Synopsis of the Ph. D thesis entitled

Characterizing the surface layers of Arabian Sea using Argo profiling float data

by

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The upper ocean is the most variable and dynamically active part of the marine environment that couples the underlying ocean to the atmosphere above through the transfer of mass, momentum and energy. The oceanic surface layer assumes many shapes and forms. More common among others are, inversion layers, mixed layers, sonic layers, and barrier layers. The thickness of mixed layer is an important parameter in determining the quantity of heat that is available for exchange with atmosphere which is capable of triggering several ocean-atmosphere coupled processes. Mixed layer also plays an important role in determining the chlorophyll biomass and biological productivity of the upper ocean. Also ocean being almost opaque to electromagnetic radiation, sound is the only means to probe the ocean interior.

Further, acoustic system plays a very important role in many civilian and military strategic applications. The depth of sonic layer plays an important role in refraction of sound rays traveling in the ocean, which in turn affects the sonar detection ranges. The present work is an attempt to study basin-scale variability of the mixed layer and sonic layer in the Arabian Sea, their inter relationship and factors responsible for it. Though sonic layer is considered almost equal to mixed layer, here we try to understand how these two are tightly coupled during different seasons.

With the advent of Argo profiling float technology observation of ocean interior has entered a new era. This international program designed to monitor the global ocean variability from intra-seasonal to the inter-annual time scales has organized the deployment of thousands of autonomous drifting profilers. These data represent now most of the real time in-situ temperature data above 1000 m and are nearly the only measurements for salinity between 10 and 2000 m or temperature between 1000 and 2000 m. They compliment the high quality, full depth CTD measurements by providing more frequent and fast delivery data. Taking this as an advantage the author made an attempt to characterize the surface layers of Arabian Sea. The chapters in the thesis are organized as follows.

**Chapter 1**

It describes the study region, Arabian Sea in detail. Review of literature related to Arabian Sea is discussed. The Arabian is unique in that it is limited in the north by the Asian continent. One consequence of this geography is that the Arabian Sea is forced by intense, annually reversing monsoon winds. Arabian sea is subject to
extreme seasonal changes in atmospheric forcing that may be sub-divided into the northeast (NE, November-February) and southwest (SW, June-September) Monsoons and two intermonsoon periods (spring, March-May and Fall, October). Many dramatic physical, chemical, and biological changes occur in the upper layers of the water column due to these differing atmospheric regimes. Seasonal upwelling/downwelling, reversing of boundary currents caused by monsoon wind are some of the notable feature of Arabian Sea. Several water masses contribute to the temperature-salinity (T-S), nutrient, and oxygen structure. The interaction of these water masses in a region of extreme atmospheric forcing, and the biological processes that occur within them, produce temporal and spatial variability. In short, signals for many important processes are quite strong in the Arabian Sea. One interesting observed feature of Arabian Sea is that there is a net annual surface heat flux into Arabian Sea. In the western Arabian Sea this flux is a direct result of coastal upwelling during Southwest Monsoon, the cold water reducing the latent heat flux out of ocean. In the central and eastern Arabian Sea it is caused by the southward advection of this upwelled water towards the equator.

**Chapter 2**

It deals with the data and methodologies used in this thesis. The work in this thesis is focused mainly on subsurface data collected from Argo profiling floats deployed in the Arabian Sea north of equator and west of 80 °E. Temperature and salinity profiles for the period 2002 – 2008 are used. In addition data from world ocean database (WOD 01) are used to have inter-comparison. All the profiles were quality controlled by passing them through 18 quality control checks as per the guide lines implemented by International Argo Data Management Team. Further the Argo data have been visually quality controlled, checked for outlier and spurious values, which were eliminated. Argo deployments began in 2000 and by mid of 2008 the array completed 100%. Besides float deployment, Argo has worked hard to develop two separate data streams: real time and delayed mode. A real time data delivery and quality control system has been established that delivers 90% of profiles to users via two global data centers within 24 hours. A delayed mode quality control system (DMQC) has been established and 50% of all eligible profiles have had DMQC applied.

The methodology section describes various objective analysis methods like Krigging, Kessler & McCreary used for gridding irregular in situ observations on
regular grid is also described in detail. The equation used for estimating sound velocity profile, various criterions for estimating mixed layer depth (MLD) and the one chosen for the work in the thesis, sonic layer depth (SLD) estimation method are all given in detail in this chapter.

**Chapter 3**

Changes in atmospheric forcing cause variations in mixed and sonic layers. In order to understand physical forcing that is responsible for the basin-wide variability of mixed layer and sonic layer depth, all possible atmospheric forcing were examined in this chapter. Towards this the atmospheric forcing such as incoming short wave radiation, net heat flux, wind speed, wind-stress curl and evaporation minus precipitation were analyzed and presented in this chapter. The atmospheric data such as monthly mean climatology of the incoming short wave radiation, wind speed, evaporation, precipitation and net heat flux obtained from Comprehensive Ocean Atmospheric Data Sets (COADS) for the period 1950 – 1995 were used to study the factors responsible for the variability of mixed and sonic layers.

**Chapter 4**

The seasonal variability of upper ocean parameters i.e MLD and SLD, their inter-relationship and factor responsible for their variability are presented in detail in this chapter. It is observed that strong stratification induced by peak solar heating and subsequent highest net heat gain by the ocean caused shoaling of MLD and SLD during March – May. During summer monsoon period (June – September) a remarkably strong and steady jet called Findlater jet is developed over Arabian Sea. This strong jet imposes a wind stress curl that lead to Ekman upwelling to the north and west of the jet, off the coast of Arabian Peninsula and Ekman downwelling to the south and east of it, in the central Arabian Sea. It is observed that Ekman downwelling caused by the negative wind-stress curl led to deepening of MLD and SLD in the central Arabian Sea, where as Ekman upwelling caused shoaling of MLD and SLD all along the coast of Oman and along the west coast of India.

During inter monsoon period (October – November) shoaling of MLD and SLD is predominantly observed owing to strong stratification induced by secondary peak observed in solar heating, weak winds and high net heat gain by the ocean, which are incapable of mixing the surface layers. During winter monsoon period (December – February) moderate, cool and dry winds are observed over Arabian Sea by which the longwave heat loss at the sea surface is high and evaporation minus
precipitation is found to be at its peak. All these factors cause buoyancy flux to be destabilizing. These destabilizing buoyancy fluxes caused deepening of mixed layer and sonic layer.

An interesting feature of SLD is observed in the south eastern Arabian Sea (SEAS) during winter monsoon period (Dec – Feb). Deep SLD were observed along the south west coast when MLD is found to be shallow. The possible reasons for the observed phenomenon are further explored. It is observed that temperature inversions (TI) form in SEAS during December and prevail up to early March. Also during this period the East Indian Coastal Current and Winter Monsoon Current acts together to bring low salinity water from Bay of Bengal into SEAS which is observed to be cooler than ambient waters in SEAS. The advection of cooler low saline water over warmer saltier water leads to the formation of TI. As sound velocity is more sensitive to temperature than salinity, SLD is found to deepen tracing up to the depth of inversion. Where as the high stratification caused by the presence of low salinity waters hampers mixing and hence shoaling of MLD.

Chapter 5

Observing the dependence of sound velocity on temperature, a new method is proposed for utilizing all the available temperature profiles for estimating SLD in this chapter. In general salinity data over the oceanic region is sparse compared to temperature alone profiles. Climatological temperature/salinity relations have been obtained to infer salinity from temperature data by many researchers. A new method of estimating SLD is proposed for maxing use of voluminous temperature profiles besides other XBT data. This method proposes estimation of SLD using temperature from XBT and salinity from World Ocean Atlas 2001 (WOA01) climatology. This method is demonstrated by using Argo temperature and salinity profiles. SLD is first estimated from Argo T/S profiles (SLD_A). The Argo salinity profiles are then replaced by climatological salinities and SLD is re-estimated (SLD_C). The monthly RMS difference between the two estimations is observed to vary between 3 – 12 m. On an average SLD_A and SLD_C matched in more than 90% of cases. To further check the robustness of proposed method skill score is estimated. Perfect skill score of value 1 is observed between SLD_A and SLD_C indicating the use of climatological salinity in place of salinity.
Chapter 6

Results of the thesis are summarized in this chapter. Results show that large quantity of Argo data enables us to estimate mixed layer and sonic layer with a quality that is better and much more homogeneous in space and season, although the observation period may be too short to discuss the long-term mean state. Further results indicated that MLD and SLD varied similarly in all seasons except during winter monsoon period where the SLD is found to be deeper than MLD in south eastern Arabian Sea due to the advection of cold low saline waters from Bay of Bengal, which resulted in formation of temperature inversions, thereby deepening SLD. New method proposed for estimating SLD making use of voluminous temperature proved that climatological salinities can be used in combination with XBT for getting near accurate SLD. Also these results indicate that climatology of salinity need to be enhanced for increasing the robustness of the proposed method.

List of Publication


