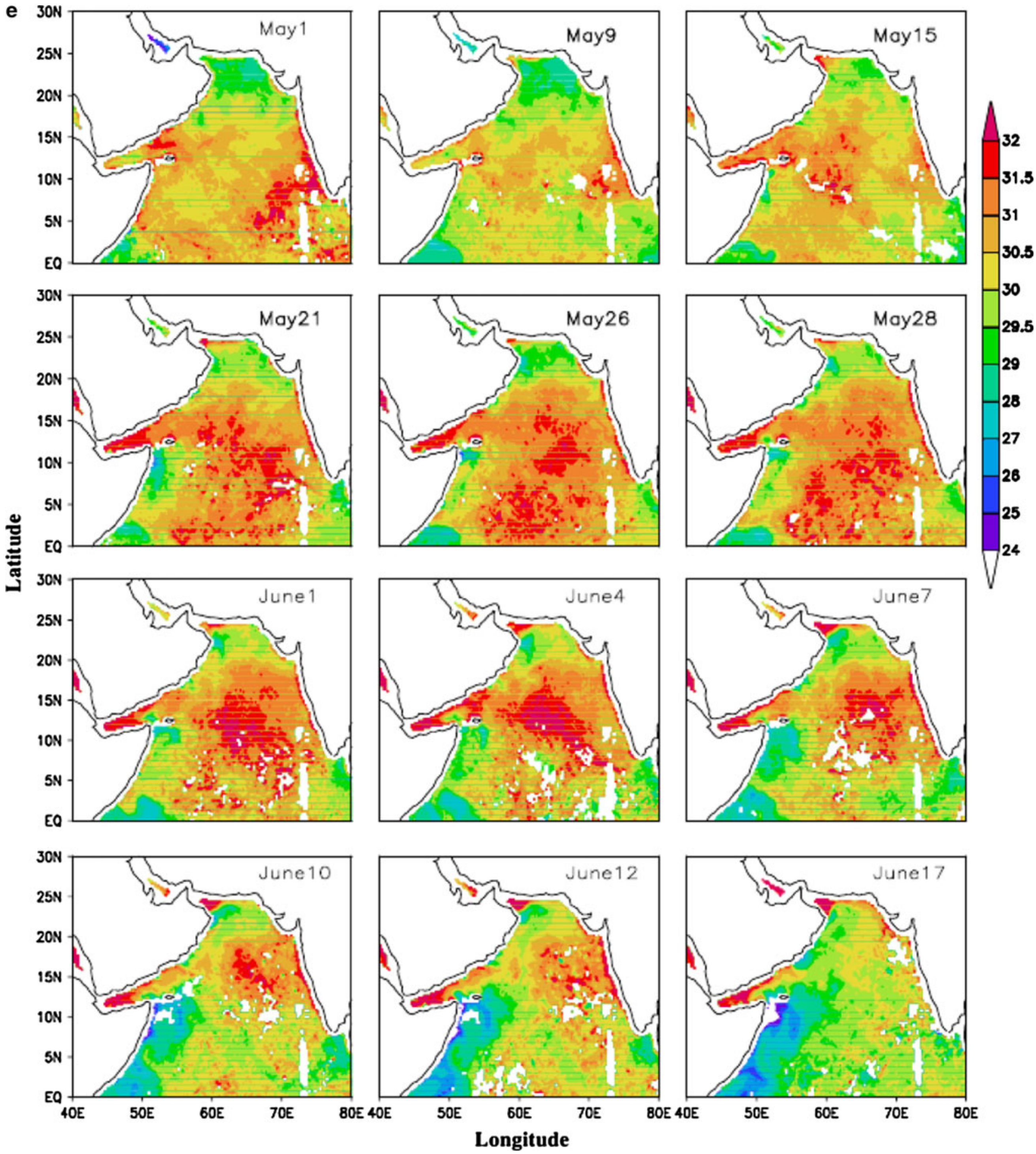

Fig. 4 continued

of monsoon over Kerala. Between 15 May and monsoon onset, temperature in the warm pool region drops by ~0.5°C (30–29.5°C). By 2 June, the cooling exceeds 1°C (30–29°C) in this region, whereas the cooling is 2°C (29°–27°C) and 1°C (30°–29°C) off Somali and southwest coast of India respectively.

The year 2001 was a normal monsoon year. In this year, the warm pool extends from the west coast of India towards the western equatorial Indian Ocean (0°–19°N and 50°–75°E). The maximum core temperature of 31.5°C is observed around 12°N on 17 May (Fig. 4f) with an area coverage of ~5,000,000 km^2, excluding the region in the

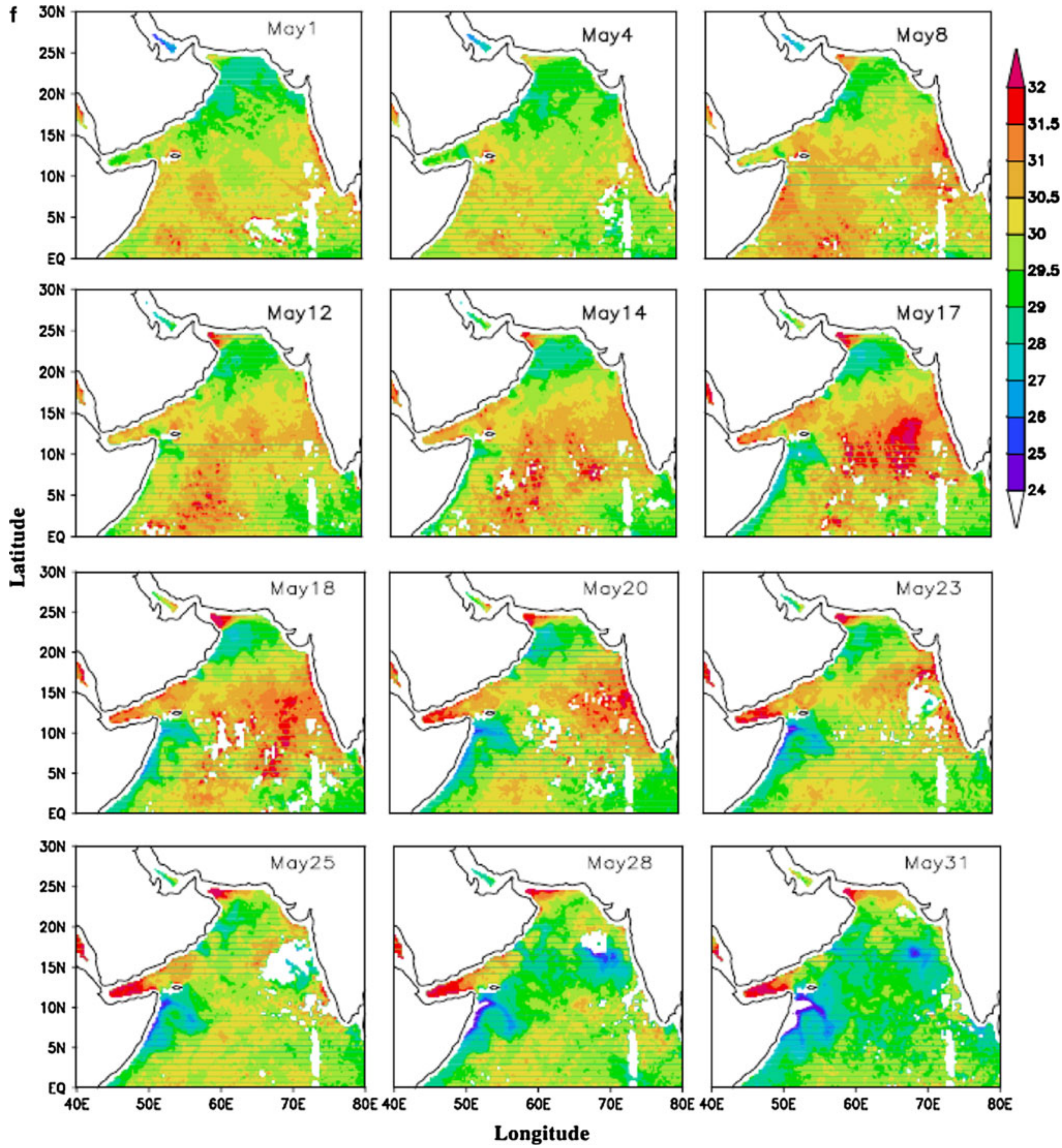

Fig. 4 continued

southeastern Arabian Sea, where temperature is less than 30°C. In the warm pool region, the cooling in the surface layers is observed from 18 May, which is approximately 6 days prior to the onset date, i.e. 23 May. Cooling in the warm pool region exceeds 1.5°C by 24 May (31.5° on 17 May to 30°C on 23 May) and 3°C (31.5°–28°C) by 31 May. In the upwelling regions off Somalia and southwest coast of India, the observed cooling is respectively 7°C (31°C on 8 May to 24°C on 31 May) and 1.5°C (31°C on 17 May to 29.5°C on 31 May).

3.3.3 Deficient monsoon year

In the case of deficient monsoon year (1985), maximum temperature in the eastern Arabian Sea is ∼29.7°C (Fig. 4c), whereas in the central Arabian Sea, i.e. between

2°–8°N and 50°–60°E, it exceeds 30°C. This suggests a westward shifting of the zone of maximum heating during this year. In this year, the warming continues up to 14 May, while in the central and eastern Arabian Sea; the warming continues up to 19 May. The dissipation of the mini warm pool coincides with the strengthening of the winds in the Arabian Sea. During this year, the onset of monsoon over Kerala was on 28 May, which indicates that the dissipation of the warm pool starts much before the onset of monsoon over Kerala. In the region of the warm pool, the temperature difference between 14 May (maximum temperature observed in the western Arabian Sea) and 28 May (onset date) exceeds 2°C (30°–28°C). Off the Somali coast and southwest coast of India also, the cooling exceeds 3°C (30°–27°C) and 1.7°C (29.7°–28°C) respectively.

During the year 2002 (Fig. 4d), which was a deficient monsoon year, evidence of the warm pool formation is noticed in the eastern Arabian Sea (0°–22°N and east of 60°E) from the first week of May itself. Even on 28 May, the warm pool is found to be very prominent between 0°–20°N and 60°–75°E. During the period, the warm pool covers an area of more than 3,600,000 km^2 with core temperature of 31.5°C centered at 15°N. The cooling in the warm pool region is observed from 30 May, which is approximately 2 weeks prior to the onset date i.e. on 13 June. Cooling in the eastern Arabian Sea exceeds 1°C (31.5°–30.5°C) between 28 May and the onset date (13 June) and more than 2°C by 20 June (Fig. 4d). The corresponding cooling off the Somali and southwest coast of India are approximately 5 and 3°C respectively.

The above analysis suggests that the extension and the core temperature in the mini warm pool vary significantly depending on the nature of the forthcoming monsoon. The dissipation of the ASMWP triggers 1–2 weeks before the normal onset of monsoon over Kerala. It is also noticed that during the excess monsoon years, mini warm pool occupy maximum area with maximum core temperature compared to normal and deficient monsoon years. In general, the trend of the warm pool is noticed to be the same for the NNR and TMI, but the slightly higher values in the TMI can be due to the high resolution (0.25° latitude × 0.25° longitude). The TMI SST also indicates maximum core temperature (32°C) and lateral extent of the mini warm pool region during the excess monsoon year compared to deficient (31.5°C, Fig. 4d) and normal (31.5°C, Fig. 4f) monsoon years.

In order to verify the above obtained results, the analysis has been extended using TMI data for the period from 1998 to 2009. Figure 5 shows the averaged SST over the region extending from 50°–75°E to 0°–15°N for the period 1 May to 15 June for each year. For each year there is a peak in SST followed by a decrease, which happens much before the onset of monsoon over Kerala. The spatial maps of these years (not presented here) also showed this dissipation much before the onset of monsoon over Kerala clearly. The scatter plot (Fig. 6a) between the onset and dissipation dates, clearly brings out the relation that dissipation happens approximately 7–14 days prior to onset date. Thus from Figs. 5 and 6a, it can be concluded that the dissipation of the warm pool happens much before the Onset date confirming the analysis in Sects. 3.3.1, 3.3.2 and 3.3.3. Similarly scatter plot (Fig. 6b) between core SST and seasonal summer monsoon rainfall for the corresponding year showed a tendency of occurrence of higher rainfall for the higher SST's. The relation between the area of the warm pool occupied during individual years versus seasonal summer monsoon rainfall (Fig. 6c) also showed a trend of larger warm pool areas occurring for higher summer rainfall activity over the Indian region.

3.4 Role of salinity in the formation of warm pool

It is well understood that the heat accumulated within a shallow and highly stratified layer prior to the onset of summer monsoon leads to the formation of the mini warm pool (Rao and Sivakumar 1999). An important question to be raised here is that what causes the formation of this highly stratified layer? One factor is the accumulation of heat under clear skies and weak winds (Rao and Sivakumar 1999). Another factor is the presence of low salinity water in the surface layers of the eastern Arabian Sea. To study this aspect, all the available in situ salinity values in the Arabian Sea are sorted for 15 days prior to onset date for each year and then computed the 1° latitude × 1° longitude averages (Fig. 7) for normal, excess and deficient years separately. The distribution of salinity in the surface layers shows considerable variation during all the three phases of the monsoon. The intrusion of low salinity water (<35 PSU) is clearly evident from the equatorial region in evident in all the cases but with a different spatial extent. During the excess monsoon year, the northward extent of the low salinity water is mostly confined to SEAS, i.e. south of 10°N and east of 60°E. In the case of normal monsoon year, the low salinity water extends up to 45°E from the eastern Arabian Sea. During the deficient monsoon year, the low salinity water is evident in the regions south of ~10°N and east of 60°E. But, interestingly, the lowest salinity values (34.5 PSU) are observed in the eastern Arabian Sea during the excess monsoon year, followed by normal monsoon year (34.75 PSU). However, during the deficient monsoon year, the low salinity waters in the eastern Arabian Sea is confined to south of 5°N.

During winter, the low saline water from the Bay of Bengal is brought into eastern Arabian Sea by the prevailing circulation pattern (Shenoi et al. 1999). This water is transported to the central and western Arabian Sea by the Rossby waves radiated from the downwelling coastal

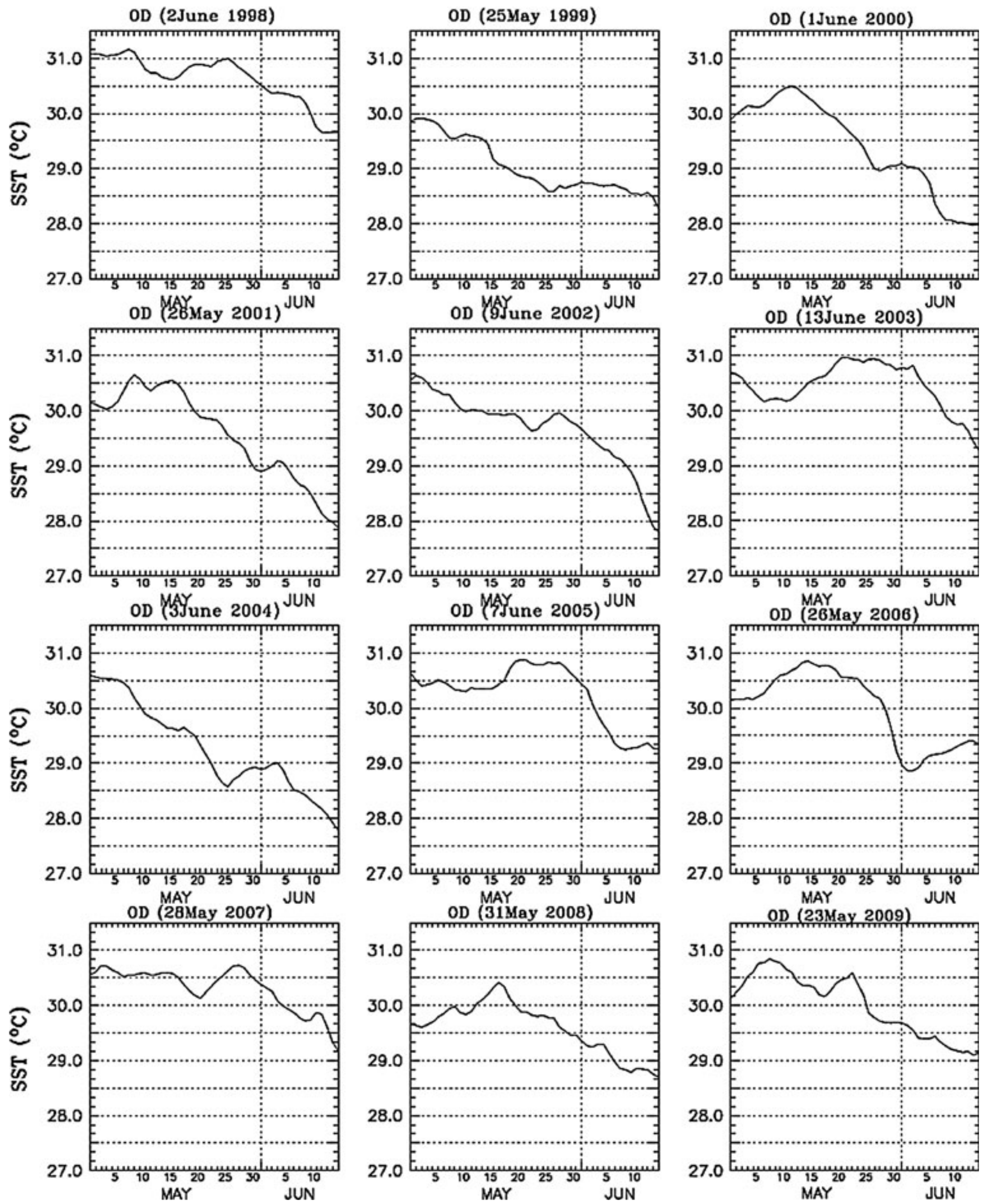

Fig. 5 TMI SST averaged over the region 50°–75°E and 0°–15°N from 1 May till 15 June for the years from 1998 till 2009 and OD is Onset Date

Kelvin waves (Bruce et al. 1994; Shankar and Shetye 1997; Shenoi et al. 1999). The circulation pattern changes to southerly along the west coast of India by April/May. With the dissipation of the Lakshadweep high and change in circulation pattern, this low saline water gets trapped in central and western Arabian Sea. So, during May, the low saline waters in the warm pool region cannot be brought by the prevailing circulation pattern. Therefore, one possibility is the re-circulation of the trapped low salinity waters from the interior Arabian Sea. Recent studies (Bruce et al. 1994; Sanilkumar et al. 2004; Hareesh Kumar et al. 2010) reported both cyclonic and anti-cyclonic in the Arabian Sea during the pre-monsoon season. The gyre circulation pattern associated with these eddies can re-circulate the low salinity water trapped in the western and central Arabian Sea to the warm pool region. The highs and lows in the TMI SST for all the years (Fig. 8) clearly indicate the eddy type of circulation in this region.

Another noticeable observation from the TMI charts is the northward extension of the water from the equatorial Indian Ocean to the interior Arabian Sea in all the 3 years (Fig. 8 a, b, c). In the year 2003 (Fig. 8c), water from the equatorial region is found to extend towards the central Arabian Sea as a tongue with core temperature of ~29.5°C. Water with same temperature (29.5°C) from the equatorial region is seen between 0–5°N and 65°–75°E during 2001 (Fig. 8a) and between 0–10°N and 70°–75°E during 2002 (Fig. 8b). The northward extension is found to be more during the year 2002 (Fig. 8b), which was a deficient year. Since the water is extending from the

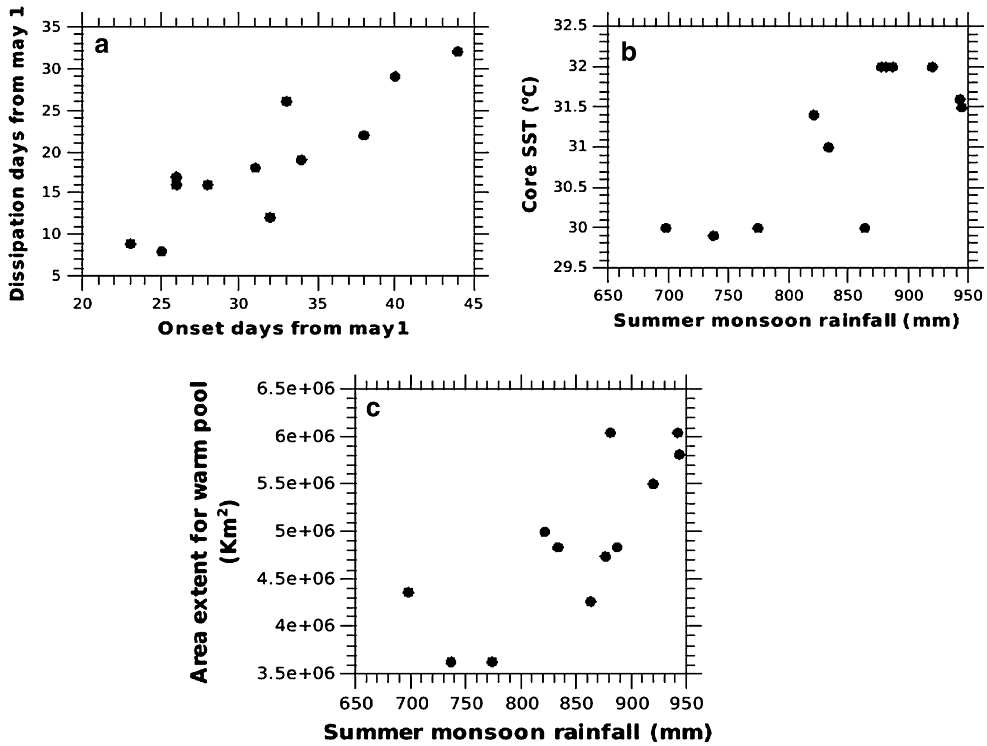

Fig. 6 Scatter plot **a** for dissipation dates against onset dates, dates are taken as days starting from May 1 **b** core SST of the warm pool prior to the onset and summer monsoon rainfall **c** summer monsoon rainfall and the area of the warm pool covered for the years considered from 1998 to 2009

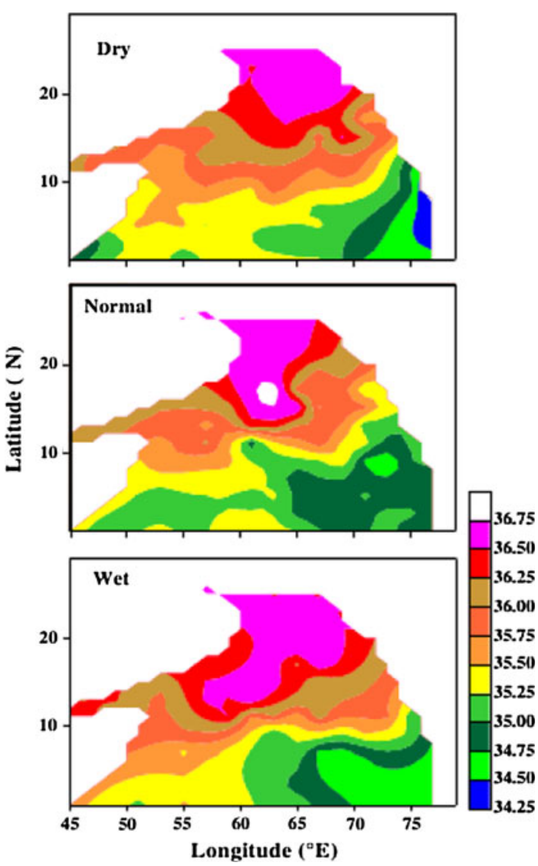

Fig. 7 Distribution of salinity prior to the onset of summer monsoon (in situ)

equatorial region towards the interior, the possible origin of this water can also be from equatorial Indian Ocean. These waters are typically low saline compared to the existing water in the Arabian Sea.

Therefore from the analysis it can be inferred that the low saline water observed in the warm pool region can be from two sources. One is the re-circulation of the Bay of Bengal water trapped in the interior Arabian Sea during winter by the eddy type of circulation. Second is the intrusion of equatorial water into the Arabian Sea and the re-circulation by the prevailing eddies.

4 Results and summary

In the Indian Ocean, an active area of recent research is the Indian Ocean warm pool and associated ocean and atmosphere dynamics. However, not much attention is paid to the ASMWP, where the onset vortex is formed. This study deals with the ASMWP, which is a part of the Indian Ocean warm pool formed in the southeastern Arabian Sea prior to the onset of summer monsoon. Utilizing 40 years of data corresponding to the onset date and corresponding rainfall, it was found that onset date undergoes a 3 years periodicity between the early onset and delayed onset. Data from NCEP/NCAR sea surface temperature for the period 1960–2010, ships of opportunities, high resolution TMI SST for typical years were utilized to study the characteristics of the ASMWP. As the temperature in the entire

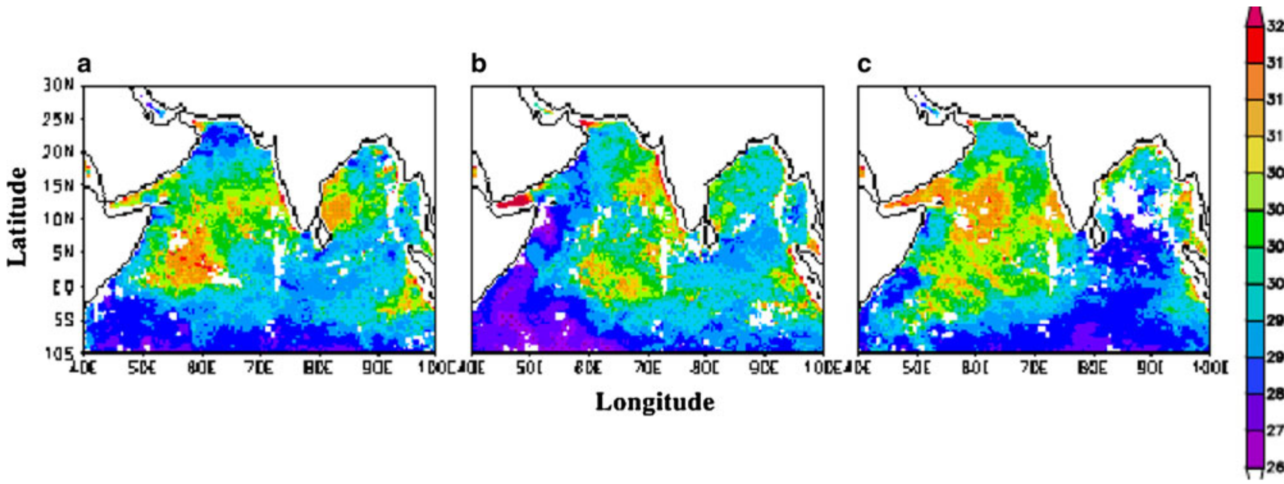

Fig. 8 Distribution of TMI SST (°C) for a single day for May **a** 2001, **b** 2002, **c** 2003

Arabian Sea exceeds 29°C during the pre-monsoon, 30.25°C isotherm was selected to represent the Arabian Sea mini warm pool in this study. The study revealed in the eastern Arabian Sea, maximum temperature occurred approximately 2 weeks prior to the onset of summer monsoon over Kerala. However, the extent and the core temperature varied depending on the nature of the forthcoming monsoon. One of the noticeable results was that the dissipation of the mini warm pool started nearly 1–2 weeks prior to the onset of summer monsoon over Kerala. This was due to the arrival of monsoon winds to the western and central Arabian Sea, which increased the vertical mixing processes. This result was verified utilizing TMI SST data for 2001 (below normal), 2002 (deficient), 2003 (above normal). It was also found that the warm pool attained its maximum core temperature (30.5°C) and lateral extent (>3,000,000 km^2) during the excess monsoon year compared to normal (30.2°C, >1,694,000 km^2) and deficient monsoon years (<30°C). The analysis of the dissipation date and onset dates for the years from 1998 to 2009 further showed that there is a certain lag of the order of 7–14 days from the day of dissipation and the day of onset. The core temperature and extent of the warm pool during the pre-monsoon season also exhibited strong relationship with forthcoming seasonal rainfall, with higher core SST and higher aerial extent noticed for most of the years with higher rainfall. This suggests that the dissipation of the Arabian Sea mini warm pool, its core temperature and lateral extent can be utilized as a tool to characterize the forthcoming summer monsoon.

The analysis of salinity data indicated the presence of low saline water in the mini warm pool region, with minimum salinity during excess monsoon year. Probably, this low saline water might have increased the vertical stratification and thereby causing the occurrence of maximum temperature during excess year. This needs further verification. Two possible sources for the low saline water in the SEAS have been proposed, one from the Bay of Bengal and other from the equatorial Indian Ocean.

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