

Remote sensing of the marine mixed layer

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Mixed layer depth (MLD) has been estimated from Geosat derived sea level alone in the equatorial Indian Ocean with an accuracy of 16 m. Since parameters like net heat gain at the ocean surface, wind speed, sea level etc. also dominantly affect the changes in MLD, the effectiveness of these parameters are examined. The incorporation of net heat gain in the multiple regression model did not improve the MLD estimation significantly. MLD in Arabian Sea and Bay of Bengal has been estimated from Geosat sea level and ECMWF analysed wind fields with an accuracy of 20 m.

Major factors affecting mixed layer depth (MLD) are wind, surface energy balance and the heat advection. MLD cannot be measured directly; it has to be estimated from the parameters affecting MLD. There are mainly two approaches for the MLD estimation: (i) modelling, both physical and statistical, and (ii) estimation from vertical profiles of oceanic properties viz., temperature, salinity and density. Physical models have not been very successful due to lack of understanding of physics of the upper ocean. However, there is a continued effort going on to understand the dynamics and thermodynamics of this layer. Krauss & Turner¹ developed a mixed layer model which explains qualitatively the annual cycle of the build up and destruction of seasonal thermocline. Time dependent behaviour of the upper mixed layer of the ocean in response to varying meteorological inputs of time scales from one to several days has been investigated by Denman². In principle any of the oceanic conservative parameter can be used to define MLD. Due to relatively more number of observations, temperature profiles are generally used to estimate MLD. Various methods exist to estimate this parameter from temperature profiles. Some of the approaches are to find the depth where temperature is (a) 28°C, (b) 28.5°C, (c) 1°C less than that at the surface, (d) 1°C less than at 10 m depth, (e) gradient method³. In this study a gradient value of 0.08°C/m is used.

Synoptic and repeated estimation of MLD by conventional methods is hindered by the limited *in situ* observations either by ship or data buoys. In general the MLD in the Indian Ocean ranges from 20 to 150 m and the depth interval generally provided to the users in this range is 25 m. The MLD estimated by any one of the extrapolation methods described above could be inaccurate by at least 12.5 m.

Estimating the MLD through remote sensing is possible only by finding relation between MLD and the surface parameters which either affect MLD or affected by changes in mixed layer thermodynamics. The surface parameters which can be remotely sensed and are useful in estimating MLD are sea surface winds, sea surface temperature (SST) through net heat gain/loss and sea level. Sea surface winds affect MLD through turbulent mixing and are not affected by changes in MLD, whereas both SST and sea level affect MLD besides themselves getting affected by it. Changes in net heat gain/loss at the ocean surface results in SST variations. The net heat gain/loss affects MLD and hence SST leads and affects the MLD in this case. On the other hand, SST is affected by changes in MLD because of the heat transfer into the mixed layer.

Similarly, when the mixed layer temperature changes due to advection of heat, the effect is seen in the sea level due to changes in its volume. On

the contrary if the water level changes due to the wind action, sea level leads the phenomenon and results in the changes in MLD due to hydrostatic pressure balance. For example, in the Equatorial Indian Ocean (EIO), south westerly wind drives the surface water towards east, piling up along the coast of Sumatra⁶. The upward sloping of the ocean surface from west to east leads to depression of the MLD towards east and lifting up towards west due to upwelling (Ekman transport) in this region⁶⁻⁹.

Methodology

Data used in present study are Geosat sea level, ECMWF (European centre for medium range weather forecasting) analysed wind fields, TOGA temperature profiles and TOGA heat budget parameters. ECMWF data are at 2.5° grids. Temperature profiles are taken as per the available observations. The study area is equatorial Indian Ocean, Arabian Sea and Bay of Bengal (5° to 25°; 45° to 100° E). Study period is from 1985-89.

In the EIO, sea level and MLD are related following the equation:

$$\Delta H = \Delta h \times p / \Delta p$$

where, ΔH is change in MLD, Δh is change in sea level, p is density of mixed layer, and Δp is change in the density of mixed layer and thermocline. MLD has been computed following the gradient method³ using temperature profiles. Regional and seasonal regression coefficients have been developed between the Geosat sea level and MLD since we do not have the factor for $p/\Delta p$. Using these coefficients, MLD has been computed on monthly basis in a grid size of 10°×2° (latitude x longitude).

Over Arabian Sea and Bay of Bengal, MLD has been computed from sea level and wind speed using statistical regression method in a grid size of 2.5°×2.5° latitude x longitude.

Results and Discussion

In EIO, MLD has been estimated with an accuracy of 16 m. In Fig. 1 MLD calculated from temperature profiles and altimeter sea surface height values are put together along the whole equatorial belt for three months April, July and December 1987 in order to infer the seasonal effect

on vertical motion of MLD. In April (Fig. 1a) variation of MLD computed from sea level along the whole belt is small with a range of 40-65 m. This is because April is a non-monsoonal month and relatively calm winds prevail over the ocean surface along the equator. Except at a few places,

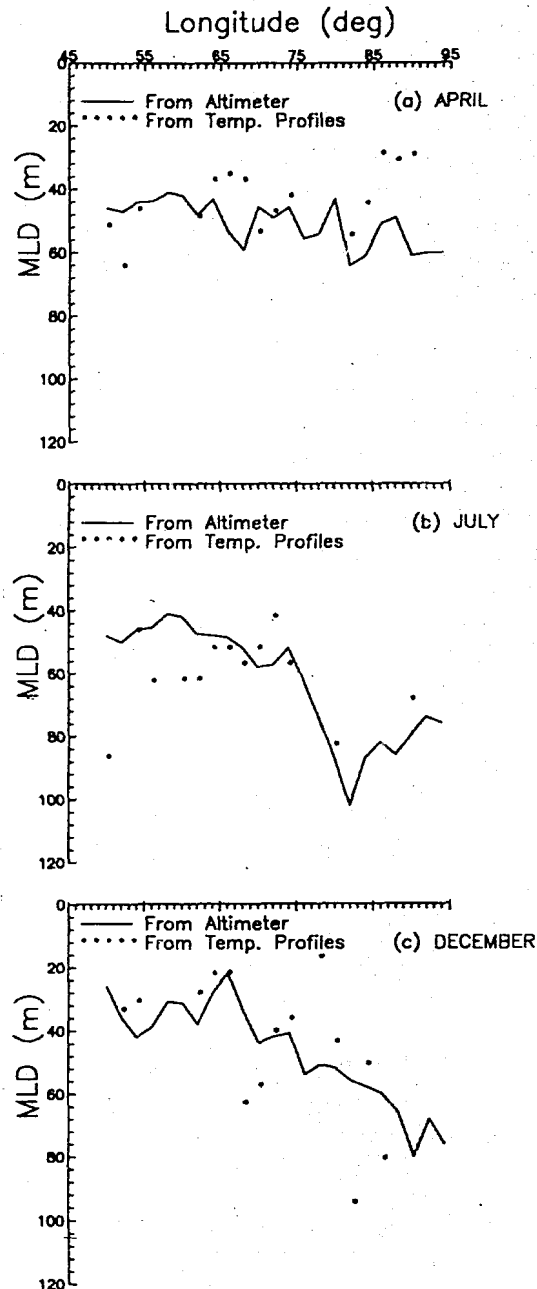


Fig. 1—MLD from Geosat SSH observations and from temperature profiles: a) April 1987, b) July 1987 and c) December 1987

MLD obtained from two sources agree well with each other. In July (Fig. 1b), a large zonal variation is seen in vertical extent of MLD having the range of 40 m to 110 m. The overall lowering of MLD towards east is due to upslope of sea level from west to east due to the south west monsoon winds driving the surface water eastward^{3,7}. Again the MLDs from two sources show a close agreement except at 50°E where a large deviation in MLD is seen. This probably is due to instrumental error in temperature profiles. In December 1987 (Fig. 1c), the overall down sloping of mixed layer depth is maintained from west to east, although the maximum depth has decreased to 80 m in comparison to July (Fig. 1b) where it was 110 m. This reduction in MLD is largely due to lower wind stress over the ocean surface.

Unlike in the EIO, MLD in the Arabian Sea and Bay of Bengal is not affected by sea level alone. Hence an attempt has been made to estimate MLD using wind speed, sea level and net heat at the ocean surface¹⁰. Various combinations have been tried using simple regression model. The multiple regression coefficients obtained by different parameters are given in Table 1. Among the three parameters studied, net heat gain correlates least with MLD and wind speed the most. No significant improvement is obtained by including net heat

gain at the ocean surface in the multiple correlations. Hence MLD has been computed from 1985 to 1988 using ECMWF analysed wind field and Geosat sea level observations. Figure 2 shows the variations in MLD for July from 1985 to 1989 as a sample case. MLD is high near the Somali region in all years because of the strong Somali jet. The pattern near this region matches with the eddy structure. Besides, the over all pattern matches with the climatological distribution of Rao *et al.*¹¹. A clear contrast is seen in the distribution of MLD between the good (1988) and the bad (1987) monsoon years. MLD in Arabian Sea ranges from 62-82 m during 1987 while it varies from 70-92 m during 1988. Accuracy in the estimation of MLD could not be improved because of (i) limitation of the depth intervals in the temperature profiles

Table 1—Multiple correlations between MLD and surface parameters

Parameters	Standard error	Correlation coeff.
Wind speed, sea level and net heat	20.43	0.43
Wind speed and sea level	20.42	0.43
Wind speed and net heat	21.4	0.31
Sea level and net heat	21.43	0.32
Wind speed	21.24	0.32
Sea level	22.02	0.22
Net heat	22.19	0.18

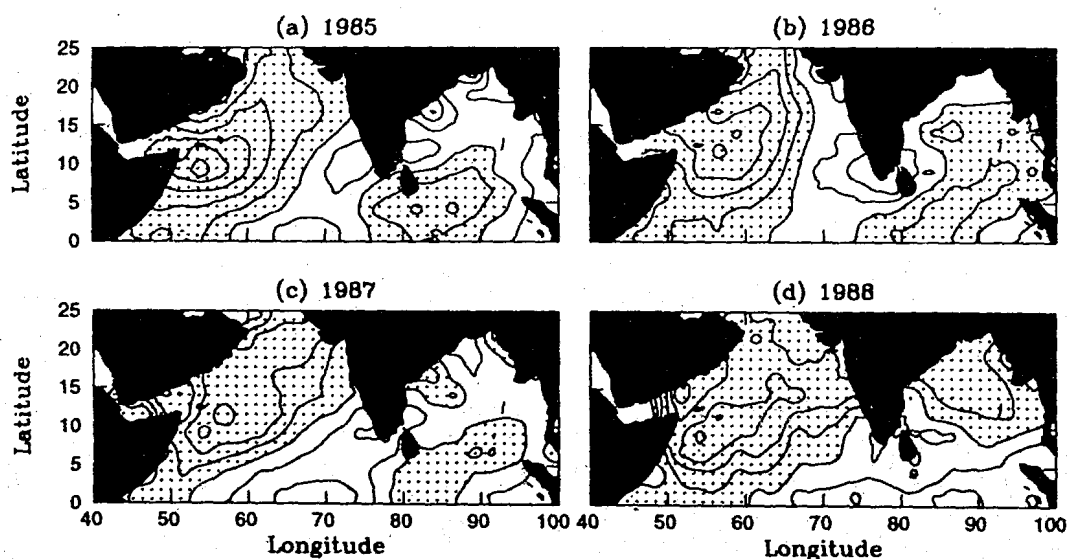


Fig. 2—Mixed layer depth variations over the north Indian Ocean during July for a) 1985, b) 1986, c) 1987 and d) 1988. The contour interval is 5 m and the values greater than 60 m are shaded

(ii) inaccuracy in the Geosat altimeter observations and (iii) non inclusion of the heat advection in the regression model.

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