MAHASAGAR
Vol.26, No.2 (December), 1993, pp. 87-93.

MIXED LAYER DEPTH OF THE NORTH INDIAN OCEAN DURING MAY AND SEPTEMBER

V. SIMHADRI NAIDU
National Remote Sensing Agency, Hyderabad - 500 037

ABSTRACT

Using a one-dimensional model, Mixed Layer Depth (MLD) is simulated for the north Indian Ocean during May and September. The results are verified with the observed values. Surface meteorological and subsurface data were collected from NODC and IDWRs for 1970-1977 period. The model results indicate that its performance in May is somewhat better in the central Arabian Sea and eastern Bay of Bengal. Excess values are simulated in the western Arabian Sea and central equatorial region. The excess values along the western Arabian Sea are due to coastal upwelling which is not accounted for in the model. In September, the model underestimated the MLD over the western Arabian Sea, whereas it highly overestimates off the west coast of India. The eastward transport of colder surface waters from the extreme western Arabian Sea may be responsible for the low simulated values over the western and central Arabian Sea. In this month, excess values are diagnosed over southern Bay of Bengal. This is the region of net heat loss and negative Ekman Pumping Velocity (EPV). Both these forces augment the mixed layer development. In the absence of EPV term in the model, low MLD should have been simulated. In contrast higher values are found. This shows the deviations in MLD are due to relatively higher values of net heat loss.

Key-words: Mixed layer depth, Indian Ocean, one dimensional model.

INTRODUCTION

A study on the variability of Mixed Layer Depth (MLD) of the north Indian Ocean during May and September, a pre and post-monsoonal warming months, assumes special significance, since it is believed that during this period upper ocean thermal structure of the region contributes significantly to the ocean dynamics (Wyrtki, 1971). In this investigation, an attempt has been made to present the distribution of diagnosed MLD of north Indian Ocean during May and September based on one-dimensional model utilising all available surface marine meteorological data from 1970 to 1977. This study has also attempted to verify the simulated results with observed values obtained from hydrographic data.

DATA AND METHODS

Surface meteorological and subsurface data of the north Indian Ocean during study period for 8 years (1970-1977) were extracted from Indian Daily Weather Reports (IDWRs) and National Oceanographic Data Centre (NODC), Washington DC, USA. Basic parameters that were extracted from the combined data set (NODC

& IDWRs) are wind speed, wind direction, cloud amount, air temperature, dew point temperature and sea surface temperature (SST). In addition to this, associated time and space parameters such as year, month, hour, latitude, and longitude were also extracted. Monthly mean value of each parameter was calculated at each 2^{o} x 2^{o} quadrangular grid. Duplicate records were deleted from the data set, if time and space parameters are same. MLD was calculated using MBT and XBT data supplied by NODC. In the present study, MLD was taken as depth at which temperature is less by 1^{o}C from the sea surface (Wyrtki, 1971; Colborn, 1976). MLD was calculated from each individual profile.

The incoming (Q_s) and outgoing (Q_b) radiative fluxes were computed from the formulae adopted by Hsiung, 1986. Latent heat (Q_e), Sensible heat (Q_h) and momentum (τ) fluxes were calculated from the well known bulk aero-dynamic formulation. Turbulent exchange coefficients for heat and water vapour were taken from the table of Bunker, 1976. The transfer coefficient for momentum was calculated from polynomial given by Hellerman and Rosenstien (1983).

Net heat flux (Q_{net}) was calculated from the formula

$$Q_{net} = Q_s - Q_b - Q_e - Q_h \qquad \ldots 1$$

Here Q_{net}, Q_s, Q_b, Q_e, Q_h are in W m^{-2} and τ is in dyne cm^{-2}.

The Model

MLD (h) was approximated diagnostically from the model (Kraus and Turner, 1967).

$$2\,(G_* - D_*) - \rho_o g \alpha h\,(Q_{net}/\rho_o c_p) - (Q_s/\rho_o c_p)\,\pi\,(\nu h) = 0 \qquad \ldots 2$$

where ν, c_p, ρ_o and α are solar extinction coefficient (0.06 m^{-1}), specific heat (4.019 W kg^{-1}), density (1026 kg m^{-3}) and thermal expansion coefficient (2.1 x 10^{-4} K^{-1}) of sea water respectively and g is the acceleration due to gravity (9.8 m s^{-2}). The solar penetrating function $\pi\,(\nu h)$ is given by

$$\pi(\nu h) = (2/\nu h)\,(1 - e^{-\nu h}) - e^{-\nu h} \qquad \ldots 3$$

It is assumed that ν is a constant and no light penetrates into thermocline. G_* and D_* are the respective rates at which mixed layer is kinematically energized and dissipated. In the above model it is considered that heat is accumulated in the topmost layer of the ocean through absorption of solar radiation. This accumulated heat is redistributed through free (convective) and forced (wind) mixing. The temperature changes associated with the frictional dissipation were neglected. However, this term cannot be neglected. In the absence of dissipation excess values of MLD are simulated (Alexander and Kim, 1976). Incorporating the effect, Kim (1976) has suggested the following formula

$$G_* - D_* = \eta\rho_o \left(\frac{\tau}{\rho_o}\right)^{3/2} - \rho_o \varepsilon_m h \qquad \text{if } Q_{net} > 0 \ldots \text{ 4a}$$

$$= \eta\rho_o \left(\frac{\tau}{\rho_o}\right)^{3/2} - \rho_o \varepsilon_m h + \frac{0.85}{2}\frac{\alpha g}{c_p} Q_{net}\, h \qquad \text{if } Q_{net} < 0 \ldots \text{ 4b}$$

where ε_m is background dissipation (2×10^{-8} m^{-2} sec^{-3}) and η is a dimensionless constant (1.25). The constant 0.85 and the value of v were taken from the study of Shetye (1986). MLD at each grid was simulated using bisection iterative scheme.

RESULTS AND DISCUSSIONS

Since the model is forced by heat and momentum fluxes, it is appropriate to present the distributions of incoming solar radiation (Q_s), net surface heat gain (Q_{net}) and momentum fluxes (τ). Onset of southwest monsoon begins in late May over the north Indian Ocean. The monsoon is at its peak in July and retreats in September. Incoming solar radiation in May and September (Figs. 1a & 2a) mostly decreases toward southeast or east from western boundaries of the Arabian Sea and the Bay of Bengal as these western regions are cloud free zones.

In case of net surface heat flux, during May, the Arabian Sea is the region of prominent heat gain, whereas net heat loss is observed in the southern Bay of Bengal (Fig. 1b). Maximum heat gain (120 W m^{-2}) is noticed off the Arabian coast. The larger positive heat flux on the western side of the Arabian Sea is the result of stronger solar heating which is caused by lower cloudiness associated with cooler SST (Hastenrath and Lamb, 1979) and reduced evaporation. In September, low values of heat gain are observed over the western Arabian Sea as compared to the values observed in May (Fig. 2b). Net heat loss is observed in the central and equatorial Bay of Bengal. The heat budget estimates in this study are 10% higher than the estimates of Hastenrath and Lamb (1979) and they are in agreement with the estimates of Hsiung (1986), since the formulation used in this study and that of Hsiung are same.

Momentum flux is comparatively less prominent during May and September as compared to those observed at the peak of monsoon in July (Naidu, 1989). In these two months wind stress decreases from west to east in the Arabian Sea (Figs. 1c & 2c). With the onset of summer monsoon strong southwest winds blow over the western Arabian Sea, where it is overlain by low level jet (Hastenrath and Lamb, 1979). Under this influence, western Indian Ocean experiences higher wind stress as compared to the other parts of the ocean. In the Bay of Bengal, larger values are noticed in the central region.

In May, shallow mixed layer is observed (Fig. 3a) over the north Indian Ocean as compared to other monsoonal months of June through September (Naidu and Rao, 1990). This shallow nature of mixed layer is due to the influence of summer heating and low wind stress on the surface waters. In this month, mixed layer is maximum in the equatorial region and decreases northward. The maximum value observed in this region is lower by 20 m when compared with earlier reports (Rao, Molinari and Festa, 1989), where MLD was obtained from MOODS data set (1948 to 1981). However, overall pattern is same. From the model results, it is noticed that the model performance is somewhat better in the central Arabian Sea and the eastern Bay of Bengal (Figs. 3b & 3c). However, the model highly overestimates the MLD by about 20 m in the region between 70°E - 90°E, 10°N - Equator. In addition, the model simulates excess values (15 m) of Arabia coast. During this month, wind stress is maximum at this region. As the wind stress is directly proportional to mixed layer depth in the

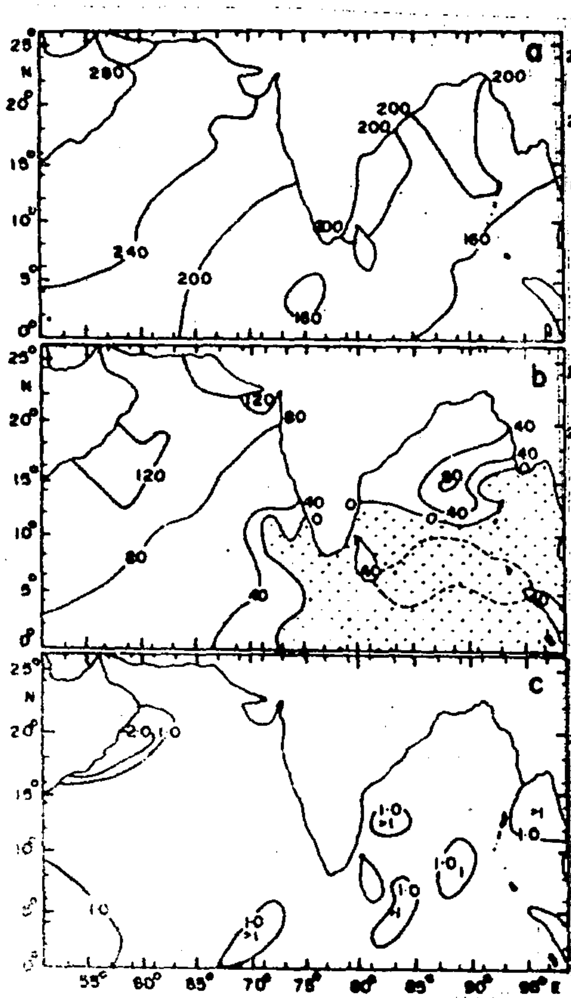

Fig. 1. Surface fluxes – Incoming solar radiation in W m^{-2} (a), Net heat flux in W m^{-2} (b) and Momentum flux in dyn cm^{-2} (c) – of the north Indian Ocean during May.

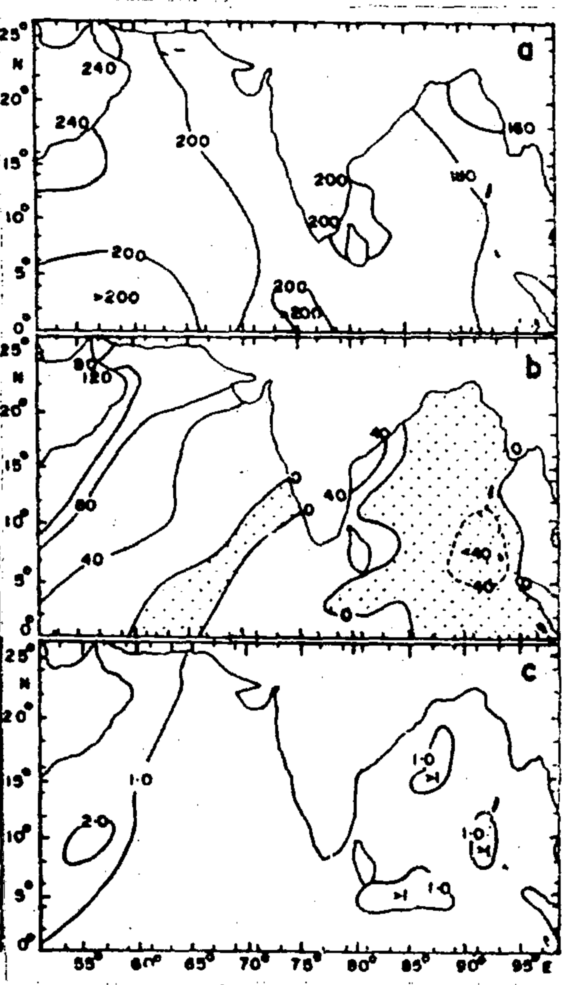

Fig. 2. Surface fluxes – Incoming solar radiation in W m^{-2} (a), Net heat flux in W m^{-2} (b) and Momentum flux in dyn cm^{-2} (c) – of the north Indian Ocean during September.

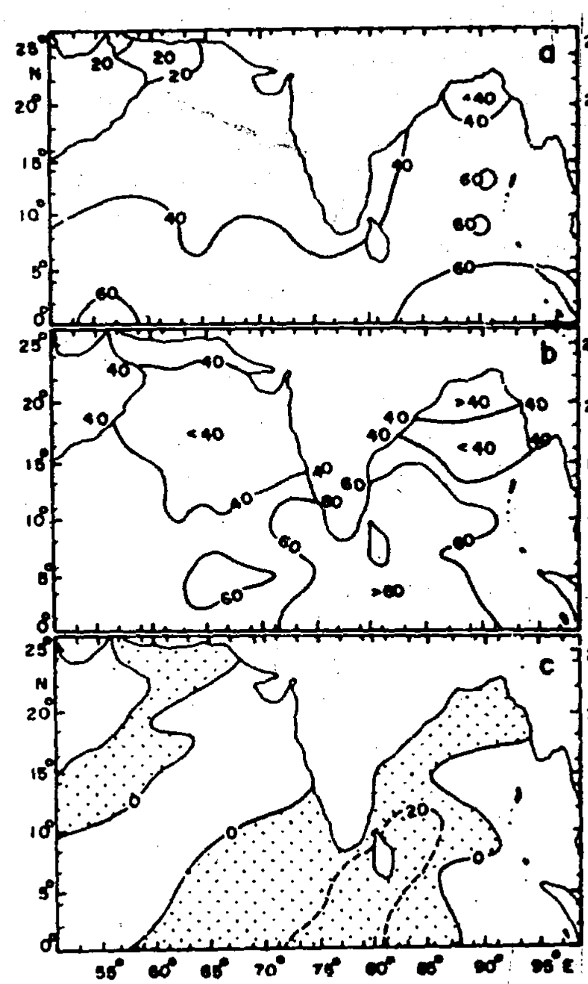

Fig. 3. Observed (a), Simulated (b) and Observed - Simulated (c) MLD of north Indian Ocean during May.

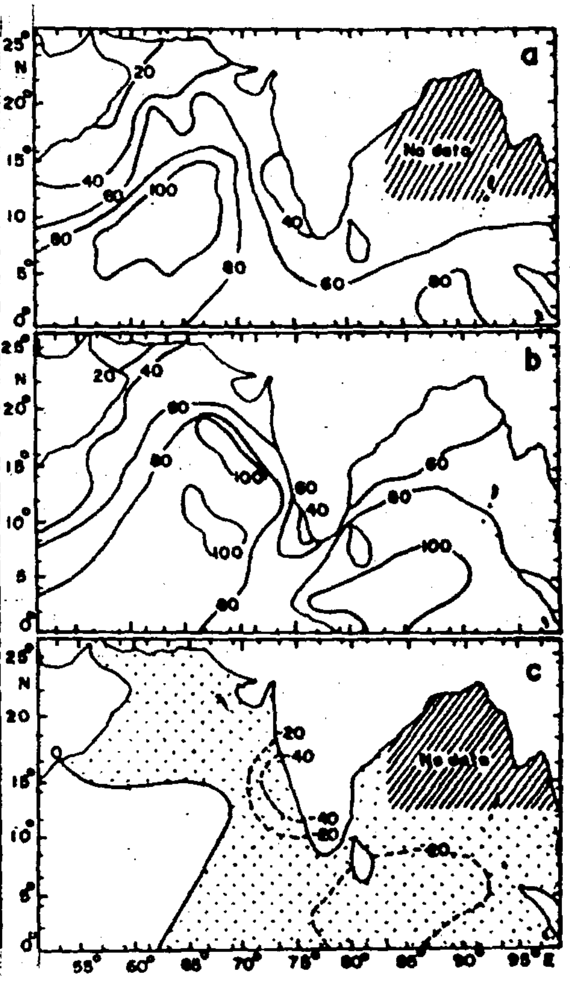

Fig. 4. Observed (a), Simulated (b) and Observed - Simulated (c) MLD of north Indian Ocean during September.

model, deep mixed layer is diagnosed. On the other hand, the wind stress over this region produces coastal upwelling, which, in turn, causes the shallow mixed layer. This coastal upwelling is not accounted for in the model. As a result, excess values are found in this region. In this month, RMS deviation between observed and simulated MLD is found to be $\pm$ 11.5 metres.

In September, observed mixed layer is maximum in the central Arabian Sea and this layer shallows radially. In the Bay of Bengal, deep layer is observed at the Equator (Fig. 4a). The maximum value observed in the central Arabian Sea is 20 m higher than the earlier reports. The model simulated excess values in September as compared to May. The RMS deviation between observed and simulated values is $\pm$ 19.0 m. The model simulated maximum values in the central Arabian Sea and the Equatorial Bay of Bengal (Figs. 4b & 4c). The model results in the central Arabian Sea are more or less in agreement with the observed depths. However, the model highly overestimates (>40 m) along the west coast of India. Excess values (>20 m) are also found along the equatorial Bay of Bengal. The model slightly underestimates (5 m) the MLD in the western Arabian Sea. In September, cold surface waters from the western Arabian Sea transport horizontally towards east (Shetye, 1986). This horizontal advection of surface currents may affect the model results. Maximum negative Ekman Pumping Velocity (EPV) is noticed in the southern Bay of Bengal (Naidu and Rao, 1990 and Murthy, Sarma, Rao and Murthy, 1992). Due to the effect of negative EPV, thermocline is pushed downward. Since this vertical velocity is not incorporated, the model should have predicted smaller values than those observed in that region. In contrast, the model simulated excess values. This discrepancy between the model simulations and the observations may be due to high net heat loss. In this study, bulk estimates are higher by about 10% than that of Hastenrath and Lamb (1979). Hence, when bulk estimations are higher, under the influence of the third term in eqn. 4b which ensures loss of potential energy when surface is cooled, the model gives higher values of MLD. Moreover, the extinction coefficient, ν, also affects the MLD results because, ν varies between 0.03 m^{-1} in clear open oceanic waters and 0.3 m^{-1} in turbid coastal waters (Ivanof, 1977). For the increase of 0.05 m^{-1} in ν, simulated MLDs decrease by nearly 20-40 metres (Alexander and Kim, 1976). Therefore, this ν should be selected in such a manner that it has higher value in the coastal waters and lower value in the open ocean. Spatial variations of ν and fluxes estimated from the remote sensors may improve the model results as having large spatial and temporal coverage.

ACKNOWLEDGEMENTS

The author is grateful to Prof. G.R. Lakshmana Rao for encouragement. Thanks are due to Dr. E.C. LaFond for providing NODC data set.

REFERENCES

Alexander, R.C. and J.W. Kim, 1976. Diagnostic model study of mixed layer depths in the summer north Pacific. *Journal of Physical Oceanography*, 6: 293-298.

Bunker, A.F., 1976. Computations of surface energy flux and annual air sea interaction cycles of North Atlantic Ocean. *Monthly Weather Review*, 4: 1122-1139.

Colborn, J.G., 1976. The thermal structure of the Indian Ocean. *International Indian Ocean Expedition, Oceanographic Monographs No. 2.* The University of Hawaii, Honololu, Hawaii, 173 pp.

Hastenrath, S. and P.J. Lamb, 1979. *Climatic Atlas of the Indian Ocean – Part II.* Oceanic Heat Budget, University of Wisconsin Press, Madison.

Hellerman, S. and M. Rosenstein, 1983. Normal monthly wind stress over the world ocean with error estimates. *Journal of Physical Oceanography*, **13**: 1093-1104.

Hsiung, J., 1986. Mean surface energy fluxes over the global ocean. *Journal of Geophysical Research*, **91**: 10585- 10606.

Ivanoff, A., 1977. *Modelling and Prediction of the Upper Layers of the Ocean*, edited by E.B. Kraus, Pergamon Press, New York, 47 pp.

Kim, J.W., 1976. A generalized bulk model of the oceanic mixed layer. *Journal of Physical Oceanography*, **6**: 686-695.

Kraus, E.B. and J. Turner, 1967. A one dimensional model of the seasonal thermocline - Part II. The general theory and its consequences. *Tellus*, **19**: 98-136.

Murthy, V.S.N., Y.V.B. Sarma, D.P. Rao and C.S. Murthy, 1992. Water characteristics, mixing and circulation in the Bay of Bengal during southwest monsoon. *Journal of Marine Research*, **50**: 207-228.

Naidu, V.S., 1989. Some studies on the surface mixed layer of the north Indian Ocean during south west monsoon. *Ph.D. Thesis*, Andhra University, Waltair, India.

Naidu, V.S. and G.R.L. Rao, 1990. Ekman Pumping Velocity and depth of surface mixed layer of the north Indian Ocean during southwest monsoon. *Indian Journal of Marine Sciences*, **19**: 257-260.

Rao, R.R., R.L. Molinari and J.F. Festa, 1989. Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean. 1. Description of mean monthly mixed layer depth, and sea surface temperature, surface currents and surface meteorological fields. *Journal of Geophysical Research*, **94**: 10801-11815.

Shetye, S.R., 1986. A model study of the seasonal cycle of the Arabian Sea surface temperature. *Journal of Marine Research*, **44**: 521-542.

Wyrtki, K.L., 1971. *Oceanographic Atlas of the International Indian Ocean Expedition*, National Science Foundation, US Government Printing Office, Washington DC.