Mixed layer processes of the Arabian Sea Warm Pool during spring intermonsoon: - A study based on observational and satellite data

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Abstract

The relative importance and contribution of various processes in the total heat budget in mixed layer of Arabian Sea Warm Pool (ASWP) during spring intermonsoon, (March-April,2004) were studied using insitu observations and satellite data. The evolution of surface heat budget has been resolved into individual components of advection, vertical mixing, eddy induced diffusion and surface heat fluxes. In the northern part of the warm pool the surface heat flux is the dominant component in the mixed layer warming while the advection plays a role to spread the warm water from the coastal region to the far west. In the southern part of the warm pool the eddy induced horizontal mixing provides a substantial amount of heat spreading which influences on mixed layer temperature evolution.
1. Introduction

The seasonal variation of sea surface temperature (SST) in the Indian Ocean is considered as an important factor for the onset and subsequent evolution of the Indian summer monsoon (Webster et al, 1998). Prior to the onset of the summer monsoon a substantial area of the Indian Ocean occupies with SST greater than 28°C, known as Indian Ocean Warm Pool (IOWP) (Joseph, 1990, Vinayachandran et al. 1991). A major part of the IOWP has outgoing long wave radiation below 240Wm\(^{-2}\) (Lukas 1998) and it is a region of deep convection. The IOWP covers the entire north Indian Ocean (equatorial region east of 50°E, the Bay of Bengal and the eastern part of the Arabian Sea) during May, with peak SST above 30°C (Vinayachandran et al. 1991, Anonymous, 2001). In the southeastern Arabian Sea (SEAS), a core of the warm pool (SST>30°C) lies in the region of Lakshadweep Sea, during May. This anomalous warm water region in the SEAS is known as Arabian Sea Warm Pool (Rao and Sivakumar 1999, Anonymous 2001).

It is hypothesized that SST high in the SEAS from February to March is related to the corresponding high sea level known as the Lakshadweep High (Bruce et al. 1994, Shenoi et al. 1999). The Lakshadweep High develops mainly due to the downwelling Rossby wave that radiates from the poleward propagating coastal Kelvin wave along the west coast of India (Shanker and Shetye, 1997). During winter (November-February), the East India Coastal Current and the Winter Monsoon Current bring cooler, low saline Bay of Bengal water into the SEAS (Cutler and Swallow, 1984, Johannessen et al.1987, Shetye et al. 1991, Rao et al. 1999, Shenoi et al. 1999) and leads to the formation of a barrier layer (Lukas et al. 1991), the layer embedded between the top of the thermocline and bottom of the surface mixed layer depth. The downwelling Rossby wave and the presence of barrier layer provide a favorable condition for the peakening of SST in the SEAS (Shenoi et al., 2004).

The thermal inversion in the barrier layer initiates mixed layer warming and alters heat budget of the area by entrainment of heat from the inversion layer (Thadathil et al. 1992, Smyth et al. 1996, Durand et al. 2004, Gopalakrishna et al. 2005, Masson et al.2005). However, Kurian and Vinayachandran (2007) suggested the role of orographic effect due to the Western Ghats which reduces the wind speed over the SEAS, resulting in positive heat flux into the ocean and increase of SST of the region.

The heat budget of the mixed layer is an important factor to be investigated to understand the air-sea interaction of the SEAS. Rao and Siva Kumar (1999) opined that the heat build-up in the mixed layer of the SEAS during the pre-monsoon (March-April) is primarily driven by the surface heat flux through the ocean-atmosphere interface. Weller et al. (2002) also suggest that, the upper
ocean processes in the pre-monsoon are primarily one-dimensional (i.e., vertical), where the warming is the resultant of the surface heat fluxes and the penetrative radiation. Thus, the previous studies in the SEAS during pre monsoon period suggested that the heat budget of the upper ocean is mainly a balance between the vertical mixing and the surface heat flux. However, studies have shown that the horizontal processes of the oceans also play an important role in forming the SST anomalies on seasonal to interannual time scale (Grotnzer et al. 1998). The intra-seasonal variability in the oceanic and atmospheric parameters affects the heat budget in the upper layers of the SEAS (Murty et al., 2006).

The one-dimensional models seldom provide a complete description of the mixed layer processes where variability may be brought by the oceanic advection and sub grid scale processes (Qiu et al., 2002). The southern part of the SEAS is an eddy prominent region with a horizontal dimension in the range of 200 to 500 km and vertical extent of hundreds of meters. These eddies play an important role in the ocean dynamics as well as transport of heat and other oceanic properties. In an eddy prominent region, the large-scale mass divergence by the mean flow is balanced by the eddy induced divergence which becomes an essential part of the turbulent cascading (downscaling) of momentum and heat in the upper ocean into sub grid scales (Gent and Mc Williams 1990). Thus, eddies in the SEAS have an important role on the evolution of ASWP which is, not been explored. Thus in this study we investigate and identify the relative importance of heat budget components such as surface heat flux, advection, eddy diffusion and vertical mixing on the evolution of ASWP.

2. Data and Methods

The study is based on the data collected during the spring intermonsoon (March-April, 2004) cruise of FORV Sagar Sampada as a part of Marine Research-Living Resources (MR-LR) program along the western shelf of India from 8°N-15°N during March-April 2004 (Figure 1). A SBE Sea-Bird 911 plus CTD (Conductivity-Temperature-Depth) was used to collect the temperature and salinity. CTD salinities were calibrated against the values obtained from the Guideline 8400 Autosal onboard. SST was measured using a bucket thermometer. The data were re-gridded into a 1° x 1° grid (7°N to 16°N and 68°E to 77°E) using linear interpolation method. Horizontal advection due to the pressure gradient was estimated using geostrophic method (Pond and Pickard, 1983). For this computation, 1000db was considered as reference level.

The mixed layer temperature tendency of the upper ocean is controlled by the surface heat fluxes, horizontal advection, eddy diffusion, vertical mixing and entrainment (Curry and Webster, 1998). The evolution of mixed layer temperature (T) can be written as,
\( \frac{\partial T}{\partial t} + \left[ (u_g + u_e) \frac{\partial T}{\partial x} + (v_g + v_e) \frac{\partial T}{\partial y} \right] + w \frac{\partial T}{\partial z} = \]
\[ Q/h \rho C_p + \frac{\partial}{\partial z} \left( K_h \frac{\partial T}{\partial z} \right) + \left[ A_h \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \right] \]
\[ \text{........................................ (1)} \]

where \( \frac{\partial T}{\partial t} \) is the mixed layer temperature tendency, \( \left[ (u_g + u_e) \frac{\partial T}{\partial x} + (v_g + v_e) \frac{\partial T}{\partial y} \right] \) is the horizontal advection includes, the geostrophic and Ekman components (Pond and Pickard, 1983), \( Q/h \rho C_p \) is the surface flux, where \( Q \) is the net radiation which includes the short wave and long wave radiation, latent and sensible heat fluxes, \( \rho \) is the reference density of seawater (taken as 1025 kg m\(^{-3}\)), \( h \) is the mixed layer depth and \( C_p \) is the specific heat of seawater per unit volume (4300 J kg\(^{-1}\)K\(^{-1}\)) at constant pressure (Liu, et al., 2005).

The surface meteorological parameters (wind speed and direction, humidity, dry and wet bulb temperatures and atmospheric pressure) were measured from all stations along the ship track using the shipboard automatic weather station. These collected data are used for the computation of long wave radiation, latent heat flux (LHF) and sensible heat flux (SHF) using bulk formula for humidity and heat exchange as,

\[ \text{LHF} = \rho C_d L_v U (q_s - q_a) \]
\[ \text{SHF} = \rho C_d C_p U (T_s - T_a) \]
\[ \text{................................................. (2) (3)} \]

where \( \rho \), the density of air, \( C_d \), drag coefficient, \( L_v \), the latent heat of vaporization, \( U \), the wind speed, \( q_s \) saturation specific humidity and \( q_a \) is the humidity. \( q_s \) is calculated using Clausius-Clapeyron equation. \( C_p \) is the specific heat capacity of air per unit volume, \( T_s \) is the sea surface temperature and \( T_a \) is the air temperature above the sea surface (Prasanna Kumar and Prasad, 1996, Stewart, 2004). Shortwave radiation used in this study is from SOC-flux climatology data (Josey et al., 1999), which provides the data on a 1° x 1° spatial grid.

The term \( A_h \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \) is the eddy induced diffusion. The \( K_h \) and \( A_h \) are the vertical and horizontal eddy diffusion coefficients in the mixed layer. The eddy induced diffusion is due to the turbulent transport of heat which can be written in the turbulent form as \( u' \frac{\partial T'}{\partial x} + v' \frac{\partial T'}{\partial y} \) (Pond and Pickard, 1983). In order to find the turbulent velocity field in the surface layer we have used the satellite altimetry measurements from the TOPEX/POSEIDON altimetry data. The SSHA is the deviation from the mean geopotential height (dynamic height) and thus assumes the removal of the mean flow associated with the mean dynamic topography. Thus remaining component is taken as the fluctuation of the mean flow primarily driven by eddies and thus it provides \( u' \) and \( v' \) through the geostrophic relation as,
\[ u' = -f/g \left( \frac{\partial \text{SSH}}{\partial y} \right) \]  \hspace{1cm} \text{(4)}
\[ v' = f/g \left( \frac{\partial \text{SSH}}{\partial x} \right) \]  \hspace{1cm} \text{(5)}

where \( f \) is the local Coriolis parameter due to the rotation of the Earth and \( g \) is the acceleration due to gravity (Stewart, 2004). This assumption is valid only near the surface, and not with standing depths where a baroclinic currents take over. The density derived mean geostrophic currents showed that there is no reversal of current direction occurring above 80 m. Thus the eddy induced surface current is well represented throughout the mixed layer since the mixed layer never exceeded 80m.

The TOPEX/POSEIDON SSHA data has a 7-day temporal resolution, a 1/3° x 1/3° spatial resolution and covers the entire study region. The fluctuation of temperature (\( T' \)) was calculated by removing monthly mean temperature data derived from the World Ocean Atlas, 2001 (WOA01) from the observed temperature. The eddy induced diffusion computed from \( u' \), \( v' \) and \( T' \) (Qiu and Chen, 2004).

We have used the K-profile parameterization (KPP-hereafter) as in Large et al. (1994) to find the vertical mixing coefficients (\( K_h \)) from the observed currents and density of the mixed layer. The vertical resolution for KPP is 1m from the surface to the bottom of the mixed layer. The KPP was performed within this mixed layer to find the vertical mixing coefficient (\( K_h \)) according to the observed currents and density of the mixed layer.

The mixed layer tendency term (\( \frac{\partial T}{\partial t} \)) is computed from the satellite derived SST, than our observation for the tendency term calculation because the ship track covered each observational location only once in one cruise, thus losing a finer temporal resolution of temperature changes at any grid location. Although the SST is not the exact representation of mixed layer temperature, it is assumed that the temporal variation in the mixed layer temperature is represented in the SST changes as well. We have taken the TRMM Microwave imager (TMI) SST on a 0.25° x 0.25° grid to get a time series at any location. The satellite data were derived in a region 7°N-16°N and 69°E- 77°E and for the period from 20 March to 10 April, 2004 (same as our period of observations). Linear interpolation is done to avoid the data gaps at certain locations. Thus we have computed the tendency of the SST at our locations from previous and future TMI SST data on a two-day time interval. For example, the tendency of temperature on 23- March - 2004 is taken as,
\[ \frac{\partial T}{\partial t} = \frac{TMI_{24-03-04} - TMI_{22-03-04}}{2 \text{ days}} \]  \hspace{1cm} \text{(6)}

The advection components are calculated by centered finite difference scheme. The finite centered differences for the individual terms in the advective formulation are \( u \frac{\partial T}{\partial x} \sim u \Delta T/\Delta x \) and \( v \frac{\partial T}{\partial y} \sim u \Delta T/\Delta y \) (Wang and Weisberg, 2001). A boundary value is provided from the observations at the domain edges of the study area. It should be noted that the observations on the individual grid
faces are done on separate days and thus the advection and diffusion component does not represent the value for a particular time. The effects of tidal processes on the heat budget terms analyzed here cannot be explicitly resolved in the given set of data. However, considering our objectives to look at the spatial pattern of heat budget terms on the evolution stage of ASWP, the effect of tides is safely disregarded.

3. Results and Discussion

The metrological conditions that prevailed in the SEAS (clear sky, high solar radiation and weak northerly winds (average 4.2 ms$^{-1}$)) during the observation time, showed the typical condition of spring intermonsoon. Spring intermonsoon in the Arabian Sea normally observe by light winds, clear skies and strong solar radiation with an average heat gain of 101.1 W/m$^2$ (Wiggert et al, 2005). The high solar insolation and relatively weaker winds during this time may enhance the surface temperature of ASWP (Figure 2a & 2b). Figure. 3a shows the distribution of observed sea surface temperature (SST). The warmer regions are close to the coast with a SST of 30.1 °C and the isotherms are almost parallel to the coast. In this study we considered the region above 29.5°C as ASWP.

Salinity structure showed that a low saline water (<34.2) occupied between 8°N and 13°N in the upper few meters and tapered towards the north. This low saline plume was confined to the shelf region with minimum value of 33.9 at 10°N (Figure. 3b). The isohalines are almost aligned in a similar pattern of isotherms. The vertical structure of isotherms and isohalines along 8° and 10° N showed an upward shift (Figure.4a & b). This upward shift in isotherms and isohalines was due to the presence of eddies as identified from the SSHA pattern (Figure.5). The low saline water mass in the SEAS is due to the intrusion of BBW by the combined effect of East India Coastal Current (EICC) and winter monsoon current (WMC) (Shetye et al. 1996, Shanker et al. 2003). In the subsurface, the presence of high saline core (>35.6) is the presence of Arabian Sea High Salinity Water (ASHSW) subducted from northern part of the Arabian Sea and advected towards the south along the main thermocline (Prasad and Ikeda 2004).

We analyzed each term of the temperature evolution equation for the entire mixed layer depth (MLD). The MLD is defined as the depth at which the surface density ($\sigma_0$) increases by 0.2 units from the surface value (Shetye et al. 1996 and Madhupratap at al. 2003), which yields an average MLD of 25 m (Figure.6). A deeper MLD (>30 m) is observed in the south than north. Shallow MLD of less than 20m is found in the southern tip of the peninsula.
4. Heat budget in the mixed layer

In this section the heat budget of the mixed layer are described as resolved from our analysis. All terms are expressed as depth integral over the mixed layer depth, unless specified otherwise.

4a. Temperature tendency

Tendency of temperature is an order of magnitude weaker than other heat budget terms and it represents the net effect brought by a combination of other mixed layer processes such as advection, vertical mixing, horizontal diffusion and surface heat fluxes. The temperature tendencies of the ASWP are positive (i.e. warming) in the northeastern side of the warm pool with a maximum value approaching 1.5x10^{-6} °C s^{-1} at the coast (Figure.7). The warming in the northwest of study area is due to the inwards net surface flux into the ocean (Figure.8). The tendency of mixed layer temperature shows that the mixed layer warming in the northern part of the warm pool mainly follows the surface heat flux. It indicates that the northern part of the ASWP surface heat flux has a larger control on the mixed layer warming.

In the southeastern part of the warm pool (south of 11°N), the spatial variability of temperature tendency has a horizontal size of nearly 100km. Positive and negative temperature tendencies with size of eddies are a prominent feature in this region (Figure.7). Here the temperature tendency does not vary in accordance with the surface heat flux. This is the region where mesoscale features were prominent during the study period as we have identified from the altimetry data. The magnitude of this warming is only 10% of that of the warming in the north (Figure.7).

4b. Advection

Advection is the processes by which a local gradient of material property (here it is the temperature) is being transported horizontally according to the currents. The advection of the northeastern part of the warm pool shows a strong positive value indicating the advective warming (Figure.9). The advection patterns in warm pool area shows strong positive contours oriented parallel to the coast upto the central region. The background mixed layer temperature was warmer in the costal side and relatively colder farther west (Figure.3a). Thus the effect of advection reduces this gradient by transferring more warm water to the western side of the warm pool and causing an advective warming in the west. The magnitude of advection in the northwestern part of the warm pool region is 0.5x10^{-5} °C m s^{-1} which is only 10% of the net surface heat flux.

In the northern part of the warm pool the surface heat flux shows the highest value (Figure.8). The advection delineates a zero contour running northwest and passing through the center of the study region (Figure.9). To the east of the zero contours the advection warms the region. Thus the
highest surface heat flux into the ocean in the northern part is exported to the west, further warming
the western side of the warm pool. Thus advection exports the heat from the warm pool, which
mostly comes as the surface heat flux in the northern side. This export causes the mixed layer depth
to an average value of 25m in the northwest. In the extreme southeast the temperature tendency
(Figure. 7) show a strong cooling as well explained by the negative advection.

The effect of local wind and subsequent Ekman transport is computed separately and
compared with the geostrophic currents in order to find the impact of Ekman transport on the total
advection of heat in the mixed layer. It is found that the Ekman velocity is much smaller than the
near surface geostrophic currents. The analysis period represents the transition period of monsoon
(from northeast to southwest monsoon), and thus the winds are generally weaker and resulting in a
weaker Ekman drift than the background geostrophy. We have also computed the advection terms
with a total current of geostrophy and Ekman drift and found no appreciable differences in the
advection term compared to the non Ekman drift case, except small changes in the south.

4c. Diffusion

Unlike the advection, the effect of horizontal diffusion is not so significant in the northeastern
part of the domain (Figure.10). The average value of diffusion is nearly zero in the northeastern part
of the domain where advection showed a warming effect. The effect of eddy diffusion becomes
significant on the southern part of the domain where eddy features were prominent. The maximum
diffusion in the southern part of the domain is found 2.5x10^{-5} °Cm s^{-1} which is greater than the
amount of advection there (Figure.8). The effect of eddy induced diffusion is to smooth the
temperature gradient. Over the southern part of the domain, the eddy induced diffusion has
mesoscale features and smoothens the temperature gradient there. It is interesting to note that mixed
layer temperature tendency also follows the diffusion term in its spatial scale. Thus the effect of eddy
induced smoothing of temperature in the mixed layer is prominent in the southern part of the warm
pool region. The surface heat flux does not have such fine scale structures to reflect in the
temperature tendency as evident from figure 6.

The magnitude of diffusion in the southern part of the warm pool region suggests an eddy
diffusion coefficient to be as large as A_h=3x10^4 m^2/sec. This high value resolved in our analysis is of
course partially related to the coarse resolution of the data (1°x1° spatial grid). The presume of a high
eddy diffusion coefficient shown by the data analysis implies that a coarse resolution model should
include this large value of eddy diffusion coefficient, in order to have reasonable account of eddy
induced lateral mixing. However such large value of eddy diffusion smoothes out the mesoscale
variability in a numerical model. This eventually points to the necessity of resolving eddy induced
diffusion as an indirect estimate of eddy induced transport as in widely used Gent and McWilliams parameterization (Gent and McWilliams 1990). Our analysis shows that the models to have a reasonable simulation of diffusive processes in the ASWP, especially in the southern part of the domain, either a finer resolution data is necessary to resolve mesoscale induced mixing reasonably or an indirect parameterization of eddy induced transports should be included.

4d. Vertical mixing

Although the horizontal advection, diffusion and surface heat fluxes can account the major features of the temperature tendency qualitatively, the effect of vertical mixing should also be considered for the detailed account of surface heat budget. Figure.11 shows the vertical mixing term integrated over the mixed layer. The negative values show the cooling by deepening of mixed layer and positive value show the warming by shoaling of mixed layer. Unlike the other terms presented above, the vertical mixing did not exhibit any similarity with the temperature tendency except in the southern domain. In the southern part of the domain the vertical mixing features of size of the order of 100 km in horizontal as similar to the eddy induced heat flux and temperature tendency. The magnitude of the vertical mixing brought by the eddy induced current are stronger in the south.

The study area is divided into two boxes (a) North box (BN) [Area between 12°-15°N] and (b) South box (BS) [Area between 8°-11°N]. The vertically integrated mixed layer heat budget terms were spatially averaged for each box (Figure. 12). The surface heat flux is stronger in the north than in the south. The vertical mixing dominates the advection in the southern part. This is clearly evident in the deeper mixed layer depth as seen in the southern part of the SEAS (Figure.6). The input surface heat is thus balanced between vertical mixing and horizontal advection in the southern part of the domain. The eddy diffusion shows a slight warming although the magnitude is relatively lower than the advection or vertical mixing. In the northern part (BN), the surface heat flux is balanced between advection and diffusion while the southern domain (BS), the advection is dominated over vertical mixing and the horizontal diffusion is negligible.

5. Conclusion

The importance of various mixed layer processes (advection, eddy induced diffusion, vertical mixing and surface flux) on the formation of ASWP during spring intermonsoon were discussed. The study show that, a considerable spatial variation exists in the mixed layer processes of the ASWP. The surface heat flux was the dominant component in the mixed layer warming in the northern part of the ASWP, where as advection have only a subsidiary role to spread the warm pool from coast to offshore. In the south of the domain, the effect of eddy-induced transport is seen as large as the
advection. This is mainly associated with the prominence of eddy in that region during the transition of monsoon.

The study is not a climatological representation of the warm pool mixed layer processes because of the limited data. The coarse resolution of the data limited our chance to get closer look into more detailed processes of mixed layer heat budget evolution of ASWP. With the available insitu data, our study categorized the significance of various mixed layer processes and its regional dominance throughout the evolution of ASWP. The study also dictates those processes which are necessary for the regional modeling of the ASWP to have a reasonable simulation.

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7. References

ANONYMOUS (2001), Arabian Sea monsoon experiment (ARMEX): Science plan; Department of Science and Technology.


Legend to Figures

Figure 1. Base map showing the station locations. The cruise is started on March-19 from south and covered 29 stations and ended on April-8, 2004.

Figure 2a. Distribution of surface winds along the SEAS during the observation time

Figure 2b. Horizontal distribution of insolation (Wm⁻²) in the study region during the observation period (March-April)

Figure 3. Horizontal distribution of (a) Temperature (b) Salinity (in PSU)

Figure 4. Vertical distribution (a) Temperature (°C) (b) Salinity (in PSU)

Figure 5. Horizontal distribution of SSHA overlaid with geostrophic currents derived from AVISO T/P merged sea level anomalies for 14-18th March, 2004.

Figure 6. Mixed Layer Depth (m) of the study region

Figure 7. Temperature tendency in Mixed Layer (x 10⁻⁵) integrated over the entire mixed layer depth. Units are in °C m s⁻¹

Figure 8. Surface flux (x10⁻⁵) from the observations. Positive means heat flux into the ocean. Units are in °C m s⁻¹

Figure 9. Horizontal advection integrated over the mixed layer (x10⁻⁵) Units are in °C m s⁻¹

Figure 10. Diffusion term (x10⁻⁵) vertically integrated over the mixed layer. Units are in °C m s⁻¹.

Figure 11. Mixing term (x10⁻⁵) vertically integrated over the mixed layer. Units are in °C.m s⁻¹

Figure 12. The heat budget averaging over north and south of the study region.
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Figure 2a. Distribution of surface winds (ms$^{-1}$) along the SEAS during the observation time.
Figure 2b. Horizontal distribution of insolation (Wm$^{-2}$) in the study region during the observation period (March-April).

Figure 3. Horizontal distribution of (a) sea surface temperature ($^\circ$C) and (b) sea surface salinity (in PSU)
Figure 4. Vertical distribution (a) Temperature (°C) (b) Salinity (in PSU)

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