4

Role of Forcing Factors

4.1 Introduction

It is common knowledge now that wind plays an important role in coastal upwelling processes. Theory says that upwelling occurs along a coast (with ocean on its western side) when the wind stress has an equator ward alongshore component or in the case of open ocean, it is positive (negative) wind stress curl in the northern hemisphere (southern hemisphere) [Stewart, 2005]. Also, coastal divergence of the seaward Ekman current is augmented by the alongshore equator ward wind stress, whereas Ekman pumping results from the wind stress curl. In the Indian Ocean, with the onset of SWM, a strong low level wind jet known as Findlater Jet [Findlater, 1977] is established across the Arabian Sea. On either side of this jet, the changing curl of wind stress would produce a region of divergence. The upwelling along the west coast of India is an illustration of an eastern boundary upwelling that is driven both by divergent currents and also, the alongshore equatorward wind stress. Many studies had been published in the past on the seasonality of the upwelling phenomenon based on various in-situ, modelled and other observational data sets (Chavez and Messie, 2009, Boe et al., 2011). With the availability of QuikScats ten year long fine resolution dataset from 1999 to 2009, it is possible to find the periodicity of wind forcing over the region during upwelling season. Apart from atmospheric forcing, in the form of SWM winds, there exists another forcing which is a manifestation of oceanic conditions driven
from elsewhere, termed here in this case as remote forcing on the coastal upwelling regime of SEAS. Kelvin waves, generated on the western African coast travelling along the equatorial wave guide reaches the eastern Indian Ocean and split north and southwards. The northern arm of the wave orients itself along the coast thus turning into a coastal Kelvin wave. This coastal Kelvin wave travels along Myanmar and east coast of India, finally reaching SEAS [Rao et al., 2010].

It is stated that Kelvin wave results in altering the East Indian Coastal Current (EICC) to turn around Sri Lanka and join the West India Coastal Current (WICC) [Shankar and Shetye, 1997]. McCreary et al. [1993] observed that winds along the eastern boundary of India generated similar Kelvin wave and thence influence WICC. Satellite altimetry provides the best observational platform to study the changes influenced by these Kelvin Waves and the subsequent Rossby waves that play a role vis-a-vis coastal upwelling in this region. The periodicity of these waves has been well established by many earlier studies (McCreary et al., 1993, Bruce et al., 1994, Rao et al., 2010). In this study an attempt has been made to understand the role of remote forcing on the SST [cooling] and upwelling related phytoplankton blooms in the SEAS.

4.2 Wind Forcing

4.2.1 Wind Stress

SEAS is a typical eastern boundary upwelling system where winds blows equator ward, along the southwest coast of India. Along shore and across shore wind stresses were computed separately from QuikScat measured winds between years 2000 and 2009. Monthly climatology was computed from the wind stress as illustrated in Chapter 3, whose variability is shown in figure 4.1. The sign convention is such that, negative sign indicates southward (Equator ward) for along shore wind stress and westward for across shore wind stress and vice versa.

It is observed that meridional wind stress was predominantly southward near to the coast all most throughout the year. During January and February, the
4.2 Wind Forcing

Figure 4.1: Monthly variability of meridional wind stress over SEAS
meridional wind stress had a similar pattern with only slight variability in magnitude; maximum northerly stress was noted at the northern end of the region. A small patch of higher order stress was observed near to the coast between 8° and 10°N extending up to 73°E. In March, all SEAS region was prevailed by stress ranging between -10 x 10^{-3} and -30 x 10^{-3} Pascal. By April, the direction of stress had shifted northward. Significantly, in May, northern and southern parts of SEAS were prevailed by positive stress with a large negative field of wind stress, extending from the coast to 71°E. This is a clear indication of changes that occur in atmospheric setting(s) which suit the onset of SWM. This scenario was further strengthened by June, when an intense southerly wind patch 11°N - 73°E from the coast was observed of the order of 10 x 10^{-3} Pascals. This confirms results from previous studies (Rao et al., 2008, Smitha et al., 2008) that upwelling commences from the southern tip of India and extends northwards along the coast. During this period, the northerly patch was observed up to 9°N with an offshore extent of approximately 150km. This northerly patch extended up to 12°N by July and further, extended up to 72°E indicating the peak phase of wind setting that results in intense upwelling. These northerly wind stress signatures extended all along the southwest coast of India and by August, brought the entire area under the influence of wind induced upwelling. During September, only a feeble northerly wind stress was observed all along the coast (extending approximately 100km from the coast). This is considered as a signature for the start of retreating phase of the SWM winds. Based on above and other results, a detailed discussion on the oceanic response with respect to upwelling to the receding SWM is presented in chapter 5. The wind structure during October was one that of an inter-monsoon phase where one can observe a lull in the winds. By November, with the onset of northeast monsoon, strengthening of northerly winds was observed and it further continued in December also.

To summarise, the meridional (alongshore) wind stress, very near to the coast, was northerly for a significant part of the year. However, the strength of such an along shore wind stress was relatively weak unlike in other places of notable eastern boundary upwelling zones around the world. To state in advance, it had two peaks associated with both the monsoons. The accurate periodicity of the wind stresses are deduced from the continuous wavelet transforms in the
following sections. The maximum extent of upwelling favourable wind stress was
observed to be around 300 - 400 km from the coast. From the along shore winds,
it is implicit that the upwelling starts at the southern tip of India and extends
northwards along the coast. Figure 4.2 shows the monthly zonal (across shore
wind stress) in SEAS. On close inspection, it is understood that unlike meridional
wind stress which has a bimodal variability, the zonal wind stress has only an
annual variability. The sign convention adopted for zonal wind stress, as stated
earlier, is such that, the positive sign indicates westerly wind stress and vice
versa. Note that, January and February showed easterly shear due to the influence
of northeast monsoon.

During the inter-monsoon periods of March - April and October, the region
was observed to be under the influence of calm winds and hence feeble wind stress.
Intense zonal winds were observed during the SWM period (the months: June,
July, August and September). During August, the wind stress was observed to be
as high as 200 x 10^{-3} Pascals. With the onset of northeast monsoon, the direction
shifted easterly by November. Additionally, the periodicity of zonal wind stress
along the coast was studied using continuous wavelet transform, based on 3 day
running mean of the stresses. The influence of wind stress had not been properly
explained by the earlier researchers and this aspect is dealt explicitly in chapter
5 in an attempt to quantify the weightage of each of the forcing factors on the
upwelling phenomenon in the region.

4.2.2 Wind Stress Curl

As per the classical upwelling theory, positive wind stress curl causes divergence in
Ekman layer and act as a catalyst for upwelling; on the other hand, negative wind
stress curl results in convergence in the Ekman layer and downwelling is expected
in the northern hemisphere. The monthly climatology of wind stress curl (Figure
4.3) showed positive curl all along the coast during the summer monsoon months
of June, July, August and September. It first starts as a small speck towards the
southern tip of India in May and extends northward with progress of time and is
well distinguishable all along the coast by August. A point to be noticed is the
presence of negative wind stress curl away from the coast during the June, July
4.2 Wind Forcing

Figure 4.2: Monthly variability of zonal wind stress over SEAS
Figure 4.3: Monthly variability of Wind Stress Curl over SEAS
and August. Negative curl was also observed at the southern tip of India during the winter monsoon season from November to February, indicating the presence of downwelling and this confirms the model studies of Rao et al. [2008]. For rest of the months in a year, wind stress curl over the region was uniform and does not show any variability.

4.2.3 Ekman Transport

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:

$$\tau_y = \rho_a C_d W_{mag} V \quad (4.1)$$

where $\tau_y$ is the meridional wind stress, $\rho_a$ is density of air which is 1.29 kgm$^{-3}$; $C_d$ is wind dependent drag coefficient calculated using Smith [1988] method, $W_{mag}$ is the magnitude of wind speed and $v$ is the meridional wind speed. Ekman transport $M_e$ is obtained as:

$$M_e = \frac{\tau_y}{f} \quad (4.2)$$

where $f$ is the Coriolis parameter $2\Omega \sin \phi \ (s^{-1})$, $\Omega$ is the angular frequency of earth ($s^{-1}$) and $\phi$ is the latitude.

Ekman transport was computed for 1 x 1 degree grid box along the 200 isobath line (Figure 4.4). Ekman transport was dependent on the direction of the wind prevailing in the region. Along the southwest coast of India, wind direction was equator-ward i.e., meridional, irrespective of the season. During SWM, wind was north-northwesterly and in northeast monsoon, it was north-northeasterly [Shetye et al., 1985] very near to the coast. The alongshore component during SWM season decreased from 8° to 10°N and again increased up to 14°N. Between 10° and 14° N, wind built-up from May to July and later showed a decrease in speed with time till the end of monsoon [Muraleedharan et al., 1995]. As wind was meridional in both the seasons, Ekman mass transport will be offshore along most parts of the coast line.
4.2 Wind Forcing

Figure 4.4: Southwest coast of India showing 200m isobath line and the boxes considered for computing Ekman transport along the shelf break

Figure 4.5: Ekman transport along the southwest coast of India
4.3 Temporal Variability

Climatology (Figure 4.5) computed from the QuikScat wind products show the pattern of Ekman transport prevalent in the region. Onshore transport was observed during the pre-monsoon months of April and 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/m²/s. Intense offshore Ekman transport was observed off 8°N during winter monsoon which is also in line with the prevailing wind direction near the southern tip of India (Luis and Kawamura, 2000, Luis and Kawamura, 2001).

4.3 Temporal Variability

In order to understand the temporal variability and its frequency, three locations were selected along the coast as shown in figure 3.8. The boxes were selected such that they are located at southern, central and northern portions of the southwest of India where the coastal upwelling is prevalent. Climatology of zonal and meridional wind speed computed from the 3 day running mean for the period 2000 to 2008, was plotted to elucidate the daily variability in direction and speed along the coast. On minute inspection, it was observed that, wind speed in box 1 was equatorward (northerly) [Figure 4.6] for most months of the year, but north-northwesterly during summer monsoon. The winds changed their direction north-northeasterly by the end of October. In the central box (box 2), the trend was similar to that observed in box 1, with slight variations in the magnitude of the wind speed. But in box 3, winds were north-north easterly till March and then northwesterly upto October. Change in direction towards northeasterly, was observed in November. It is noted that the direction of wind was oriented northerly in box 3 during summer monsoon, while in the remaining two regions; winds were oriented more northwesterly during the same season. This indicates that the SWM winds are influenced by the orographic effect of the Western Ghats present along the coast and thus the winds are oriented along the coast and are equatorward thereby resulting in an apt setting for an eastern boundary upwelling regime in SEAS. Within the SWM season, intra-seasonal
variability was observed which can influence the upwelling related responses from the ocean on those time scales. The definite temporal variability is deduced by applying continuous wavelet transform at these three boxes using the wind stresses derived from 3 day running mean for all the years considered for this study.

### 4.3.1 Wavelet Transforms

**Meridional (Along Shore) Wind Stress** To ascertain the periodicity of wind stresses along the coast, daily wind data from the selected boxes were subjected to continuous wavelet transform with Morlet wave as mother wavelet as followed in Torrence and Compo [1998]. Figure 4.7 shows the wavelet transform for along shore wind stress in Box 1 near to the southern tip of India. The figure has three sub figures: a. time series of the meridional wind stress for the entire time period of 2000 to 2008; b. shows the power spectrum of the stress. [In figure 4.7, x-axis indicates the total days and y-axis indicates different frequencies of...
4.3 Temporal Variability

Figure 4.7: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of Meridional Wind Stress in Box 1

variability with a cone of significance set at 95%]; c. presents the global wavelet spectrum. From power and global wavelet spectrum, the predominant frequencies were observed at 4, 8 - 16 days, 32 - 64 days, semiannual and annual modes. The modes which were significant are 32 - 64 day band (Madden - Julian Oscillation), semi annual and annual. Post 2005, the annual and semi annual modes seem to be reduced in intensity while the other modes were still prevalent. This is directly attributed to the decrease in the meridional component of wind speed during that period [Jayaram et al., 2010a].

In the central portion of the southwest coast of India (Figure 4.8), the significant frequencies of variability observed to be were semi-annual and the MJO. Apart from these, there existed other minor frequencies also like 8 - 16 days and annual variability. Within a short distance of 2 degrees (∼ 200km), a factual change was observed in the frequency of variability. Again further, towards the northern region (box 3), the annual mode of variability was observed to be significant while the semi annual mode was completely absent (Figure 4.9). The other dominant frequencies like seasonal (64 - 128 day), MJO were also observed, though not significant. Thus it can be deduced that even though the region
4.3 Temporal Variability

Figure 4.8: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of Meridional Wind Stress in Box 2

Figure 4.9: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of Meridional Wind Stress in Box 3
is small, there seems to be spatial variations in the wind structure all along the coast. These spatial and temporal variations of the along shore (Meridional) wind stress do have implications on upwelling. It can also be stated that the availability of quality, high resolution remote sensing data products on wind alone can deduce these minor oscillation, that have great potential to affect the upwelling intensity in the region for any given year. A similar wind pattern was noticed in the northern region (box 3) also (Figure 4.9). Thus it can be summarised that the differences in the wind stress structure along the southwest coast of India implicitly modulate the upwelling pattern in the SEAS.

Zonal (Across Shore) Wind Stress Though the zonal wind stress does not have influence on triggering of upwelling, it does have a certain role to modulate the after effects of upwelling, like cooling in SST and changes to primary productivity of the region. In order to ascertain the role of zonal (across shore) wind stress, the zonal component of wind stress for the above selected boxes was subjected to continuous wavelet transform. From the figure 4.10, it can be observed that the annual mode was significant and rest of the minor frequencies were located between 8 - 16 days and less. A noticeable fact was the absence of MJO in the zonal wind stress in this region. Zonal wind stress in box 2 was analogous to that of box 1.

A similar pattern to that of box 1 was observed in box 2 also (Figure 4.11). But in the box 3, both semi annual and annual modes were significant. From the time series graph (Figure 4.12), it was observed that there was a peak in each SWM season and during rest of the year, zonal wind stress was minimal while there many many number of minor to major oscillations in the meridional wind stress.

To abridge, on the role of wind in triggering the upwelling in SEAS, it can be stated that the meridional (along shore) wind stress is the main contributing parameter. Meridional wind stress showed different periodicities within the region, though the extent of SEAS being small. The dominant modes of variability are observed to be MJO at 40 - 60 days, semi annual and annual modes. There are other minor frequencies with a time period less than 15 days and these can modulate the upwelling related productivity within the upwelling regime of SEAS.
4.3 Temporal Variability

Figure 4.10: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of Zonal Wind Stress in Box 1

Figure 4.11: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of Zonal Wind Stress in Box 2
In the zonal (across shore) wind stress, the dominant mode of variability is the annual mode. There are minor frequencies on the scales of less than one week. In the zonal mode, the MJO are absent. The role of major and minor frequencies on modulating the upwelling is to be investigated in chapter 5.

4.4 Remote Forcing

The Sea Level Anomaly (SLA) derived from altimeters characterises dynamic topography pertaining to circulation and density field of the entire water column. Also, SLA reveals information on steric effects and the effects of stationary and planetary waves [Fu et al., 1992]. Planetary waves like Kelvin, Rossby and Yanai waves are manifested due to surface wind and buoyancy flux and these will influence the near surface circulation through local and remote forcing, as reported for the tropical Indian Ocean (McCreary et al., 1993, McCreary et al., 1996, Bruce et al., 1994, Schott and McCreary, 2001, Schott et al., 2009, Rao et al., 2010). Altimeter records have made possible the mapping of these planetary waves propagation and their influence on coastal circulation. During SWM
season, the westward propagating upwelling Rossby waves are triggered off the southwest coast of India and are further strengthened by local wind stress forcing and result in large negative SLA [Shankar et al., 2004]. Thus SLA can be used to index the strength of upwelling and downwelling [Florenchie et al., 2004]. Figures 4.13, 4.14 and 4.15 show the temporal variability, wavelet power spectrum and global wavelet spectrum of SLA along the southwest coast of India. The data used here is the merged weekly SLA for the three boxes (following figure 3.8) selected along the southwest coast of India. The X-axis of these figures shows the number of weeks starting from 1993 to 2009.

Kelvin waves reach the SEAS by early April / May after turning around Sri Lanka. The signatures of Kelvin wave propagation can be observed from altimeter data. In the present work, the periodicity of the SLA along the coast was deduced using wavelet transforms. It is understood from the figures (Fig No: 4.13, 4.14 and 4.15), that the dominant mode of variability is annual. Minor frequencies are observed in box 1 and 3 during 4 - 8 weeks. In order to establish the spatial variability, Empirical Orthogonal Function (EOF) has been computed and presented in Figure 4.16. The first principal component has a variance of
4.4 Remote Forcing

Figure 4.14: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of SLA for Box 2

Figure 4.15: a. Time Series, b. wavelet power spectrum and c. Global wavelet spectrum of SLA for Box 3
4.4 Remote Forcing

Figure 4.16: Empirical Orthogonal Function (First Mode) of SLA in SEAS

64%, and EOF shows maximum variability between 74° - 75°E and 7° - 8°N. This is the same region of the Lakshadweep High and Low. Westward propagation of the planetary waves is also observed from the EOF mode 1 of SLA in figure 4.16. Thus it can be inferred that maximum variability of SLA in the region is due to Rossby waves.

Long term weekly data plotted along the southwest coast of India as a Hovmuller like diagram with latitude on y-axis and time on x-axis as per the boxes chosen along the coast (Figure 4.17) aids the understanding of the spatial and temporal propagation of Kelvin / Rossby waves. The locations along the coast were selected such that they are parallel to the coast line and situated away by 0.5° from the coast as altimeter data are prone to errors near to the coast. The figure (Figure 4.18) well captures the downwelling / upwelling Rossby waves in this region. During January, positive anomalies were observed all along the coast from 7° to 15°N. By February, the intensity of these positive anomalies had reduced to the north of 10°N whereas, intense positive anomalies were persisting to the south of 10°N. A sort of balanced state prevailed by March with SLA observed to be near zero. By late April, the sea level began to fall and was prevailed completely by negative anomalies by the end of May; this, indicating the arrival
of upwelling Rossby waves in the region. Intense negative anomalies were observed up to 14°N during July and August. Less intense negative anomalies were observed between 8° and 12°N during September and this aspect was observed to be intensifying for a brief period. The positive anomalies were noticed from November which further intensified by December, completing an annual cycle of SLA in the region.

4.4.1 Weekly Evolution of SLA in the northern Indian Ocean

From the long term averages of SLA computed using altimeter data between 1993 and 2009, weekly SLA was plotted to map the propagation of Kelvin waves and the resultant Rossby waves all along the coastal wave guide of the Bay of Bengal and into SEAS (Figures are included in Appendix 1). From the weekly figures the following inferences are derived:

1 1 - 12 weeks: Negative anomalies are prevalent all along the BoB coast indicating the evolution of first upwelling Kelvin wave. During this period, positive SLA was observed in SEAS indicating downwelling phenomenon in the region.
4.4 Remote Forcing

Figure 4.18: Sea Level Anomaly along the coast during a climatological year

2 13 - 24 weeks: During 13 - 18 week period, positive anomalies were observed but with decreasing intensities indicating the gradual shoaling of thermocline in the region. By 19th week, negative SLA was observed along the coast up to 20°N and these negative SLA was found to be heading westward, indicating the westward propagating upwelling Rossby waves. By 22nd week, two distinct eddies were observed, one at the southern tip of India and the other centred on 74°E and located between 8° - 10°N. By this time, upwelling was well established in the region.

3 25 - 36 weeks: The upwelling phase of westward propagating Rossby waves stood enhanced by the wind induced upwelling in this region, thereby, shoaling the thermocline. This is well resembled by the intense negative anomalies. By the 29th and 30th weeks, the Rossby waves were spreading further westward. The first downwelling wave signatures are observed in the BoB as reflected by the positive anomalies. By 35th week, the negative anomalies along the coast were observed to be nearing zero; however they persisted away from the coast.
4.4 Remote Forcing

437 - 48 weeks: The westward propagation of negative SLA was present till the 41st week and was replaced by positive SLA by 42nd week indicating the conclusion of the upwelling phase. The positive SLA indicated downwelling in the region, as observed by 47th week. Apart from this, evolution of a second upwelling Kelvin wave was observed in the coastal BoB during this period.

549 - 52 weeks: The manifestation of Lakshadweep High can be clearly identified during this period. A well developed high sea level is maintained off the southwest coast of India centred between 74° - 75°E and 7° - 10°N, and it was found to be moving westward. This completes the full cycle of downwelling - upwelling - downwelling phase of sea level in SEAS during a year.

To sum up, on the forcing factors of upwelling in SEAS, it is discerned that the main contributing factors for the generation of upwelling are the along shore wind stress and remote forcing. The present study concentrates on the modulation of upwelling vis-a-vis these forces. The intra-seasonal variability of the wind stresses and the strength of coastal Kelvin wave have the potential to modulate the after affect of upwelling, say, the biological productivity. Thus it is on these minor frequencies that one needs to concentrate upon - this aspect is dealt in chapter 5. From the wavelet transforms of both the components of wind stress, it is observed that the meridional (along shore) component of the wind stress showed variability within the basin and has both significant semiannual and annual modes of variability along with other minor frequencies like the MJO. The zonal component of wind stress has only annual mode of variability and the MJO are absent. Wind stress curl is positive near to the coast during the SWM season indicating the presence of upwelling. Wavelet analysis of SLA along the coast showed significant annual mode of variability. To discern the region of variability, the SLA data was subjected to Empirical Orthogonal Function on spatial scale. The resultant first mode was having 67% variance and has been located between 74° and 75°E longitudes and 7° and 9°N latitudes, which is the region of Lakshadweep High and Low. The propagation of these waves results in high and low in winter and summer monsoon seasons, respectively. Since these offer
maximum variability in this region, they are reflected in the first mode of EOF of SLA. Hovmuller diagram of SLA along the coast indicated the northward limit of these waves and also the strength of upwelling as obtained from SLA studies. The response of ocean to these external forces will be discussed in the next chapter.