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Article

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Interannual Variability of Upwelling Indices in the Southeastern Arabian Sea: A Satellite Based Study

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Abstract – Increase in sea surface temperature with global warming has an impact on coastal upwelling. Past two decades (1988 to 2007) of satellite observed sea surface temperatures and space borne scatterometer measured winds have provided an insight into the dynamics of coastal upwelling in the southeastern Arabian Sea, in the global warming scenario. These high resolution data products have shown inconsistent variability with a rapid rise in sea surface temperature between 1992 and 1998 and again from 2004 to 2007. The upwelling indices derived from both sea surface temperature and wind have shown that there is an increase in the intensity of upwelling during the period 1998 to 2004 than the previous decade. These indices have been modulated by the extreme climatic events like El–Nino and Indian Ocean Dipole that happened during 1991–92 and 1997–98. A considerable drop in the intensity of upwelling was observed concurrent with these events. Apart from the impact of global warming on the upwelling, the present study also provides an insight into spatial variability of upwelling along the coast. Noticeable fact is that the intensity of offshore Ekman transport off 8ºN during the winter monsoon is as high as that during the usual upwelling season in summer monsoon. A drop in the meridional wind speed during the years 2005, 2006 and 2007 has resulted in extreme decrease in upwelling though the zonal wind and the total wind magnitude are a notch higher than the previous years. This decrease in upwelling strength has resulted in reduced productivity too.

Keywords – Southeastern Arabian Sea, upwelling, global warming, upwelling indices, temperature gradients, Ekman transport

1. Introduction

The postulation on enhancement in the coastal upwelling with global warming was first put forward by Bakun (1990). It is stated that the global green house warming will intensify the alongshore winds thereby increasing the intensity of upwelling. To support this concept, the increase of green house gases has resulted in increase of day time heating of the oceans and decrease in night cooling (Bakun 1990). This results in building up of pressure gradients between the oceans and the adjacent land, thereby intensifying the alongshore winds. A study applying ecosystem models for estimating coastal upwelling under the global warming scenario, carried out by Mote and Mantua (2002) however, could not bring out considerable inter–decadal changes in the intensity of coastal upwelling. A more recent study on the impact of global warming on the productivity of the Arabian Sea was by Goes et al. (2005), who attributed the increase to the warming of Eurasian land mass. But it is found later that the reported increase in the productivity was limited to western Arabian Sea and not in the Eastern regions (Prakash and Ramesh 2007). The present study is aimed at investigating the characteristic role of agencies that bring about variability in upwelling along the southwest coast of India, through its indices based on SST and the offshore Ekman mass transport from two decades of satellite measured high resolution data products.

Arabian Sea forms the western arm of the northern Indian

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Ocean which comes under the direct influence of monsoon and its annual cycle. The coastal circulation in this region shows a well marked seasonal cycle (Shetye and Shenoi 1988). This cycle results in intense air - sea interactions on varying time scales; and this has varied and profound impacts on the upper hydrographic structure including current systems (Hastenrath and Lamb 1979; Hastenrath and Greischer 1991). The semi-annual wind field is dominant during January and July. During the summer monsoon (southwest monsoon), an intense low - level wind jet (*Findlater Jet*) blows diagonally across the Arabian Sea producing coastal upwelling along the Somalia, Oman and the southwest coast of India (Wyrtki 1973). Thence, a clockwise circulation develops in the Arabian Sea that leads to an equator-ward coastal current called the West India Coastal Current and later an opposite flow was observed in this region during winter (Shetye et al. 1990).

Upwelling along the southwest coast of India is an annually recurring phenomenon that occurs during the southwest monsoon (June to September) and is the dominant mechanism in the Arabian Sea for its summer cooling. The net heat change accounts for more than 65%, greater than the combined effects of net radiation gain, heat loss through evaporation and sensible heat loss (Duing and Leetma 1980). Though this upwelling is less in intensity when compared to the other thoroughly studied upwelling regimes of the Arabian Sea [like those at Somalia and Oman] it has profound impacts on the coastal fisheries of India. While the west coast of India accounts for 70% fish yield of the total Arabian Sea production (Luis and Kawamura 2004), the southwest coast alone accounts for 53% (Sanjeevan et al. 2009).

In the past there have been many studies on the behavior of the upwelling phenomenon in this region starting from the early studies as part of the IIOE and other cruises by Banse (1959, 1968), Darbyshire (1967) and Sharma (1973). It is understood that the upwelling along the SW coast of India sets in some time during February / March (Johannessen et al. 1987) and could be mapped from sea level anomaly (Shankar and Shetye 1997; Haugen et al. 2002a). Variability of temperature field, influence of along shore winds on the upwelling phenomenon and Ekman transports between 8° and 15°N was well expounded, by Shetye (1984). The wind induced mass transports associated with this coastal upwelling regime are comparatively less than the other regions elsewhere (Hastenrath and Greischer 1991). Propagation of coastal Kelvin wave from the Bay of Bengal and thus the radiation of Rossby waves and their dynamics in this region and their role in formation of Lakshadweep 'High' and 'Low', both in respect to sea level and SST and their role during the upwelling period is reflected in the works of Shankar and Shetye (1997), Shenoi et al. (1999) and Rao et al. (2010). The upwelling as a result of equator-ward alongshore winds lowers the sea surface temperature commences at the southern tip of India and propagates northward along the coast with the advancement of monsoon (Madhupratap et al. 2001; Luis and Kawamura 2004; Rao et al. 2008 and Smitha et al. 2008). Apart from all these studies, there is still more to understand on changes in the wind pattern and the rise in global SST from this region with respect to upwelling phenomenon.

Direct measurement of upwelling is often difficult as one of the important signatures, namely, the chlorophyll concentration is not well ascertained to the presence of thick clouds during the south west monsoon period. Another way to quantify upwelling is by making use of "upwelling indices" as a proxy for the same. Upwelling indicators can be of two types. As upwelling regions are characterized by relatively cooler waters than the surrounding areas, a difference in the temperature of the area of interest with a region far away from the same, along the same latitude, can be considered as an indication. This is defined as "Latitudinal Temperature Gradient" (LTG). As a matter of fact, meridional winds which blow along the eastern boundary of an ocean transports water away from the coastline. This offshore transport of water is balanced by a supply of cool, nutrient rich water from beneath the Ekman layer. The strength of upwelling can then be estimated based on the wind speed and the wind induced offshore mass transport [Ekman transport] (Bakun 1973). Thus the strength of the Ekman transport can be considered as another proxy for determining the features of upwelling of that region. Hence, LTG and strength of Ekman transport can be considered as good upwelling indices and the inter-annual variability thereof is examined in the present work. Rest of the document is structured as follows: Sect. 2 describes the data used for the study and the methods employed to arrive at the results. Sect. 3 explains the spatial distribution of the upwelling indices with respect to the climatology of SST and Ekman transport. The interannual variability of these indices as well as their anomalies is also penned. Sect. 4 discusses the conclusive findings of this study.

2. Data and Methods

Data

Over the past, many studies on upwelling made use of *in-situ*, satellite and model derived datasets for understanding the upwelling phenomenon along the southwest coast of India. But those studies are limited to describing events / features of a particular year or on the general phenomenon of upwelling and there has not been an attempt to investigate the inter-annual variability. With the advent of satellite applications in oceanography, data provided by different sensors has become a handy tool for continuous measurements and thereby to conduct analysis over a larger area. In this study an extensive use of satellite real time data products for SST and wind were made use of to understand the variability of upwelling over the past two decades.

Monthly day time SST of Advanced Very High Resolution Radiometer (AVHRR), Pathfinder 5 data with 4 km spatial resolution was obtained from PO-DAAC, Jet Propulsion Laboratory, for a period of 20 years, from 1988 to 2007. Monthly wind data from Scatterometers onboard ERS 1 & 2 was again accessed from the above laboratory with a spatial resolution of 1 × 1 degree for the period 1992 to 1999 and the Quikscat Scatterometer Winds (2000-2007) of 0.25 × 0.25 degree resolution was obtained from Asia Pacific Data Research Center, Hawaii. SeaWiFS measured monthly chlorophyll-a concentration of 9 × 9 km spatial resolution obtained from Goddard Space Flight Center of NASA is used for comparing the upwelling trends with respect to the productivity of the study region during the period 1998 to 2007. Modified two minute resolution topography for the Indian Ocean was obtained from IODC of NIO, India to clearly mark the 200m isobath line (Fig. 1).

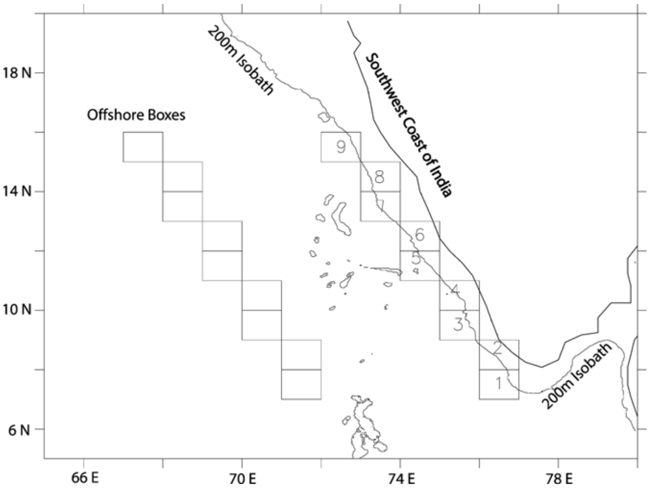

Fig. 1. Study Region.

Computation of upwelling indices

Latitudinal Temperature Gradient (LTG)

One of the characteristics of coastal upwelling is that the coastal surface water is of lower temperature than that of the surrounding waters. The coastal upwelling index is defined as the temperature difference between the coastal waters and of those waters which are five meridians offshore, along the same latitude. In some of the previous studies of similar kind, by Smitha et al. (2008) and Naidu et al. (1999), along with Munikrishna (2009), the offshore limit for computing temperature gradients were taken as three degrees and mid ocean, respectively. In yet another study on the inter-annual variability of upwelling along the North African coast by Nykaer and Camp (1994), the five meridians distance was selected as the outer limit of offshore box and results were found to be fruitful. A detailed account on the offshore limit of coastal process along with upwelling was presented in Antony et al. (2002); *in-situ* and altimetry measurements had shown the offshore limit of coastal processes along the west coast of India to be approximately 350 to 400 kms. The method of selection of three degree meridian and mid-ocean difference, as applied to the present study region, say, off 10ºN and down south, cooler SST's were observed as far as 72ºE meridian which is approximately four degrees offshore from the coastline - this reflects on the drawbacks of these methods. Following Antony et al. (2002) observations and also in order to have uniformity all over the study region, yet retaining similar oceanographic conditions, five degree meridian distance was taken as a benchmark for computing temperature gradients for coastal upwelling index for south west coast of India. This upwelling index is referred to as Latitudinal Temperature Gradient (LTG), which is the function of temperature difference along given latitude and time. The geographical positions (8º to 15ºN) for which LTG have been computed are selected as mid-shelf, i.e., along the coast at 200 m depth contour which is taken as the offshore limit of the coast line (Shetye et al. 1985) as shown in Fig. 1. Spatial resolution of the data being very fine and also different from that of wind products, it is cumbersome to compute LTG for every grid point. In order to get a meaningful result, we have computed the average SST for a 1 × 1 degree box along the coast and a box of similar size, five degrees offshore.

Ekman transport

Another classical method of estimating the amount of upwelling is through Ekman mass transport. As the west coast of India is oriented along the meridional axis with an angle of 24° with north (Shetye 1984), and the wind direction during the upwelling period (coinciding with southwest monsoon) being north-northwesterly along the coastline to the south of 15°N, it is understood that the predominant contribution for the Ekman mass transport would be from the meridional (along-shore) component (Prasannakumar and Prasad 1996; Luis and Kawamura 2001) of wind stress for coastal upwelling studies for this particular region. However, for better clarity in understanding, the zonal (across-shore) component is also considered. In the present study ERS - 1 & 2, Quikscat measured wind speeds are used which replace the use of assimilated products, lacking spatial resolution due to the "smoothing" involved, as opined by Liu et al. (1998) in his study involving satellite measured wind products finding better accuracy as applied to coastal upwelling studies.

Upwelling intensity can be estimated from Ekman mass transport which is perpendicular to the direction of the wind in the region. Ekman mass transport (M_e) for the southwest coast India was computed from the bulk aerodynamic formula as used for satellite derived wind stresses by Koracin et al. (2004) and Petit et al. (2006) and the references therein:

$$\text{Along shore wind stess } (\tau_y) = \rho_a\ C_d\ w_{mag} v \tag{1a}$$

$$\text{Across-shore wind stress } (\tau_x) = \rho_a\ C_d\ w_{mag} u \tag{1b}$$

where, ρ_a is density of air which is 1.29 kgm^{-3}; C_d is wind dependent drag coefficient calculated using Large and Pond (1981) method, w_{mag} is the magnitude of wind speed, v is the meridional wind speed and u is the zonal wind speed.

$$M_{ev} = \tau_y / f \tag{2a}$$

$$M_{eu} = \tau_x / f \tag{2b}$$

Where M_{ev} and M_{eu} are the Ekman Mass Transport due to the along-shore and across-shore winds respectively, f is the Coriolis parameter ($2\,\Omega\ \sin\ \varphi$) (s^{-1}), Ω is the angular frequency of the earth (s^{-1}) and φ is the latitude.

Again, the spatial resolution of the wind products being different, for uniformity, Ekman transport was computed for 1 × 1 degree grid box along the 200 isobath line, same as that of the LTGs. The existing differences between the Ekman transport values in the 0 to 300 kg/m^2/s range are attributed to the inherent inefficiency of ERS scatterometers to measure the wind speeds which are less than 3 to 4 m/s. The best correlation between ERS and Quikscat scatterometers' were found to be between the range of 5 to 15 m/s (Bentamy et al. 2000).

Both upwelling indices are plotted along the coastline at each latitude with respect to time to understand the temporal as well as spatial variation of the upwelling intensity. As the wind is equator-ward, the negative sign for M_{ev} is taken as offshore transport (upwelling) and vice - versa (Pankajakshan et al. 1997).

3. Results

Sea surface temperature variability

Oceanic heating has been attracting wide spread concern owing to its influence on the bio diversity of a region and its adjacent land mass. There have been studies by Levitus et al. (2000, 2001) and the references therein on the extent of warming of the oceans. The warming of Indian Ocean was studied in detailed by Bijoy et al. (2008) using model simulations and observational data and they concluded that there is an increase of 0.4°C in SST. This warming trend was observed to be more dominant to the north of 12°N in the eastern Arabian Sea but a cooling trend was observed along the Somalia coast. The satellite measured SST for the study region embedded between 67-77°E and 7-15°N (Fig. 2) shows a slight increase over the past two decades, of which the warming was rapid during the period 1992 to 1998 (1.2°C) and again from 2004 to 2007 (0.7°C). The cooling episodes of 2-3 years were observed within the 20 years period confirming the quasi decadal variability of the

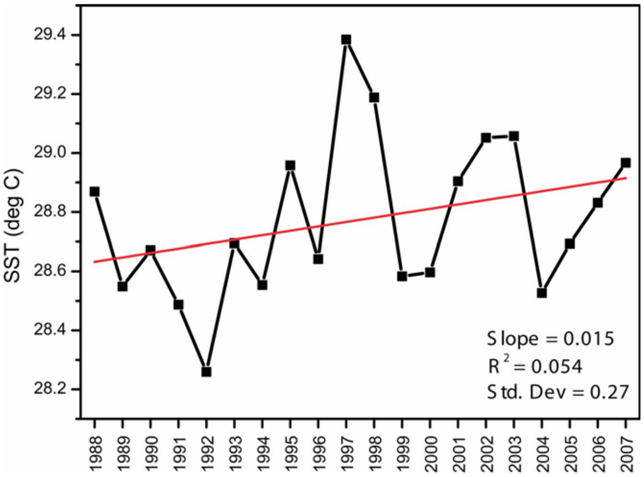

Fig. 2. Annual mean of SST in the study region.

Arabian Sea (Bijoy et al. 2008). This dynamical behavior of SST over the study period has its influence on the strength of upwelling which is explained in the following sections.

Spatial distribution of upwelling indices

SST upwelling index

With the onset of summer monsoon (Wyrtki 1973), upwelling starts from the southern tip of India with cooler SST and propagate northward along the coast (Rao et al. 2006a and Rao et al. 2008). The 20 year temperature difference computations between coastal and offshore regions confirm the fact that upwelling is an annual phenomenon that predominantly occurs during southwest monsoon (Levy et al. 2007). Fig. 3 shows the climatology of SST for the years 1988-2007 in the study region for the summer monsoon months (JJAS). From SST climatology, progressive cooling of the ocean surface with each passing month can be observed from June to August. This cooling began dispersing by September and will be completely replaced by warm waters in October. For all the four months, a patch of warmer waters is observed between the coastal and mid ocean. The cooling of central Arabian Sea to the north of 10ºN is because of the open ocean upwelling during the summer monsoon (Muraleedharan and Prasanna Kumar 1996). This justifies the selection of 5 degree spacing between the coastal and open ocean waters to compute the LTGs.

The climatology of SST upwelling index computed from 1988 to 2007 data presents an insight into the spatial distribution of the temperature gradients along the coast. From the figure (Fig. 4) the maximum positive gradient is observed from 8º to 10ºN latitudes with the temperature difference greater than 1ºC during the months of July and August. Even though positive temperature gradients were observed from 8 to 10ºN during the period April to December, higher positive gradients of greater than 0.5ºC were observed from June to September upto 12ºN latitude. The same results are obtained from the World Ocean Atlas of 2001 with slight variations in the northern latitudes of the region; confirming the indices computed from satellite measurement. The correlation obtained between these two climatologies is 0.85. The increase in temperature gradients during June to September, as inferred from Fig. 4, concurs with the months of southwest monsoon and the resultant intensification in upwelling. The decrease in the temperature well before the onset of southwest monsoon winds could be due to the presence of remote forcing induced by the upwelling Kelvin wave that sets in the actual process of upwelling in the region (Johannessen et al. 1987; Shankar

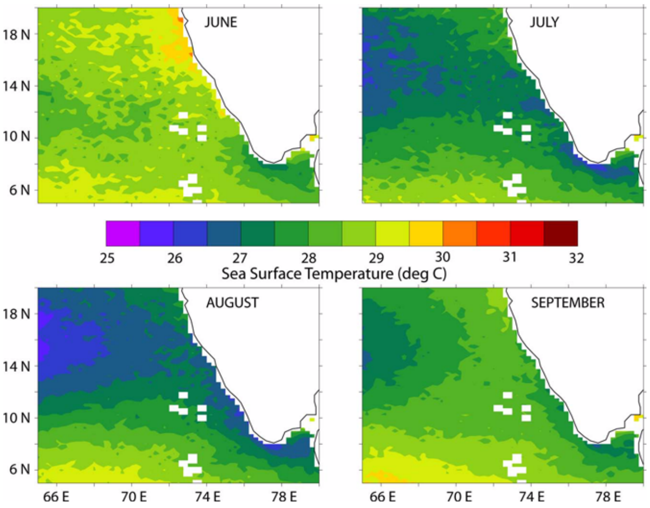

Fig. 3. Climatology of SST during summer monsoon.

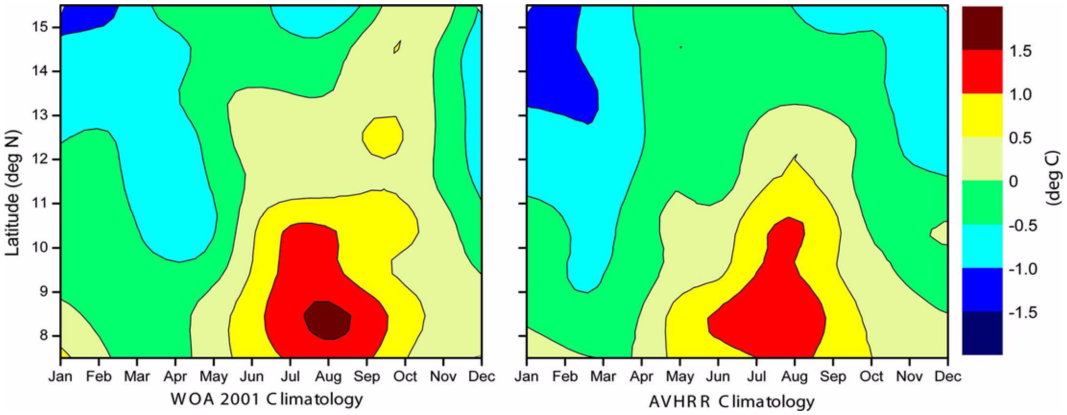

Fig. 4. (a) Climatology of latitudinal temperature gradient from WOA 2001 (b) Climatology of latitudinal temperature gradient from AVHRR.

and Shetye 1997; Haugen et al. 2002a and Shenoi et al. 2005). North of 13ºN negative latitude temperature gradients were observed all through out the year within the range of 0.0 to -0.5ºC. A downwelling process is observed between 13º and 16ºN latitudes from January and February with the temperature gradients ranging from -1.0 to -1.5ºC. The offshore cooling of the Arabian Sea during the northeast monsoon to the north of 15ºN (Madhupratap et al. 1996 and Prasannakumar & Prasad 1996) is attributed to the impact of convective cooling taking place in the northern Arabian Sea. Thus negative temperature gradients were observed as the offshore waters are cooler than the coastal waters. Existence of positive LTG above 12ºN during November - March may indicate that a mild downwelling process is prevalent.

Ekman upwelling index

Ekman transport is dependent on the direction of the wind prevailing in the region. During southwest monsoon, wind is north-northwesterly (Fig. 5) and in northeast monsoon, it is north-northeasterly (Prasannakumar and Prasad, 1996; Shetye et al. 1985). The alongshore component during southwest monsoon season decreases from 8º to 10ºN and again increases up to 14ºN. Between 10º and 14ºN, winds build up from May to July and show a decrease in speed with time till the end of monsoon (Muraleedharan et al. 1995). Fig. 5 shows the QuikScat measured wind speeds and direction of the wind prevalent along the west coast of India during the southwest monsoon months. As wind is meridional in both the seasons, Ekman mass transport will be westward along most part of coast line. One noticeable fact is that the wind field near southern tip of India is divergent for both the seasons (Luis & Kawamura 2000, 2001, 2004; Rao et al. 2006a, 2006b, 2008). Climatological wind speed along the southwest coast of India during southwest monsoon is within the range of 5 to 6 m/s and in northeast monsoon it is 2 to 3 m/s.

The climatology (Figs. 6a, 6b) computed from the scatterometer wind products show the pattern of Ekman transport prevalent in the region. The Ekman mass transport due to the zonal component of wind stress (M_{eu}) does not show much variation over the years as M_{ev}. High southward (equatorward) transport was observed during the summer monsoon owing to the wind direction prevalent during that season. As mentioned above, Ekman mass transport due to meridional component of wind stress (M_{ev}) is negative for most part of a year for the entire region. Onshore transport was observed during the pre-monsoon months of April and

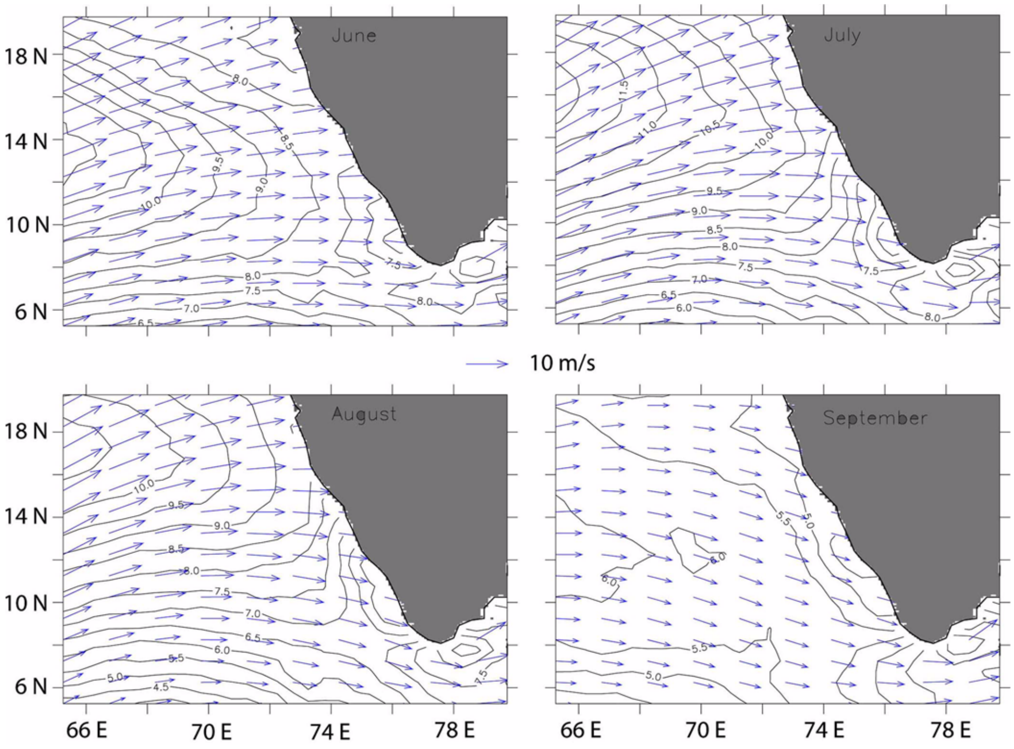

Fig. 5. Climatology of wind speed and direction during summer monsoon.

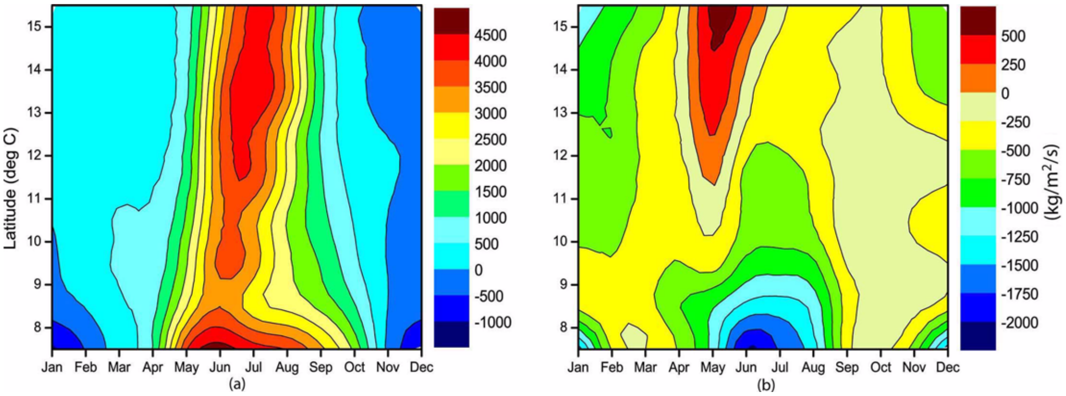

Fig. 6. Ekman transport climatology (a) Due to zonal component of wind stress (b) Due to meridional component of wind stress.

May from 12° to 16°N. Mild offshore transport observed between 9° and 10°N latitudes during winter monsoon is due to the wind blowing parallel to the coast for that period at this region. Maximum offshore mass transport was observed for the summer monsoon period between 8° and 10°N latitudes ranging from 500 to 2000 $kg/m^2/s$. Intense offshore Ekman transport was observed off 8°N during winter monsoon also which is in tow with the prevailing wind direction near the southern tip of India (Luis & Kawamura 2000, 2001; Rao et al. 2006a, 2006b). Influence of the Kelvin waves along the coast is felt only to the north of 9°N and therefore the upwelling observed between 8° and 9°N is purely wind induced (Smitha et al. 2008). From Figs. 4 and 6, it is also evident that the combined effect of wind and remote forcing of Kelvin waves or the downwelling Kelvin wave along the equator reaching the southwest coast of India (Shankar and Shetye 1997) is less on upwelling to the north of 9°N when compared to the upwelling induced by wind alone between 8° and 9°N. Inter-annual variability of these upwelling indices is explained in the following sections.

Inter-annual variability of upwelling indices

SST upwelling index

The SST upwelling indices (Fig. 7), computed and compared between last two decades indicate that the temperature gradients along the coast with respect to their offshore components have increased in the latter. It can be attributed to two reasons, one of them, certainly is the increase in offshore temperatures and the other, could be due to greater decrease in the coastal temperatures; of these two reasons, based on Fig. 2, we relate the increase in temperature gradients to the rise in offshore temperatures with time in the global warming context (Jayaram et al. 2009). Next, upwelling signals were predominant from 8° to 12°N for all the study years. Particularly, for the year 1988, positive temperature gradients, up to 0.5°C were observed all along the coast during summer monsoon, while for the remaining years, the gradients is limited up to 12°N with varying magnitudes. As an exception, during 2002 and

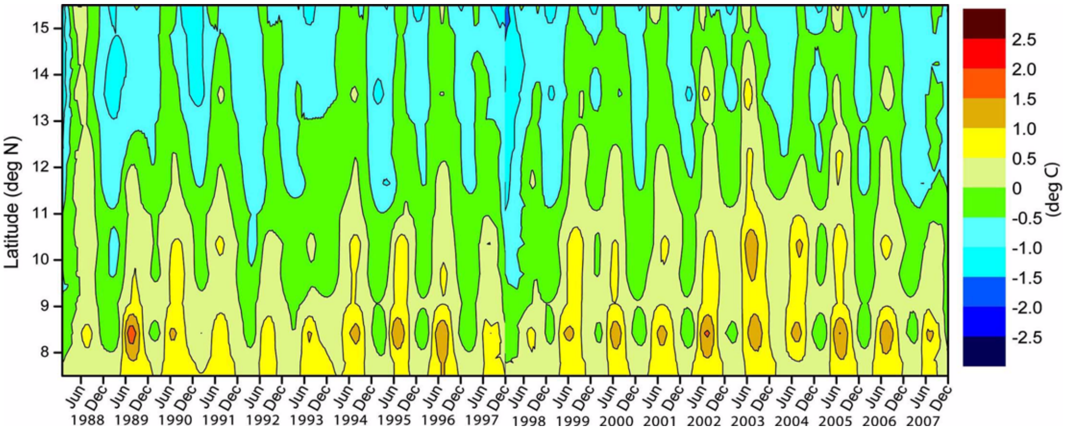

Fig. 7. Inter-annual variability of latitudinal temperature gradient.

2003, positive gradients were observed up to 15ºN. For the later years, a continuous fall in the northward extent of upwelling was observed up to 2007. Further, the temperature gradients were observed to be high during 2003. For all the years, high upwelling index of SST was observed between 8º and 9ºN, but for the year 2003, a secondary peak was also observed between 10º and 11ºN. This phenomenon was repeated, though very mildly, in 2004 also.

To substantiate and clearly distinguish the positive temperature gradients during all the years, SST upwelling index anomalies were computed by subtracting the monthly climatological mean [computed from AVHRR data] from the actual monthly latitudinal temperature gradient (Nykaer and Camp 1994). From the SST upwelling index anomaly (Fig. 8) it was observed that, the period between 1998 and 2007 had higher upwelling conditions favoring development of temperature gradients along the coast than the previous decade of 1988-1997; this is due to greater increase of offshore temperatures in the recent decade. For the year 1988, positive anomalies were observed from north of 11ºN which was not intense during the years, 1988 to 1997. Following are the high upwelling years as evident from the SST upwelling index (LTG and its anomaly): 1989, 1996, 2002, 2003 and 2005 & the weak upwelling years are 1988, 1991, 1992, 1993, 1997, 1998 and 2007.

Ekman upwelling index

Ekman mass transport computed along the southwest coast of India is an indicator for the intensity of upwelling in the region for the years 1992 to 2007 (Figs. 9). It may be noted that since the data was obtained from two different platforms there is bound to occur differences in the actual magnitudes of the transport (Bentemy et al. 2000), but there is no conflict in the pattern of variability. Since, M_{eu} does not show prominent variability over the years except that it is annually recurrent; emphasis has been laid on the variability of M_{ev}. During the year 1992, intense onshore transport was observed during southwest monsoon and also during 1999, though in lesser intensity. High Ekman offshore transport (M_{ev}) was observed between 7º 30' and 9ºN from years 2000 to 2004 during summer monsoon. The mass transport values lie in the range of 500-2500 kg/m^2/s. Later from 2005 to 2007, offshore Ekman transports have decreased. This was due to the weak meridional winds prevailing along the coast during the upwelling seasons of 2005-2007 (summer monsoon) (Table 1). As the wind direction is always meridional (Shetye 1984) along the coast, the Ekman transport is offshore even in the non upwelling season; this would be of very less intensity (Figs. 9a, 9b).

To delineate high upwelling regions and periods, anomalies were computed by subtracting the monthly climatological Ekman transport from the corresponding monthly values. The regions where high upwelling was prevalent, these regions would have higher values of Ekman transport (Nykaer and Camp 1994). The anomaly (Figs. 10a, 10b) shows a clear picture of the Ekman transport in the study region for years 1992 to 2007. Greater positive anomalies were observed during 1992, 1996, 1997, 1998 and 1999, indicating less offshore Ekman transport. The year 2000 was having higher values among all the years of study. During the year 2004, both the monsoons had equal amount of offshore transport. For the years 2005 to 2007, the picture was completely different from the previous years. During that period, positive anomalies were observed all along the

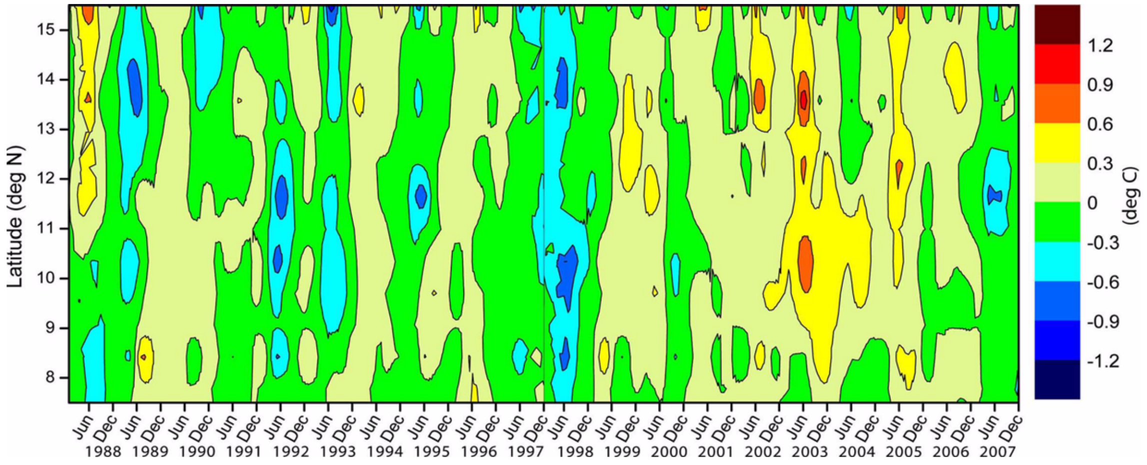

Fig. 8. Inter-annual variability of latitudinal temperature gradient anomaly.

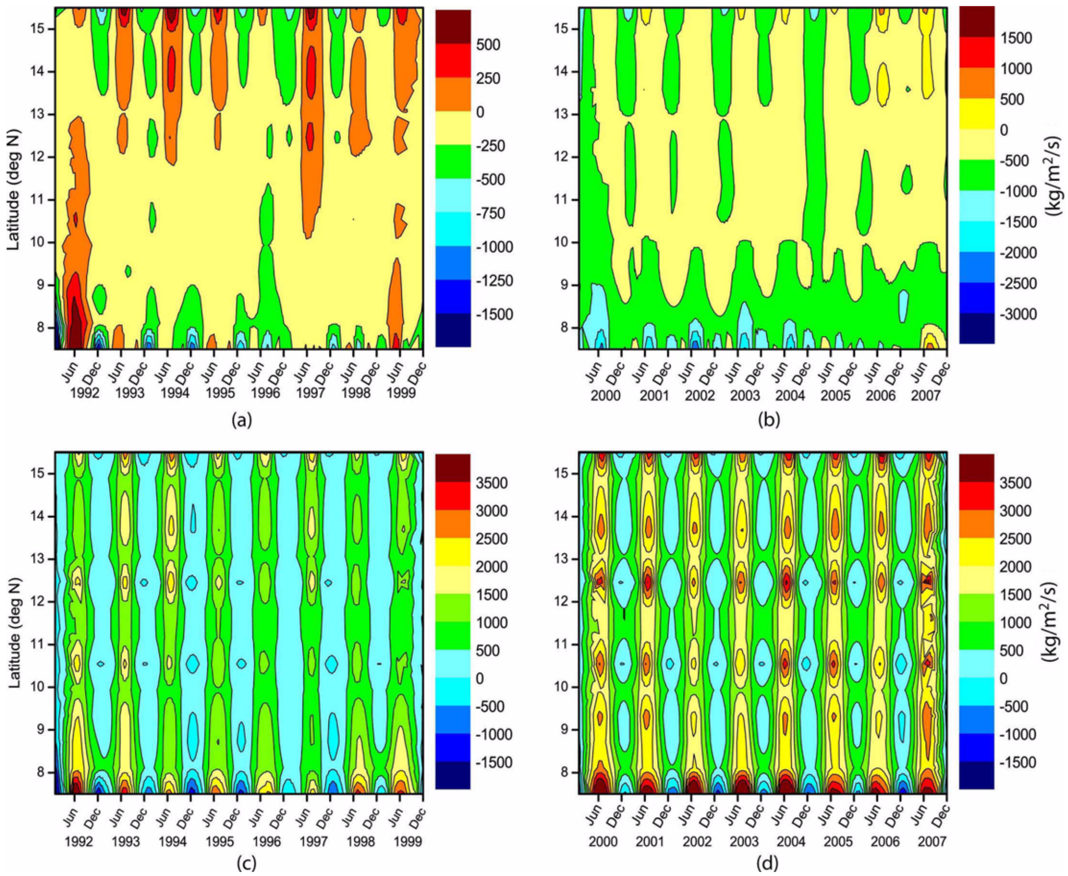

Fig. 9. Inter-annual variability of Ekman mass transport (a) M_{ev} computed from ERS - 1& 2 (b) M_{ev} computed from QuikScat (c) M_{eu} computed from ERS - 1& 2 and (d) M_{eu} computed from QuikScat.

Table 1. Average of wind speed magnitude, zonal and meridional during SW monsoon months of June, July, August and September

Year	Wind Magnitude (wmag) in m/s	Zonal Component of wind speed (u) in m/s	Meridional Component of wind speed (v) in m/s
1992	6.131	6.043	0.266
1993	6.257	6.164	-0.150
1994	5.996	5.879	0.348
1995	5.843	5.757	-0.062
1996	5.745	5.569	-0.856
1997	5.132	4.981	-0.757
1998	5.655	5.600	-0.048
1999	5.269	5.180	-0.086
2000	7.384	7.191	-1.319
2001	7.436	7.226	-1.138
2002	7.251	7.014	-1.438
2003	7.278	7.102	-0.914
2004	7.305	7.139	-0.939
2005	7.730	7.629	-0.620
2006	6.918	6.861	-0.220
2007	7.663	7.597	-0.198

coast. The year 2005 show positive anomaly during summer monsoon, indicating very feeble offshore transport. A significant observation was the prevalence of upwelling off 8ºN during October and November of 2005; this coincides with the reported anomalous upwelling in the region during 2005 by Gopalakrishna et al. (2008). In 2006, the negative anomalies were punctuated by positive anomalies. Dominant negative anomalies indicating offshore transport were observed during the winter monsoon months. Offshore Ekman transport was found to be very feeble in 2007. This drop in the offshore component of Ekman transport is attributed to an enormous drop in meridional wind speed in the region during 2005, 2006 and 2007 years. In order to confirm the speeds of wind during the upwelling season, the regional average wind speed, its zonal and meridional components during the summer monsoon months (JJAS) are provided in Table 1.

From Table 1, it is observed that, even though the magnitude of total wind and zonal component of the wind have maintained certain uniformity, meridional wind speed

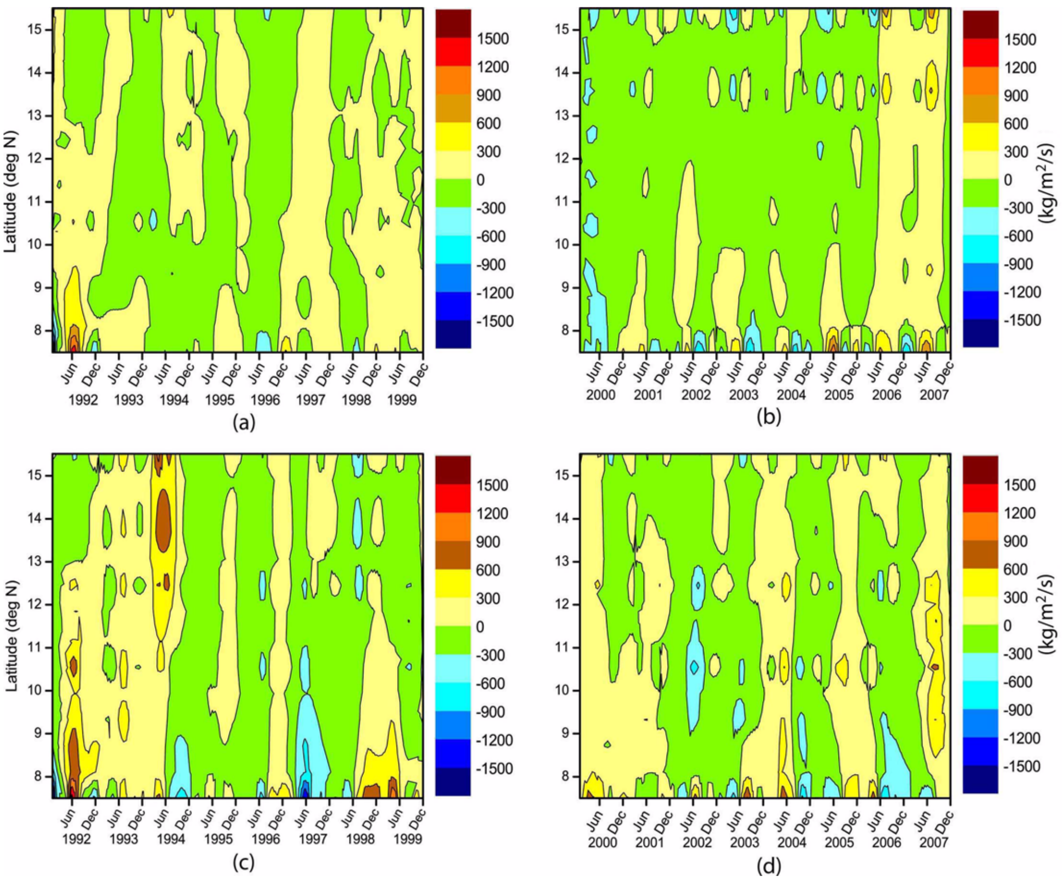

Fig. 10. Inter-annual variability of Ekman mass transport anomaly transport (a) M_{ev} computed from ERS - 1 & 2 (b) M_{ev} computed from QuikScat (c) M_{eu} computed from ERS - 1 & 2 and (d) M_{eu} computed from QuikScat.

during southwest monsoon along the coast for the years 2005, 2006 and 2007 has decreased significantly from the previous years. A pictorial representation of the along-shore wind speed and the corresponding Ekman mass transport at 8ºN, 10ºN, 12ºN and 15ºN along the southwest coast of India is shown in Fig. 11, for better understanding. An interesting pattern in wind observations for those three years was that the total wind speed and zonal component were higher than the previous years while the meridional component showed a decline. This was also observed in LTG where the temperature gradient between the offshore and coastal regions for those years was minimal (Fig. 7).

The decrease in the intensity of upwelling and the resultant drop between 2005 and 2007 in the productivity of the region were evident from the results on chlorophyll-a concentration of the study region (Fig. 12). This figure shows the mean chlorophyll-a concentration during the summer monsoon period from 1998 to 2007. The decrease in productivity for 2005 to 2007 is attributed to the lack of sufficient amount of offshore transport of nutrient rich coastal waters due to weak meridional winds and thence cooler, nutrient rich subsurface waters remained trapped below, inhibiting the chlorophyll-a production in the surface waters. This also resulted in greater coastal SSTs for those years.

Cross-correlation between the two indices

The upwelling indices were computed from two different parameters and platforms; an inter-comparison of these is necessary to build up the confidence on the index for this region, where south west monsoon (upwelling periods) and non-monsoon (non-upwelling periods) cycles occur. Cross correlation was computed between the two indices for each month and in each degree box and represented spatially (Fig. 13). Positive correlation is observed in the winter months alone for the latitudes north of 12ºN and also between 8º and 9ºN (February and March). Also, the entire coast line has negative correlation values, mostly

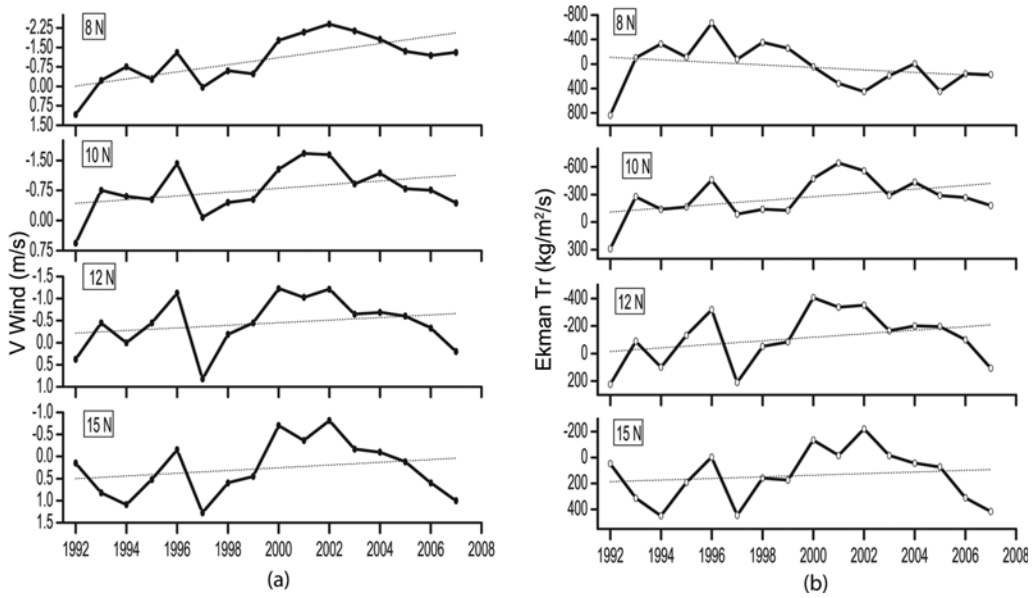

Fig. 11. Temporal variability of the (a) along-shore wind speed and (b) offshore Ekman mass transport at 8°, 10°, 12° and 15°N latitudes during the upwelling months of JJAS with respect to the long term trend.

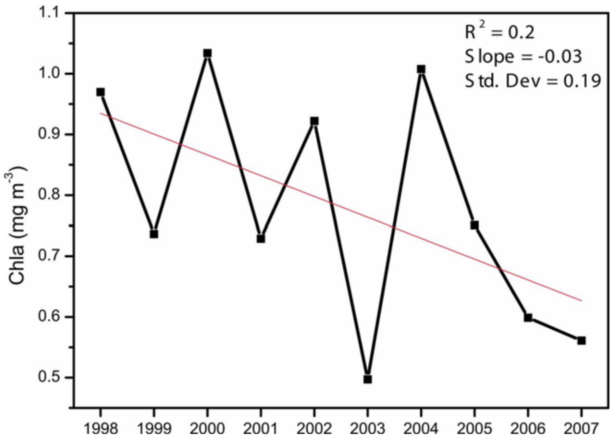

Fig. 12. Inter-annual variability of mean chlorophyll-a for summer monsoon months (JJAS).

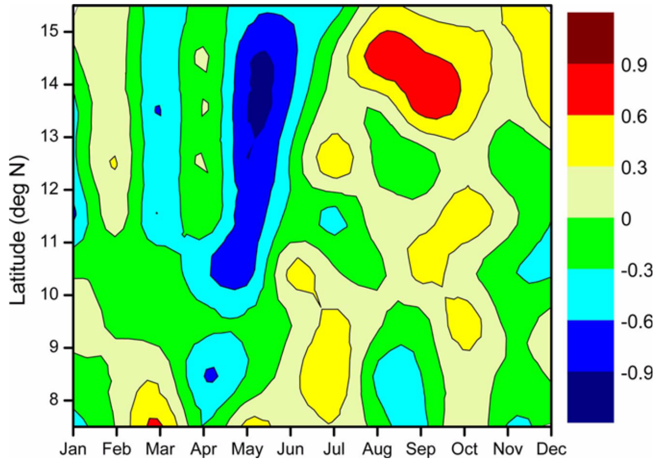

Fig. 13. Cross-correlation between the two indices.

prevailing during March, April and May. This period (non-upwelling) coincided with the event when SST was very high and south west monsoon winds had not set in for initiating upwelling. Again, positive correlation was observed between the two indices off 8° and 11°N during July only and from 14° to 15°N in the months of August and September, which is the upwelling period. Another interesting observation is the negative correlation during August and September between 8° and 10°N. The reason for this form of correlation is due to the fact that wind speeds will be higher during the initial stages of monsoon, till July and later, will retreat, slowly towards the end of monsoon phase (by the end of September). But the memory of the ocean with respect to SST cooling is retained for longer duration, which has been observed during late monsoon months of August and September (Muraleedharan et al. 1995). Thus the study based on cross correlation between the climatologies of both the indices enhances our present understanding on the upwelling along the west coast of India.

4. Discussion and Conclusion

The impact of global warming and climate change vis–a–vis coastal upwelling along the southwest coast of India was studied for the period 1988 to 2007. The term upwelling is frequently applied to illustrate a variety of conditions involving upward transport of waters in the ocean and often there arises a confusion in describing the effect of process rather than the actual process itself (Sharma 1973). To circumvent this mystification, a driving force (alongshore winds) and its influence as an after effect (low sea surface temperature) has been emphasized. In southeastern Arabian Sea, the signatures of upwelling from the low sea level anomaly are noticeable from February / March itself (Johannessen et al. 1987; Haugen et al. 2002b), but the associated lowering of SST and an increase in productivity (Smitha et al. 2008) is actually noticeable only with the onset of southwest monsoon winds which often occur by the end of May or early June. To decipher the intensity of upwelling, temperature gradients computed between the coastal ocean and at 5 degrees offshore along the same latitude and the Ekman offshore transport perpendicular to the coast was derived from the alongshore component of wind as computed by Nykaer and Camp (1994). The cross correlation computed between these two indices to deduce their inter-dependency, has thrown insight to their variation over time. The correlation was positive during the initial phases of monsoon and negative during the months of August / September, indicating the prevalence of cooler temperatures as wind speeds showed a decline. Factually, maximum upwelling was observed between 8° to 9°N. Ekman transport for the past two decades has shown hitherto unknown features like the intra - regional variability along the coast on an annual time scale.

The computation of upwelling indices showed an increase in temperature gradients with time, brought about by the cooling of coastal waters. The investigation had covered two decades of events which reveal that during the later decade, especially upto 2004, a consistent enhancement in the strength of upwelling could be observed. Additionally, a notable decrease was observed for the last three years (2005 – 07) and also during the years (1991-92 & 1997- 98) when ENSO and IOD appeared together (Saji et al. 1999). The Ekman transport during 1992 and 1997, which happen to be ENSO years, showed strong onshore transports, as observed from Fig. 9. Offshore transport at 8° and 15°N was greater during winter monsoon. Though wind direction is considered as the driving factor for the occurrence of coastal upwelling, wind speed is also an important factor in determining the strength of upwelling. This is evident from our calculations on the indices for 2005, 2006 and 2007 when the meridional component of wind speed was less and thereby feeble upwelling transpired. This decrease was also observed from the chlorophyll data (Fig. 12) for the same region. Therefore it should be understood that the nutrients present in the sub surface layers were not being transported to the surface owing to mild Ekman transport. Further, even in a global warming scenario, for coastal upwelling to increase or decrease, more conducive wind pattern is a necessary pre-condition.

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