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Mixed Layer Variability in Northern Arabian Sea as Detected by an Argo Float

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Abstract – Seasonal evolution of surface mixed layer in the Northern Arabian Sea (NAS) between 17° N–20.5° N and 59° E–69° E was observed by using Argo float daily data for about 9 months, from April 2002 through December 2002. Results showed that during April - May mixed layer shoaled due to light winds, clear sky and intense solar insolation. Sea surface temperature (SST) rose by 2.3 °C and ocean gained an average of 99.8 Wm^{-2}. Mixed layer reached maximum depth of about 71 m during June - September owing to strong winds and cloudy skies. Ocean gained abnormally low ~18 Wm^{-2} and SST dropped by 3.4 °C. During the inter monsoon period, October, mixed layer shoaled and maintained a depth of 20 to 30 m. November - December was accompanied by moderate winds, dropping of SST by 1.5 °C and ocean lost an average of 52.5 Wm^{-2}. Mixed layer deepened gradually reaching a maximum of 62 m in December. Analysis of surface fluxes and winds suggested that winds and fluxes are the dominating factors causing deepening of mixed layer during summer and winter monsoon periods respectively. Relatively high correlation between MLD, net heat flux and wind speed revealed that short term variability of MLD coincided well with short term variability of surface forcing.

Key words – argo, mixed layer depth, surface fluxes, wind stress, Arabian Sea

1. Introduction

The mixed layer depth (MLD) is an important oceanographic parameter which plays a vital role in several physical, chemical, biological oceanographic and climatic phenomena, including heat budget of the oceans, air-sea interactions and feedback, phytoplankton bloom etc. The mixed layer is affected by several factors like wind generated turbulence, convective cooling, and current shears. This region of the ocean thus forms an interesting area for the study of air-sea interaction and feedback mechanisms. Further, MLD variability on several temporal scales is an important indicator of climatic variability and also provides a wealth of information essential for the study of ocean-atmosphere interdependence. In addition to these, modelling the ocean's climate variability requires reliable information on the space-time variability of MLD. Thus, the prediction and study of MLD variability forms the cynosure of oceanographers, climate researchers and ocean modelers worldwide.

The conventional approaches of MLD estimation using climatology temperature and salinity (T/S) profiles (*e.g.* Suga and Hanawa 1990; Montery and Levitus 1997; Kara *et al.* 2000) or, *in situ* temperature and/or density computed from *in situ* T/S observations from CTDs are limited in terms of their spatial and temporal spreads. Statistical and analytical models which were developed to estimate MLD from meteorological forcings also suffer from lack of sufficient *in situ* data for their validation and fine-tuning (*e.g.* Price *et al.* 1986; Chen *et al.* 1994, Godfrey and Schiller 1997). Such studies thus necessitate large data sets of the ocean subsurface with high temporal resolution and spatial coverage.

The international Argo project that was envisaged towards building an archive of real-time *in situ* ocean T/S observations had a humble beginning in 2000. Under this program, several floats have been deployed worldwide, and as of May 2007, 518 floats are active in the Indian Ocean region. These profiling floats provide a real-time capability for measurement of T/S profiles within the upper 2000 m of the ocean (The Argo Science Team 2001; Ravichandran *et al.* 2004). This continuous measurement of T/S from the

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Argo program has enabled the measurement of mixed layer to an unprecedented degree. Ohno *et al.* (2004) examined winter mixed layer depth using Argo float data. Bingham and Suga (2006) studied the distribution of mixed layer properties in Northern Pacific water mass formation areas using WOA01 data and compared it the with those obtained from Argo. de Boyer Montégut *et al.* (2007) studied the control of salinity on the MLD in the world ocean using comprehensive data sets including Argo. Kako and Kubota (2007) studied the variability of MLD in Kuroshio/ Oyashio region. These and many other studies highlight the importance of Argo data in studies relating to MLD.

Normally, observation periods of most of the Argo floats deployed in Arabian Sea (AS) is 5 or 10 days, but two floats (WMO ID 2900210 and WMO ID 2900211) were deployed with observational periods of one day. In this paper, the T/S data obtained from float (WMO ID 2900211) during its deployment and operation period from April 2, 2002 till Dec 12th 2002 has been used to investigate mixed layer variations on seasonal and much shorter time scales in the northern Arabian Sea (NAS). This particular Argo float has enabled the observation of the surface and subsurface ocean layers with high time resolution for a considerably longer period of time. Furthermore, we study the seasonal evolution of upper layer conditions such as temperature, salinity, density and MLD based on profiles obtained by the float in order to understand the influence of seasonal atmospheric phenomena on the ocean in the region.

2. Data and Methodology

The profile data used in the present study were obtained by the Argo float (WMO ID 2900211) that was deployed at 19.0°N and 59.7°E on April 1, 2002 and data was obtained until December 12th, 2002. The float had been designed to measure T/S profiles from 700 dbars to about 8 dbars every day, unlike other standard Argo floats which are designed to measure every 5/10 days. The float repeated the cycles until December 12th, 2002. In all, 220 sets of T/S profiles from 8 dbars to about ~650 dbars were made available after subjecting them to real time quality control checks (Wong *et al.* 2006). The trajectory of the float is shown in Figure 1a. Starting and ending positions of the float trajectory are indicated by circle and star respectively. All the locations corresponding to each month are included in box and are labeled accordingly which help locating the T/S values.

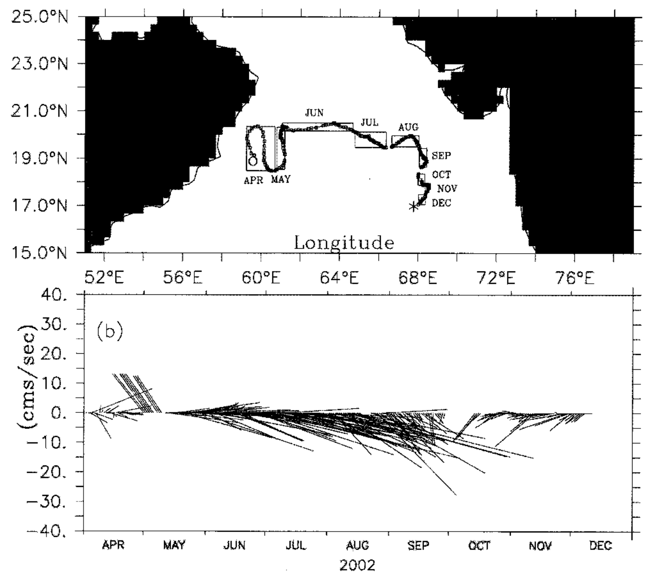

Fig. 1. (a) Trajectory of float (WMO ID 2900211) during its life cycle. Starting and ending points are represented by circle and star respectively. Profiles corresponding to each month are provided in single box (b) Ekman currents derived from QuickScat winds along the float trajectory.

Argo float stays on surface for ~14 to 17 hours, transmitting data packets to Argos satellite. Moreover it takes ~ 4 hours for diving to parking pressure and surfacing. Since the float (WMO ID 2900211) measured T/S on day to day basis, for the majority of the time it is on the surface, and is subjected more to wind driven currents, as can be observed from the float movement from west to east in response to the Ekman currents shown in Figure 1b.

Density was first calculated at each observation level based on high-pressure equation of state (Millero *et al.* 1980). Then temperature, salinity and density were linearly interpolated with a 1m depth interval. Ekman currents were obtained from 3-day composite gridded QuikScat wind data, provided by remote sensing systems (RSS). The National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) daily averaged reanalysis data (Kistler *et al.* 2001) of surface heat and radiation fluxes (net short-wave and long-wave radiation and sensible and latent heat fluxes) are used to estimate surface heat flux. Fresh water flux (E-P) data was obtained from Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite (HOAPS-3). A linear interpolation method was applied to the above mentioned data sets to derive net surface heat flux, currents, wind and fresh water flux along the float trajectory during the observation period.

3. Results and Discussion

The North Indian Ocean is influenced by seasonally reversing monsoonal wind forcing, apart from winter cooling, radiative forcing and fresh-water forcing. All these factors affect the mixed-layer dynamics and contribute to its variability. Prasad and Bahulyan (1996), Weller *et al.* (2002), and Udaya Bhaskar *et al.* (2006) attributed variations in solar insolation, wind stress and buoyancy flux as the significant factors that determine the MLD variability in Arabian Sea. Thermohaline structure of the upper ocean in the central Arabian Sea goes through a unique semiannual cycle. During both monsoons, the sea surface temperature (SST) in the Arabian Sea cools and the mixed layer deepens (Weller *et al.* 2002). Time-depth sections of the T/S in the upper 300 m depth are shown in Figure 2. From this figure we observe that T/S are dominated by the signal of two monsoon seasons. Primary manifestation of the monsoon, a cooling and deepening of mixed layer, is clearly observed in each season. The time series of MLD is shown in Figure 3a, as well as overlayed on temperature and salinity in Figure 2. A simple definition of MLD, defined as the depth at which the density is greater than the surface by 0.125 kg/m^3 (Ohno *et al.* 2004; Udaya Bhaskar *et al.* 2006) is used in this analysis. Since the average surface-most observation is ~9 m, density at 10 m depth was used instead of the surface value to define MLD. Also, temperature at this surface-most observation is considered as SST. The gaps in MLD plots in Figure 3a correspond to profiles starting at a depth greater than 10 m or due to missing profiles. Twice-annual cycle of deepening

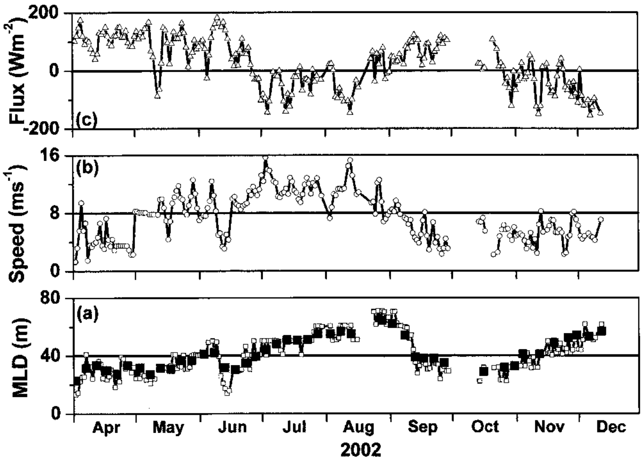

Fig. 3. Time series of (a) MLD (blank squares and filled squares represent MLD from float and objectively analysed product respectively) (b) Wind Speed, (c) net surface heat flux along the float trajectory.

and shoaling of MLD is clearly reflected in the data covering 3 full seasons and the winter monsoon period partially. To substantiate the results obtained from (WMO ID 2900211), weekly objectively analyzed (OA) data from (http://www.coriolis.eu.org/cdc/ObjectivesAnalysis/objective_analyses.htm) for the year 2002 is used and MLD is estimated with similar criterion. Further MLD along the float trajectory is obtained by linearly interpolating the data set. This MLD is also shown in Figure 3a overlayed on MLD computed from float (WMO ID 2900211) profiles. It is clearly observed from Figure 3a that MLD variability from weekly OA data shows a similar trend to that of daily MLD. Interestingly day to day MLD variability is clearly

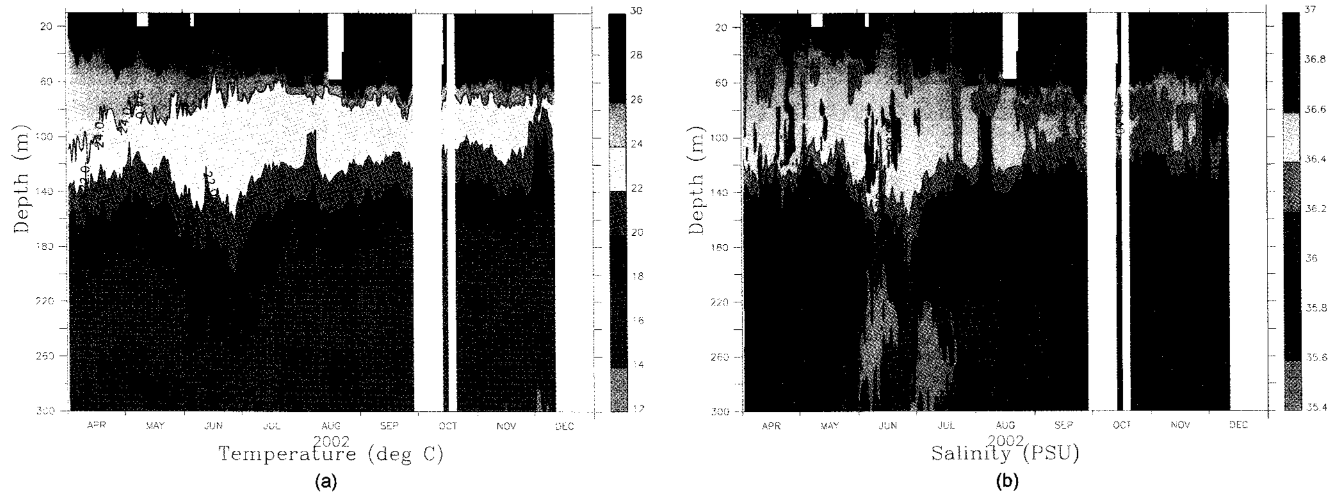

Fig. 2. (a) Time-depth sections of temperature. Contour intervals are 2.0 degrees. Thick line indicates mixed layer depth. (b) Time-depth sections of salinity. Contour intervals are 0.2 PSU. Thick line indicates mixed layer depth.

observed, which is averaged out in the MLD estimated from OA data.

The temporal variations of MLD during the observation period show a clear seasonal evolution, which can be divided into four stages (within the available period) viz., (a) Pre-summer monsoon (April - May), (b) Summer monsoon (June - September), (c) Post-monsoon (October) and (d) Winter monsoon (November and December, since data is available up to December). During the transition month of October, the data gaps correspond to profiles that were not reported by the float.

Pre-summer monsoon (April - May)

The pre-summer monsoon period is characterized by light winds, clear skies and intense solar insolation and is a period of strong net heat gain, as can be seen by the steady rise in near surface temperatures (Figure 4a). These strong surface heating and moderate winds are instrumental in heating up the ocean surface. During the course of April - May, SST increased steadily, starting from a minimum of 27.4 °C in April and reaching a maximum of 29.7 °C in May (Table 1). The ocean's average net heat gain was about 99.8 Wm^{-2}. Temperatures at depth of 20 and 40 m started to rise, as can be observed from Figure 2a and 4a. This can be attributed to penetrative radiation warming up the region below shallow mixed layer (Weller *et al.* 2000). Salinity varied consistently with the surface forcing which is strongly evaporative (Figure 4c). This strong evaporative surface forcing caused salinities at depth between 10-40 m to increase throughout the period (Figure 4b), keeping deeper salinities more constant. Net heat flux was positive (Figure 3c) and evaporation dominated precipitation throughout this period (Figure 4c). MLD remained shallow as a result of weak winds and stratification of the upper part of the water column due to strong positive heat flux. This is clearly seen in Fig. 3a, with MLD fluctuating largely from 41 m to 13 m within a short period, beginning in April until the end of May.

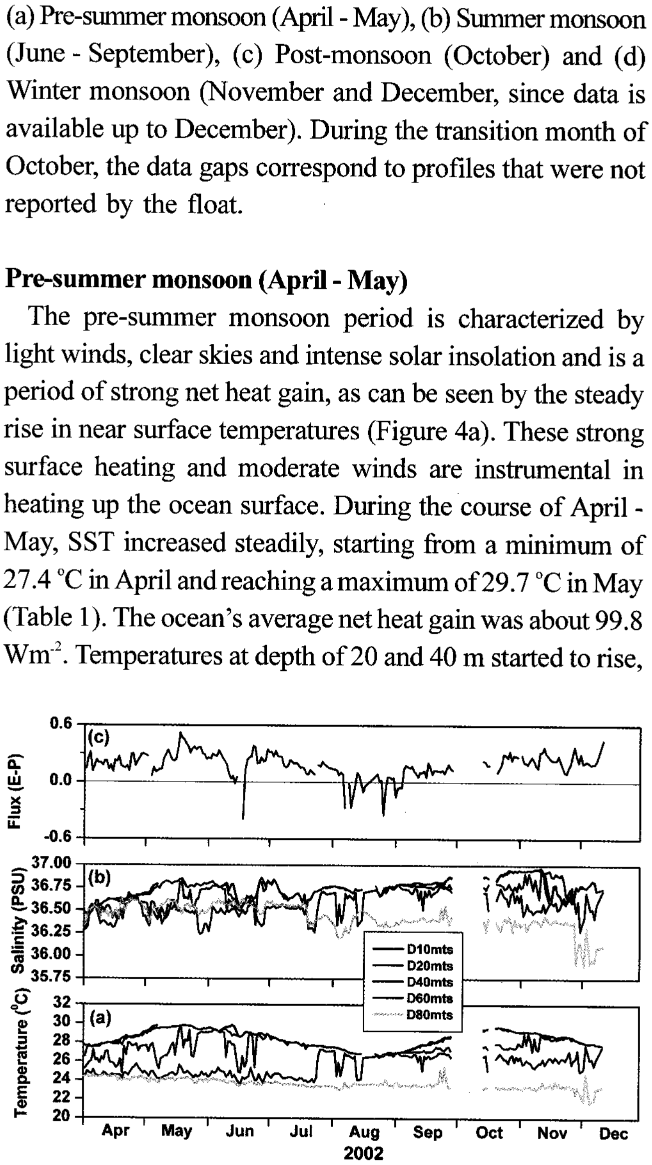

Fig. 4. Time series of (a) Temperature (b) Salinity for the indicated depths (c) Fresh water flux (E-P) data along the float trajectory.

Summer monsoon (June - September)

During the summer monsoon season, the Arabian Sea experiences some of the strongest and steadiest winds. In general, this period is characterized by strong winds, cloudy skies and moist air starting from early June until mid September (Weller *et al.* 2002). Solar insolation decreases due to cloud cover and these strong winds play a major role in determining MLD (Udaya Bhaskar *et al.* 2006). Surface temperature during the first half of the summer monsoon showed a general cooling trend. Temperatures within mixed layer remained fairly constant starting from July until the end of August, after which it started to rise. Uniform salinity values ranging between 36.5-36.75 PSU are observed during the period (Figure 4b) as a result of cooling and strong currents prevailing during this period. The observed uniform salinity can be attributed to advection playing an important role in controlling salinity. Wind speed varied with standard deviation of 3.1 m/s at an average of 9.07 m/s. Despite the strong winds, evaporative heat loss from the ocean is limited by extreme humidity in the air (Weller *et al.* 2002). This is clearly depicted in Fig. 3b with strong winds ranging from 8-14 m and net heat flux staying positive during most part of June, highlighting the

Table 1. Statistics of the surface parameters observed along the track for all seasons.

Season	Wind (m/s)		Flux (Wm^{-2})		MLD (m)		SST (°C)	
	Avg	Stdev	Avg	Stdev	Max	Min	Max	Min
Pre-summer monsoon	6.4	2.9	99.8	49.5	40.9	13.3	29.8	27.5
Summer monsoon	9.0	3.1	17.8	78.6	70.9	14.0	29.9	26.6
Post-summer monsoon	5.3	1.5	2.6	55.7	31.9	22.3	29.7	29.2
Winter monsoon	5.2	1.5	-52.6	58.6	61.7	31.5	29.2	27.7

oceanic gain during the southwest monsoon. But the ocean started to lose heat starting from the last week of June until the third week of September, as observed from the negative heat flux (Figure 3c). Over the entire period of June - September (summer monsoon period), the ocean gained an abnormally low average of 18 Wm^{-2} and SST cooled by 3.4 °C. This abnormal net heat flux can be attributed to the break in summer monsoon during July 2002 (Chowdary *et al.* 2005). Mixed layer deepened gradually starting from June through the end of August. During the second week of June, the wind speed suddenly dropped below 4 m/s, temperature rose to as high as 29.9 °C, and high net heat gain of 181 Wm^{-2} was observed. MLD shoaled to a season low of ~14 m during this period (Figure 3). From the third week of June onwards, conditions restored to normal, with a drop in surface temperature and increase in wind speed. MLD started to deepen again, reaching a maximum of about ~71 m late in August.

Post-summer monsoon (October)

In general, post-summer monsoon periods have similar characteristics of surface forcing as that of pre-summer monsoons. The period is marked by light winds ranging from 2-6 m/s and strong sea-surface heating. SST started to rise again, reaching a second high of 29.7 °C for the entire observation period. During this transition period, MLD shoaled and maintained a depth of 20 to 30 m.

Winter monsoon (November - December)

The winter monsoon period is marked by comparatively dry and quite steady northeasterly winds. SST dropped steadily from 29.2 °C to 27.7 °C by the end of the observation period. The wind speed varied on an average of 5.2 m/s, with a standard deviation of 1.5 m/s (Table 1). Saltier water (by ~ 0.4 PSU) was observed above the mixed layer during the early weeks of November (Figures 2b and 4b), due to excess of evaporation over precipitation (Figure 4c). This layered structure was lost starting from the second week of November and similar conditions persisted until the end of the observation period. Loss of layered structure could be due to cooling of water below the mixed layer causing nearly uniform salinity in the upper 100 m compared to early weeks of the winter monsoon. Daily net surface heatflux observed during this period changed sign from positive to negative during the first three week of November and finally settled to negative during the rest of the observation period (Figure 3c).This short term change in heat flux had effect on MLD variability. With weak wind speed forcing high insolation and high long wave heat loss at the surface, the air-sea boundary is always destabilizing. This convective mixing due to winter cooling results in deepening of MLD. This is clearly reflected in Figure 3a, with moderate wind speeds ranging from 2-8 m/s, negative surface fluxes, and gradual deepening of MLD. Temperature below mixed layer warmed initially during November and by the end of November a steadily cooling was observed. The ocean lost an average of 52.5 Wm^{-2} of heat and SST cooled by 1.5 °C during this one and half month period. MLD started to deepen gradually, beginning from November, reaching a maximum of 62 m in December.

Analysis of the four seasons (discussed above) suggested that seasonal variations of surface heat flux along with the seasonal variation of wind coincided well with those of the MLD, as expected in all seasons. Spectral analysis of the wind speed, net heat flux and MLD revealed short term variability ranging between 5-7 days (figure not included). Short term changes in MLD can be associated with the short term changes in wind speed and net heat flux respectively. From Figure 3 we can clearly observe that short term variability in MLD coincided well with variability in net heat flux and wind speed. Comparing the observed MLD, surface heat flux and wind speed, the correlation coefficient (R) between MLD - surface heat flux and MLD - wind speed for the entire observation period is observed to be 0.61 and 0.58 (figure not included). This relatively high correlation coefficient must be a reflection of the similarity in seasonal and short term variations of the two observations.

4. Conclusions

MLD derived from time-series temperature and salinity data along track Argo float (WMO ID 2900211) clearly reflected a dominant twice-yearly cycle of mixed layer deepening and cooling that characterizes the monsoonally forced Arabian Sea. Analysis of wind, net surface fluxes, and SST showed that surface forcing of summer and winter monsoon varies drastically. This study showed that the float observation continuously captured seasonal evolution of surface mixed layer in the northern Arabian Sea for a period of 9 months, from Apr 2, 2002 till Dec 12, 2002. The results showed that the mixed layer shallowed in the first two months. It reached its maximum depth of about 71 m at the end of August, after which the mixed layer shallowed considerably and deepened by the mid of December. Analysis of surface fluxes and wind suggested that wind is the dominating factor, causing deep mixed layer during summer monsoon periods, and fluxes are the dominant factor responsible for deep mixed layer due to convective mixing during the winter monsoon period.

The present study demonstrated the enormous capability of Argo profiling floats and their usefulness in observing the surface mixed layer of the ocean. With the availability of more Argo floats in the future, the interannual variability studies of MLD and mixed layer heat budget can be successfully carried out.

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