Analysis of thermocline development in the Persian Gulf

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Abstract. Thermocline is often observed in the open ocean and can be as a seasonal phenomenon in the shallower part of the ocean or as a permanent one that is usually seen in the deeper part of the open ocean. There are different forcing and climatic parameters that affect the thermocline development in the PG from winter to summer. These include tide, river inflow, solar radiation, evaporation, northwesterly wind and water exchange with the Oman Sea. Thermocline development that evolves from east to west is studied using numerical simulation and comparing the results with some existing observations. Results show that as the northwesterly wind in winter, at summer transition period, weakens the fresher inflow from Oman Sea can penetrate much further into the PG and the lake of wind lowers mixing which with stronger solar radiation lead to the near surface thermocline formation and its development from winter to summer even over the northwestern part of the PG. The analysis results show that for the more realistic monthly averaged wind experiments the thermocline develops as is indicated by summer observations. The results indicate that weaker winds and particularly stronger solar radiation in summer months can lead to an intense thermocline in the whole of the PG including in the northern part and vice versa for winter.

Keywords: Persian Gulf, Thermocline, Temperature, Salinity

Introduction

The thermocline is a thin but distinct layer in a large body of fluid (or water column) in which temperature changes more rapidly with depth. In the ocean, the thermocline may be thought of as an invisible blanket which separates the upper mixed layer from the calm deep water below. Recent observations have revealed an important aspect of inter-annual to decadal extra-tropical thermocline variability, which is that the sea surface height (SSH) anomaly propagates predominantly westward at all latitudes (Liu, 1998). Thermocline is the dominant feature of temperature gradient in the oceans. Productivity is low where it is stable and high where it is broken by stirring and upwelling. This is due to the fact that in the latter case vertical mixing of nutrient from bottom and oxygen from top can more readily occur. In the oceans, firstly, important energy transformations occur at or near the ocean surface. A major fraction of the radiative heat from the sun which enters the earth's atmosphere is absorbed in the upper ocean, much of the absorbed heat energy is transferred to the atmosphere as water vapor, and it is the release of this latent energy through condensation which then drives the large scale atmospheric circulation. On smaller scales the atmospheric motion is modified by the drag of the ocean surface, and the transfer of momentum gives rise to waves and currents as well as modulating the evaporation and the sensible heat transfer. Secondly, the atmospheric boundary layer over the ocean is representative of the part of the troposphere in which we live. The historical archive of meteorological measurements almost entirely represents surface conditions. From a human viewpoint, understanding and simulating conditions in the lower atmosphere has many direct applications (Taylor, 1984). In summer rather than winter, the surface buoyancy removal allows deep convection which is induced in part by high evaporation rates sustained by warm surface water temperature relative to the atmosphere (Gordon, 1986). Heat radiated on water surface affects the thermocline depth in shallow waters; heat content variability also shows a similar pattern as that of thermocline depth. Decrease in the heat content in the coastal waters such as the ones in the Indian Ocean appears to be the result of entertainment cooling forced by thermocline upwelling. The highest value of the heat content is associated with deepest thermocline with shallow mixed layer depth (Anilkumar et al., 2006).

Materials and Method

Some observations

In this study, we evaluate the thermocline formation and its axis displacement through water column in the PG numerically while using some observational data.

Before the analysis results are presented some observations on the T, S, and sigma-T fields for the PG based on the ROPME Mt. Mitchell Cruise (winter and summer of 1992) are presented. Figure 1 shows a map of the PG which is approximately 900km in the east-west and 300(km) in the north-south, [47-57]^{0}E, [24-30]^{0}N.
The analyses are based on the CTD data (temperature, salinity and density as a function of water depth) for winter and summer1992. Using temperature, salinity and density data we have made transects of their fields along the PG axis for winter and summer.

Fig.2 shows contours of depth variations. Apart from the Strait of Hormuz region where the exchange flow occurs all the time and a small region near the head of the PG in which the river inflow creates stratification, there is almost no vertical stratification in the water column and it appears to be uniform in density. As it could be seen in winter most of the northern part of the PG becomes vertically mixed, with maximum density and highest salinity off the Saudi coast. This dense water finds its way to deeper levels in the stratified areas towards the entrance of the PG (this has also been seen by Brewer et al., 1978).

However in summer time the thermocline is well established and extends well into the PG. The main reasons for the formation of the thermocline in summer are strong solar heating and more importantly the diminishing northwesterly winds which are very strong in winter time. During summer the layer below the thermocline is similar in character to the deep water in winter. Above the thermocline the temperature in summer is also much higher. Summer thermocline creates strong stratification near the surface leading to a strong barrier against the vertical exchanges between the surface water and deeper regions. In such a situation the environment is prone to formation of internal waves due to different factors tidal flow over bottom topography, flow around the island and wind disturbances near the surface. Internal waves can break (with fastest growing disturbance for wave number K~0.85/h, where h is the shear zone thickness in the thermocline, (Woods, 1968), for Richardson number less than its critical value of 0.25). Breaking of internal waves is the only mechanism in the strongly stratified fluid with no substantial vertical shear as in the ocean thermocline that can lead to mixing. The strong temperature gradient under surface layer well inside the PG in summer represents the existence and formation of seasonal thermocline inside the PG.

Existence of the Arvand River in northwestern part of the PG helps in vertical gradient of temperature and especially salinity and hence stratification. Of course internal waves could occur in whole of the PG water in summer because of thermocline formation in this season. As it could be seen in the variations of temperature with depth it is not considerable through the water column in winter while a negative gradient with depth takes place under surface layer in summer, representing summer thermocline formation; so seasonal thermocline could be formed in whole of the PG during summer. According to the temperature diagrams, variation of T with depth represent marked vertical gradients in temperature in summer but due to waves activities and eddying motions in the PG it almost disappears in winter. On the whole based on these profiles there are three regions in the PG (Fig.1), one is the northern head in which one observes mainly vertical salinity gradients (e. g. stations 105 and 109) due to river in flow during the year, the middle of the PG in which we see winter uniformity and summer strong thermocline (e. g. stations 52, 80) and the region near the strait of Hormuz (e. g. station 16) which have a rather permanent vertical salinity gradient due to the exchange flow. The depth of thermocline as represented by the depth of a selected isotherm or density surface is a measure of the amount of upper-layer water present at a location. If variations of thermocline are related to variations in sea surface temperature, fluctuations in upper-layer volume can be monitored continuously by sea surface temperature (Niiler and Stevenson, 1982). Thermocline formation in summer despite in winter could be resulted in deep zone of the PG paying attention to the Fig. 3.

Near the surface formations of the thermocline in summer in the whole of the PG is also marked. Development of thermocline from winter to summer is a process that depends on some climatic factors such as evaporation, wind and solar radiation which seem to be important in this semi enclosed seas. Variability in time series of temperature represents thermocline variations in deep zone of the PG, as (Liu et al., 2001) mentioned that seasonal variations in time series of temperature show the spatial and thermal variability of thermocline. The main question is how fast this thermocline is developed and the lack of observation does not let us find this, hence using an analysis with proper surface boundary forcing as buoyancy flux may help answer this. After averaging temperatures, densities and salinities of the stations in deep zone of the PG in summer, when thermocline forms, profiles of these three parameters are as in the Fig. 4.

Result and Discussion

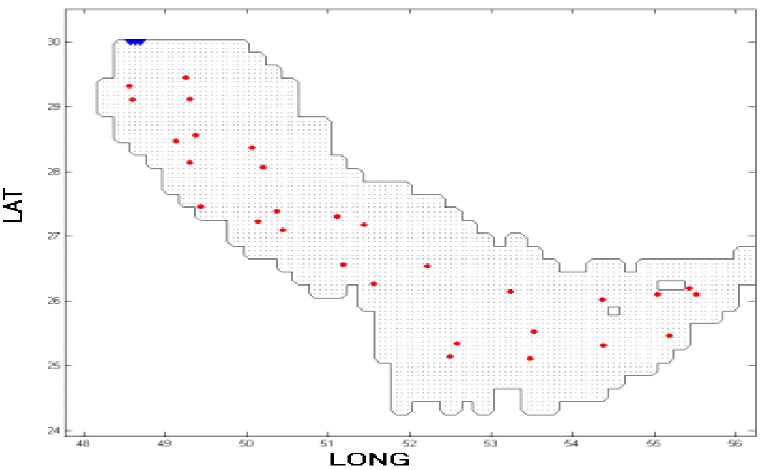


Fig.1 A Map of the PG and ROPME measurement stations in 1992

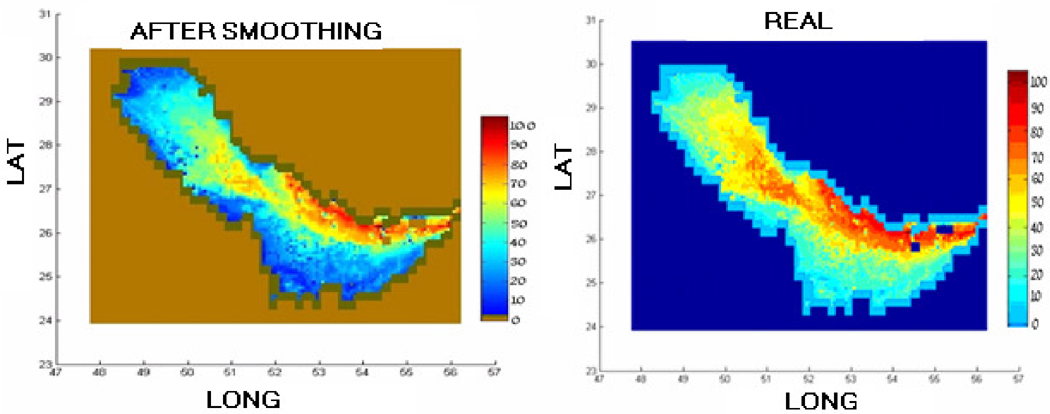


Fig.2 Depth variations through bottom of the Persian Gulf in real and smoothes states,1992

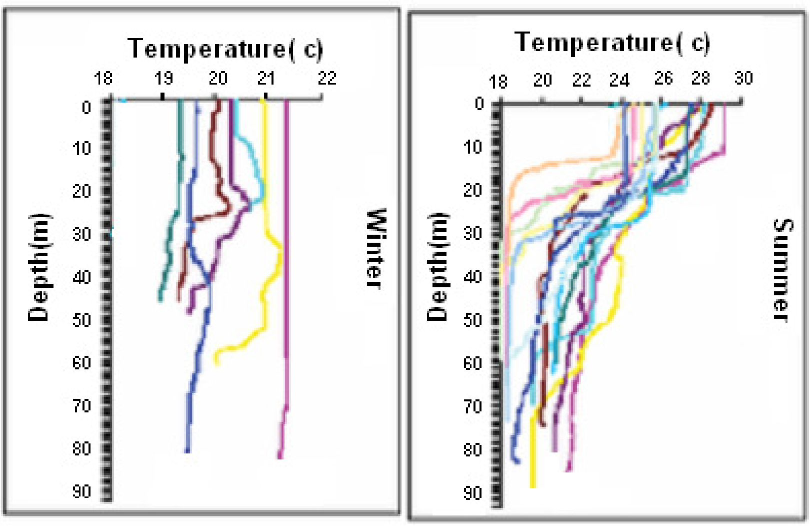


Fig. 3 Temperature profiles in stations located in central part (Deep zone) of the PG in summer and winter 1992

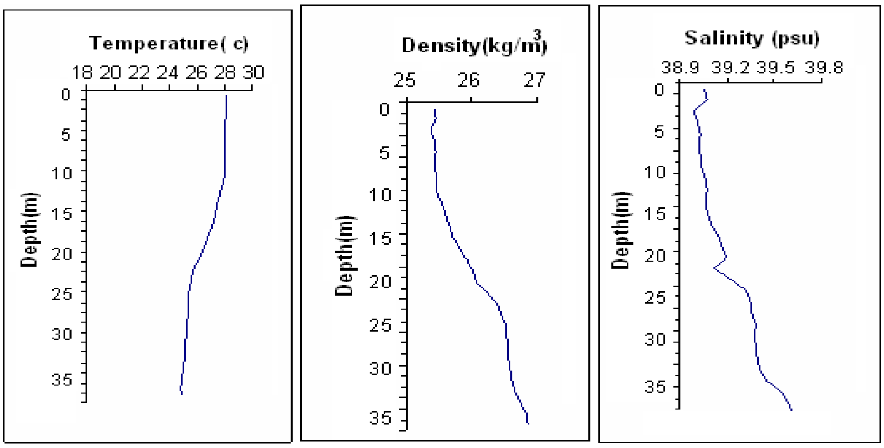
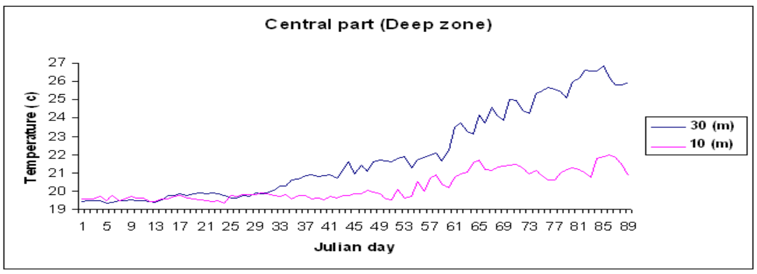
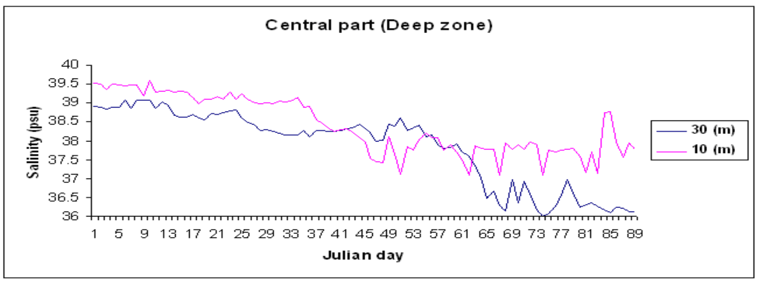


Fig.4 Profiles of mean temperature, density, salinity in central part (Deep zone) of the PG





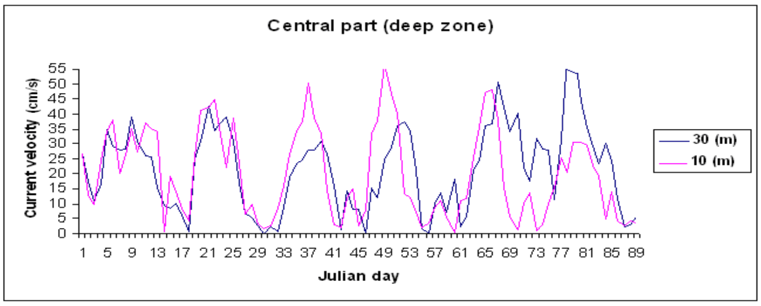


Fig. 5 Time series of daily temperature, salinity and current at (26.22, 53.45) during March to May 1992. Measurements from a mounted CTD in depth of 94 (m)

[dominant current velocity component, in direction of −x]

According to the above figure mean thermocline in this zone of the PG forms in depth of 10(m) to 20(m). Fig.5 shows time series of temperature, salinity and current velocity in deep zone of the PG during Mar-May when thermocline develops in the PG.

The observations of T and S in the PG show that in winter time due to strong northwesterly wind the water is highly mixed, particularly in northern part as vertically mixed PG in winter is expressed in (Brewer et al., 1978). As the summer approaches and surface winds weaken over the PG and stronger solar radiation helps establish a thermocline all over this semi-enclosed sea, as mentioned in (Reynolds, 1993), uniform warming across the PG throughout spring and summer coincides with the development of a steep seasonal thermocline in the PG and this is particularly important for summer as thermocline is well developed in most parts of the PG and; Stephen and Bower (2002) attribute the temperature increase to solar heating rather than to influx of warm surface water from the Gulf of Oman. It is indicated by (Reynolds, 1993) that the strength of summer stratification is evident at the PG surface. As we do not have data to bridge the gap between the two seasons, we have conducted a series of numerical experiments using an analysis to see how the thermocline develops during the transition period from winter to summer. The analysis simulation using observed evaporation, solar radiation, Arvand river inflow and current from the Oman Sea to the PG indicates that summer thermocline can form and that is influenced by westerly winds. The analysis was set up by the initial winter data, and surface atmospheric and radiative forcing were applied using meteorological data. Two cases of constant surface northwesterly fixed wind and variable monthly averaged wind were tried for these experiments while other forcing was held the same. The seasonal thermocline development is influenced by wind and evaporation in the PG.

Conclusion

The analysis results show that the thermocline starts to develop with slow rate but intensify at the beginning of the summer. This is the case for monthly averaged wind and the maximum vertical temperature gradient occurs in July. The results also show that the development of the thermocline in the deeper central part is gradual but in the northern part it occurs rather quickly and it intensifies without the depth change. Also we can say that the analysis studies suggest that the atmosphere forcing plays an essential part of the thermocline evolution in the PG as a shallow water and thermocline variations are predominantly forced by wind stress.

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