Study of the mixed layer depth variations within the north Indian Ocean using a 1-D model

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[1] Mixed layer depth (MLD) over the north Indian Ocean (30°S to 30°N and 40°E to 110°E) is computed using the simple one-dimensional model of *Price et al.* [1986] forced by satellite-derived parameters (winds and chlorophyll). Seasonal chlorophyll observations obtained from the Coastal Zone Color Scanner allow us to examine how biology interacts with physics in the upper ocean by changing the absorption of light and thus the heating by penetrative solar radiation, an effect we refer to as biological heating. Our analysis focus mainly on two aspects: the importance of varying biology in the model simulations relative to runs with constant biology and secondly, the contribution of biology to the seasonal variability of the MLD. The model results are compared with observations from a surface mooring deployed for 1 year (October 1994 to October 1995) in the central Arabian Sea and also with available conductivity-temperature-depth (CTD) observations from the Arabian Sea during the period 1994–1995. The effect of biological heating on the upper ocean thermal structure in central Arabian Sea is found to be greatest in August. In other months it is either the wind, which is the controlling factor in mixed layer variations, or the density variations due to winter cooling and internal dynamics. A large number of CTD observations collected under the Joint Global Ocean Flux study and World Ocean Circulation Experiment have been used to validate model results. We find an overall improvement by approximately 2–3 m in root-mean-square error in MLD estimates when seasonally varying chlorophyll observations are used in the model. *INDEX TERMS:* 4572 Oceanography: Physical: Upper ocean processes; 4255 Oceanography: General: Numerical modeling; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; *KEYWORDS:* biological heating, ERS scatterometer wind, extinction depth, 1-D mixed layer model, mixed layer depth variations

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1. Introduction

[2] The Oceanic mixed layer is the quasi-homogeneous region of the upper ocean, where the physical properties like density, salinity, and temperature are nearly vertically uniform. The dynamics of the mixed layer and consequently its depth are known to be influenced by surface heat flux, horizontal and vertical advection, and vertical turbulent mixing due to wind. As a consequence, MLD varies on several temporal scales; diurnal, intraseasonal, and seasonal [*Fischer*, 1997, 2000; *Weller and Farmer*, 1992; *McCreary et al.*, 2001]. The depth of the mixed layer (MLD) has significant importance in the field of acoustic propagation [*Sutton et al.*, 1993], in biology [*Fasham*, 1995], and in understanding air-sea interactions involving air-sea heat, buoyancy, and momentum exchange [*Chen et al.*, 1994]. To this end, numerous attempts have been made to study the oceanic surface layer using either depth-integrated bulk models or differential models. These models derive their theoretical foundation from *Mellor and Yamada* [1974] for differential models and from *Kraus and Turner* [1967] for bulk models. Each model type has advantages and disadvantages in terms of realistically simulating the vertical profile and computing time requirements.

[3] The transfer of mass and energy across the sea surface, and solar heating in particular, strongly influence the temperature stratification in the upper layers of the ocean. This stratification, in turn, affects the mixed layer dynamics by influencing layer thickness. SST prediction in one-dimensional (1-D) mixed layer models has been shown to be sensitive to the parameterization of the solar extinction with depth [*Kantha and Clayson*, 1994]. Hence it is well acknowledged that chlorophyll concentration has an

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immense impact on the local heating in the upper layers of ocean through the absorption of solar radiation [*Ivanov*, 1977; *Simpson and Dickey*, 1981a, 1981b; *Simonot et al.*, 1988; *Lewis et al.*, 1990; *Large et al.*, 1994; *Morel and Antoine*, 1994]. *Sathyendaranath et al.* [1991] found a significant biological impact on the sea surface temperature (SST) of the Arabian Sea using a model in which SST and vertical temperature gradient at the base of MLD was assumed to be known at the start of each month. They found the additional contribution of increased absorption due to living organisms, which we here refer to as biological heating, to be 4°C per month in this region. *Frouin et al.* [2000] found that on a global and annual scale, SST is increased by 0.04°C due to the biological modulation of short-wave radiation absorption. *Lewis et al.* [1990] argued that SST overestimation in a western Pacific Ocean General Circulation Model (OGCM) might be attributed to ocean transparency. *Rochford et al.* [2001] studied the importance of subsurface heating on surface mixed layer properties in an OGCM that included the attenuation of solar irradiance with depth. *Nakamoto et al.* [2000] investigated the modulation of SST due to biological heating in the Arabian Sea using an OGCM forced with Coastal Zone Color Scanner (CZCS) data. Recently, *Murtugudde et al.* [2002] also studied the effects of penetrative radiation on the upper ocean using OGCM and CZCS derived attenuation depths.

[4] Complementing these OGCM studies that necessarily have coarse vertical resolution, this paper seeks to examine the potential impact of biological heating on how the upper ocean responds to "local atmospheric forcing" using a series of 1-D simulations at high vertical resolution within the region 30°S to 30°N and 40°E to 110°E. The simulations provide the means for us to exploit ocean color data available from satellites. The most artful part of the model employed in this study [*Price et al.*, 1986] is that it allows for mixing in the stratified fluid below the mixed layer and gives quite realistic profile structures. The model application is presented in section 2, while details of the data processing, validation of ERS winds, and different criteria used for estimating MLD from in situ profiles are described in sections 3, 4, and 5. Model runs with different water type classifications carried out using CZCS chlorophyll data and ERS winds are discussed in section 6. Simulated MLDs are compared with conductivity-temperature-depth (CTD) observations and also with 1-year (October 1994 to October 1995) of measurements from a surface mooring in the northern Arabian Sea. Results are summarized in section 7.

2. Model

[5] A 2-year simulation with a 1-D mixed layer model including biology is used to study the mixed layer variability in the Indian Ocean. The model, mixing parameterizations, and implementation is illustrated in detail by *Price et al.* [1986]. A few notable features are described here in brief. The diurnal cycle of the variables (velocity and temperature) is derived in response to vertical wind mixing and radiation process driven by the local surface fluxes of heat and momentum [*Niiler and Kraus*, 1977]. The conservation equations of heat, salt, and momentum are prescribed in their 1-D forms.

[6] The forcings are solar flux (I), evaporation minus precipitation (E), and wind stress (τ), whose surface values are presumed to be known. The vertical profiles of I, E, and τ are to be determined. The heat loss is presumed to leave directly from the sea surface, while solar insolation is absorbed within the water column with double exponential depth dependence. Various input parameters required by the model are the air-sea heat flux positive downward, peak solar radiation of the day, and the wind speed.

[7] The 1-D equations implicitly assume horizontal homogeneity, since they predict the horizontal velocity at the single point but ignore the implications of the velocity in advecting horizontal property gradients. The terms that are missing from a full (hydrostatic and Boussinesq) oceanic evolution equation are turbulent flux terms (horizontal), momentum forces due to horizontal pressure gradients, and horizontal and vertical advection of momentum, heat, and salt. *Rao and Sivakumar* [2000], using the climatological data sets, ascertain that over much of the tropical oceans, local surface heat fluxes overwhelm horizontal advection in the seasonal evolution of the mixed layer temperature. *Lee et al.* [2000] examined climatology and found that local surface forcing appeared to have a much stronger role than Ekman pumping on influencing the MLD.

[8] Temporally and spatially variable extinction depths were used in out simulations. The penetrative solar flux is expressed as

$$I(z) = I(0)\left(I_1 \exp\left(\frac{-z}{\lambda_1}\right) + I_2 \exp\left(\frac{-z}{\lambda_2}\right)\right). \qquad (1)$$

Subscripts 1 and 2 refer to the red and blue-green components of the penetrating insolation, and z is positive downward with z = 0 being the sea surface. In the above equation, I_1, I_2, λ_1, and λ_2 are biologically dependent attenuation parameters. The following parameters are typical of water type IA (open ocean) of *Jerlov* [1968] water classification:

$$I_1 = 0.62 \qquad \lambda_1 = 0.6 \text{ m}$$

$$I_2 = 1 - 0.62 \qquad \lambda_2 = 20 \text{ m}.$$

About half of the solar insolation incident on the ocean surface is absorbed within the uppermost meter of the water column. The remaining short-wave radiation, principally the blue-green light, is absorbed with the attenuation scale of 20 m. In the present analysis, the attenuation scale corresponding to blue-green light is derived from the CZCS seasonal climatological data following *Parsons et al.* [1984],

$$\lambda_2 = 0.04 + 0.0088 \text{ chl} + 0.0054 \text{ chl}^{2/3},$$

where chl is the chlorophyll pigment concentration. Other parameters I_1, I_2, and λ_1 in our simulations are taken from *Jerlov*'s [1968] look-up table.

[9] At each time step, the model calculates the density profile from a linear state equation taking into account the temperature and salinity profile,

$$\rho = \rho_0 + \alpha(T - T_0) + \beta(S - S_0), \quad (2)$$

where, in this case, ρ_0 = 1.025 × 10^3 Kg m^{-3}, T_0 is the SST, $\alpha = -0.23$ Kg m^{-3}°C^{-1}, S_0 is the sea surface salinity value, and $\beta = 0.76$ Kg $m^{-3}ppt^{-1}$.

[10] The solar cycle is modeled as follows:

$$I_i = I_{\max} \times \cos\left(\frac{2\pi t}{\text{pqfac}}\right),$$

where t is time and I_i is the solar radiation at the ocean surface at a particular time. It was set to zero for the negative value occurrence. Here *pqfac* is the duration of sunshine hours for a given day of model run, and $I_{\max}$ is the peak solar radiation or maximum noon radiation. Vertical mixing occurs in this model in order to satisfy several stability criteria, which requires that

$$\frac{\partial \rho}{\partial z} \geq 0 \quad (3)$$

for static stability,

$$R_b = \frac{g\Delta\rho h}{\rho_0(\Delta V)^2} \geq 0.65 \quad (4)$$

for mixed layer stability, and

$$R_g = \frac{g\partial\rho/\partial z}{\rho_0(\partial V/\partial z)^2} \geq 0.25 \quad (5)$$

for shear flow stability.

[11] In the mixed-layer criterion (equation (4)), h is the mixed layer depth, and ΔV ($\Delta\rho$) takes the difference between the mixed layer velocity (density) and that of level just beneath. The first condition (equation (3)) models convection; the second (equation (4)), a condition for mixed layer stability, is meant to emulate the entrainment process. These two conditions create a slab-like mixed layer with a sharp discontinuity at its base. The last condition for shear-flow stability introduces mixing at the above jump at the mixed layer base. This creates a transition layer beneath the mixed layer connecting it to the oceanic interior. The model has no mechanism for driving flow or internal mixing below this transition layer.

[12] For the present study, the model was run on a vertical grid with 1-m resolution with a time step of 15 min. The model was initialized with a linear interpolation of climatological *Levitus* [1982] profiles (temperature/salinity). It was forced with satellite-derived daily winds and seasonal chlorophyll data. The daily winds were linearly interpolated to the 15-min time step of the model. The values of attenuation depth derived from seasonal chlorophyll observations were kept the same at each time step for a particular season. Monthly net heat flux at the ocean surface was taken from climatological data sets. MLD at each time step was obtained from model computed density profiles as the depth where the density was greater than the surface value by 0.125 kg m^{-3} [*Levitus*, 1982]. Finally, we averaged these MLD estimates to get monthly mean values for the analysis.

3. Data Description and Processing

[13] The study period (1994–1995) was primarily chosen due to availability of continuous observations from a surface mooring in the central Arabian Sea. *Goswami and Sengupta* [2003] found that mean as well as intraseasonal variability in the National Centers for Environmental Prediction (NCEP) reanalysis surface winds are underestimated in the equatorial Indian Ocean. Hence we used satellite scatterometer wind to force the model. Surface meteorological and air-sea flux and subsurface oceanographic observations for 1 year (October 1994 to October 1995) from a surface mooring deployed by Woods Hole Oceanographic Institution [*Weller et al.*, 1998] at 15.5°N, 61.5°E in the Arabian Sea were used in this study. Data from Joint Global Ocean Flux Study (JGOFS) and World Ocean Circulation Experiment (WOCE) program in the Northern Indian Ocean (NIO) have also been used. The track wind data of the ERS scatterometer winds were used to generate daily fields. The daily data had many gaps, which were filled in two steps: first by performing a 3-day running average and then, in the second stage, by filling the residual gaps by an inverse interpolation technique. Seasonal chlorophyll data (averaged over the period 30 October 1978 to 30 June 1986) derived from the CZCS were used to account for variable biology in the present study. Monthly climatological data of heat loss and peak solar radiation at the ocean surface were taken from Comprehensive Ocean-Atmosphere Data Set [*Da Silva et al.*, 1994].

4. Validation of ERS Scatterometer Winds

[14] To examine how well ERS wind speeds replicate the actual winds, we made comparisons with the surface mooring observations in the Arabian Sea (15.5°N and 61.5°E). The ERS winds are given at a standard height, 10 m, whereas the buoy data is at 3 m height from the sea surface. Using a logarithmic approach following *Mears et al.* [2001], the data buoy measurements were first converted to 10-m neutral stability wind speeds. Figure 1 shows the daily time series of these two wind products from October 1994 through October 1995. The wind speeds range from 1 to 17 m s^{-1} over the period of comparison. During the southwest monsoon season (June 1995 through August 1995), when the winds are quite strong, the ERS winds are quite close to the observed winds. The root-mean-square difference between the two series is 1.68 m s^{-1}, and the correlation is 0.88. However, there are some isolated peaks in both the series. However, overall the ERS wind speeds are close to the observations. Wind stress (computed from the ERS winds) was also compared with the surface mooring data over the same time (figure not shown). ERS derived wind

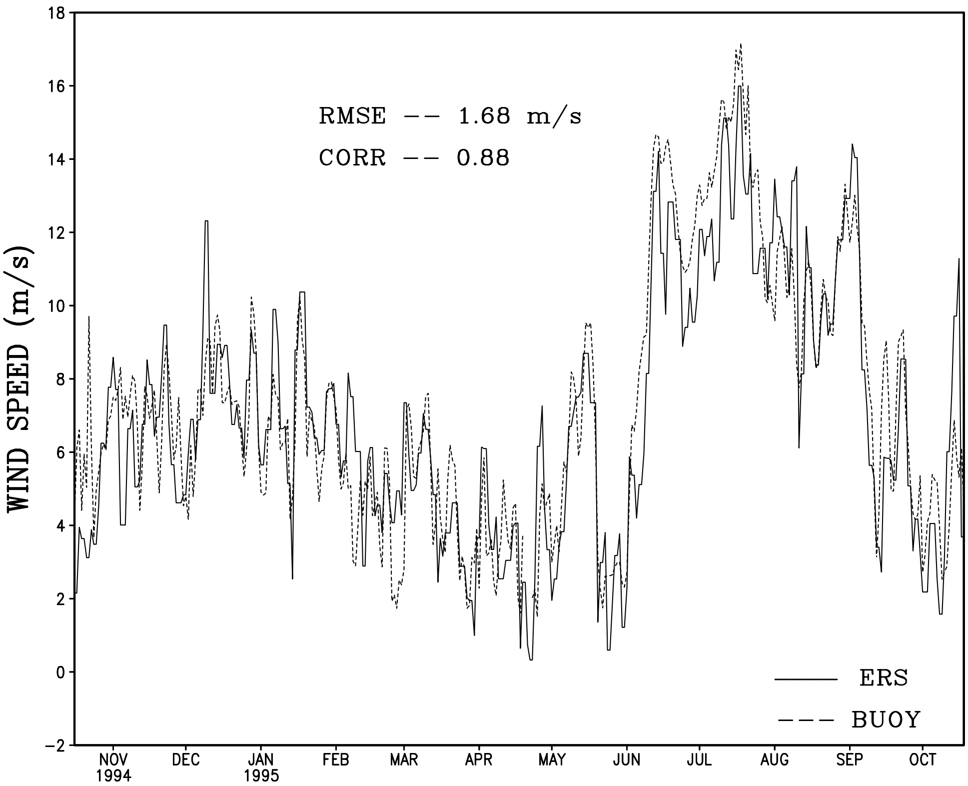

Figure 1. Time series of the daily averaged ERS scatterometer wind speed (dashed line) and observed daily averaged wind speed (solid line) at the mooring site (15.5°N and 61.5°E).

stress compared well with that of the buoy observations. The correlation between the two series was found to be 0.89.

5. Estimation of MLD From Vertical Profiles (Temperature and Density)

[15] The MLD criteria used by researchers vary widely. Various schemes based on fixed temperature gradient [*Ali and Sharma*, 1994], fixed density difference [*Levitus*, 1982], statistical significance criterion of *Bathen* [1972], and fixed temperature difference [*Monterey and Levitus*, 1997] have been utilized in the past. *Sprintall and Tomczak* [1992] pointed out that the temperature criterion for MLD estimation ignores salinity effects, which can lead to errors of typically 10–20 m. Recently, *Kara et al.* [2003] made a detailed study of the temperature and density criterion used for defining the surface mixed layer of the world ocean. In regions like Bay of Bengal, where due to the fresh water influx, the stratification is high, the two criteria may lead to quite different values. Hence it is necessary to compare the different MLD criteria. However, the lack of adequate CTD data on longer timescales hampers study in Bay of Bengal. In the future, profiling ARGO floats (see http://www.argo.ucsd.edu/whatisargo.html) will provide salinity as well as temperature profiles and make significant improvements to data availability. Here we compute MLD from both temperature and density profiles in order to assess the differences. The approach is different than the one adopted by *Kara et al.* [2003]. We considered the Levitus criteria for computing MLD with density profiles. For this purpose, subsurface profiles from the Woods Hole Oceanographic Institution (WHOI) mooring in the central Arabian Sea were used.

[16] MLD computed from density (Levitus criteria) and temperature (0.1°C from water temperature at the surface) profiles for the yearlong observations are shown in Figure 2. MLD computed from the two criteria match well over a large part of the mooring record. The average difference between the two MLDs is about 14 m. During 15 February to 15 March, the two estimates show large differences. In this period, MLD (computed using density criteria) fluctuations were also too large. This was a period of intense heating, leading to enhanced stratification, and shallow MLDs, which are represented well by the temperature criteria. However, MLDs computed with the density criteria show some isolated large values. It is known that salinity variations are generally not large in this region, and when we looked at the salinity data from this period, no abnormal pattern in its distribution was noted. This indicates that differences in the MLD estimates, computed using the two criteria, are derived from the different values selected as thresholds for determining MLD from temperature and density profiles. One point worth noting is that almost throughout the period, MLD is slightly deeper using density criteria than the temperature one. However, the results remain qualitatively the same regardless of the particular criterion used; that is, the time series patterns of mixed layer properties are equivalent. However, the differences between the two MLD series vary from 4 to 80 m (differences are large during February–March, the reason for which has already been explained). This certainly cannot be consid-

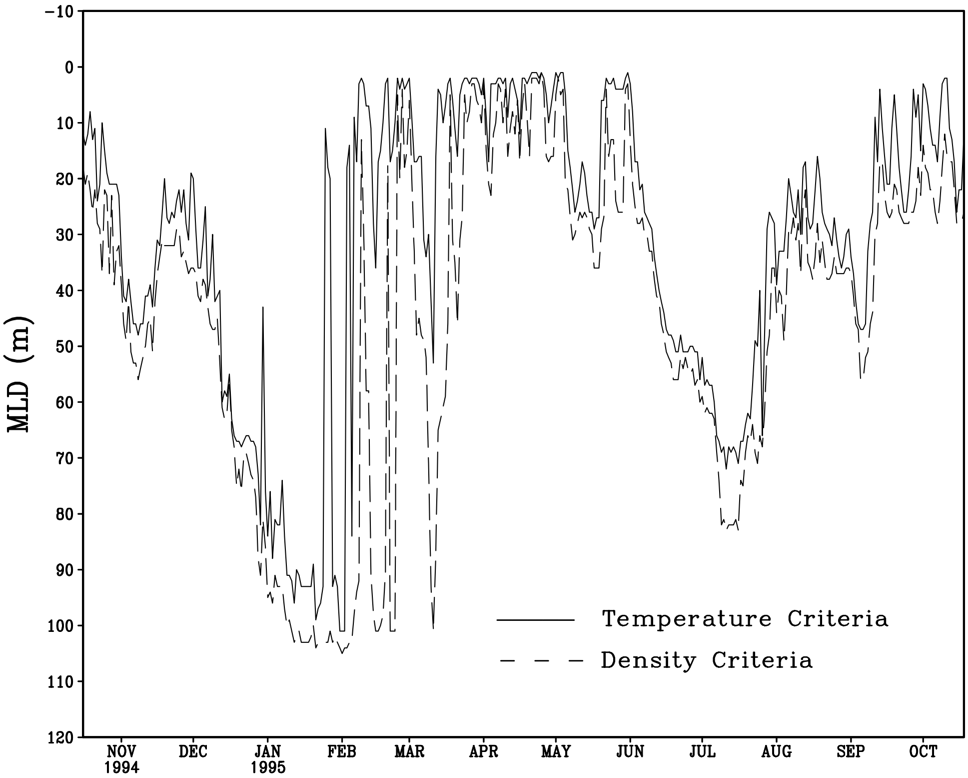

Figure 2. Time series of MLD (meters) computed with density (dashed line) and temperature (solid line) criteria at the data buoy location in central Arabian Sea.

ered to be statistically insignificant. Hence one should be cautious in using the temperature criteria to define MLD.

6. Analysis of the Model Simulations

[17] The model was run for a period of 2 years (1994–1995), and the density profiles obtained were diagnosed to quantify MLD variability. For the same period, the model was also run without including variability in biological heating, i.e., with constant extinction depths of 0.6 m and 20 m for the red and blue-green components, respectively, as typical of clear water. In each of the 1-m layers, change in heat was computed from the vertical mixing of heat between adjacent layers as well as the solar radiation profile. At each time step (900 s), solar radiation is absorbed according to equation (1) and the heat loss and fresh water flux are extracted from the surface. The density profile is then computed and adjusted to achieve static stability, if required. From these profiles, using the density criterion (mentioned in the previous section), MLD is obtained. We will denote MLD with constant biology by MLD_{cb}, that with variable biology by MLD_{wb} and the in situ (based on ocean observations) MLD by MLD_{insitu}.

6.1. Comparison of Simulations With In Situ Observations

[18] During 1994–1995, a large (∼700) number of CTD observations were collected as part of JGOFS experiment in the Arabian Sea and also by the WOCE program. Model results are validated with these observations. There is a definite improvement by including biology in to the model. The root-mean-square error (RMSE) reduced from 17 to 14.9 m. The scatter between MLD simulated using variable biology and MLD from in situ profiles is shown in Figure 3. The coefficient of determination (R^2) is about 0.66.

6.2. Evolution of MLD in the Central Arabian Sea

[19] Figure 4 shows an annual evolution of simulated MLDs (with and without biological heating) and the observed MLD at the mooring location. We also show the

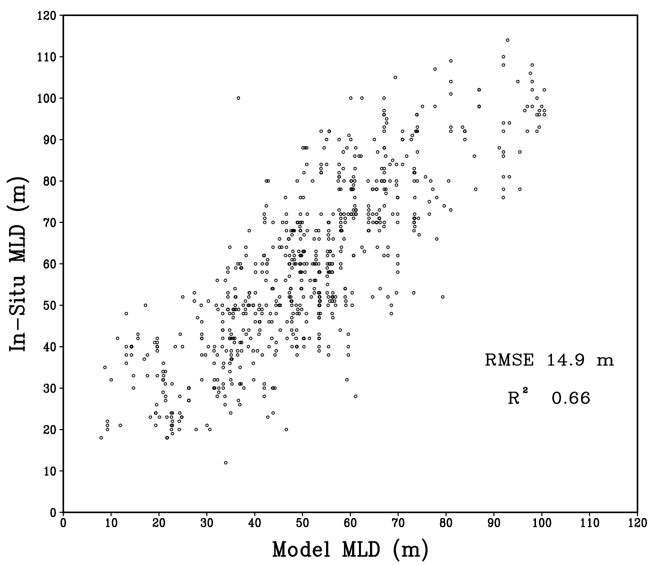

Figure 3. Scatterplot of MLD simulated with variable biology versus observed MLD from CTD observations.

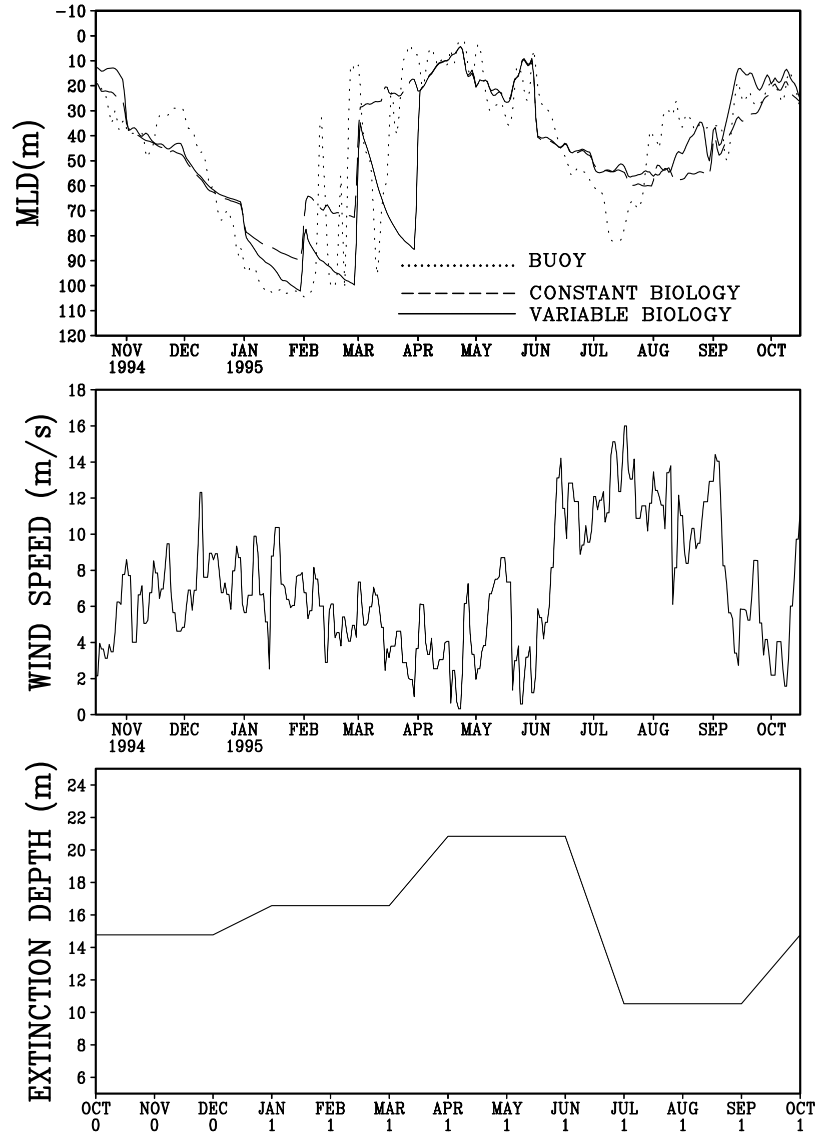

Figure 4. (a) Annual changes of MLD at the central Arabian Sea (15.5°N and 61.5°E) simulated from model with constant (dashed line) and varying biology (solid line), and MLD from in situ observations (dotted line). Time series of (b) wind (m s^{-1}) and (c) extinction depth (meters).

time series of extinction depth derived from the CZCS chlorophyll maps and wind speed in the same figure. The reason for plotting these two parameters is to see the relative importance of biological heating and wind speed on MLD. MLD clearly shows a semi-annual oscillation: (1) one maxima during January–March due to convective mixing because of winter cooling [*Shetye*, 1986; *Rao and Mathew*, 1990; *Rao and Sivakumar*, 1998], where there is not much effect of wind and biological heating, and (2) a second maxima during July and August, where there is competitive effect of high winds and high chlorophyll abundance. The extinction depth is very small (12 m) during July and August, due to high chlorophyll content. This is in agreement with the earlier finding by *Sathyendranath et al.* [1991]. In the Arabian Sea, chlorophyll concentration peaks in August (3 mg m^{-3}) due to the summer plankton bloom induced by coastal upwelling. A higher abundance of chlorophyll increases the absorption of solar radiation and heating rate in the upper ocean, resulting in decreasing the mixed layer thickness. Although the pigment concentration is high during July, the MLD is deep; this is due to the high wind speed leading to higher turbulence and increased MLD. However, during August, due to a drop in wind speed, the effect of biological heating overcomes the wind mixing effect, which leads to shallow MLDs. Here, MLD_{wb} values are very close to MLD_{insitu}, whereas the same is not brought out in MLD_{cb}. In the month of March, there is a large discrepancy between simulations (constant and variable biology) and observed MLD. A sudden deepening in the MLD occurred around mid-March in the observations. MLD_{wb} becomes deeper, but toward the end of the month, whereas MLD_{cb} remains shallow throughout March. This lag of around 15 days in the simulated MLD with variable biology is definitely not due to the chlorophyll effect. Also, the mooring data demonstrated that this was not a period of strong advection. It may be that heat flux has

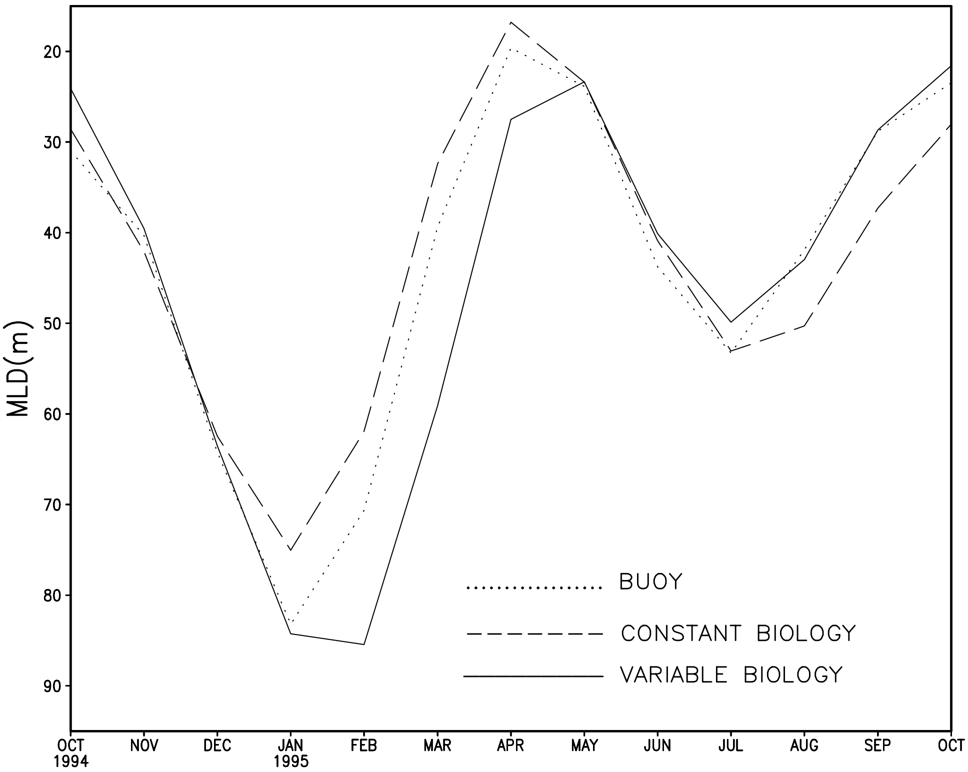

Figure 5. Monthly averaged mixed layer depth at the central Arabian Sea (15.5°N and 61.5°E) simulated from model with constant and varying biology. Also shown is the MLD from in situ observations.

a role to play here; however, the reason for this lag is not clear. Overall, there was a reduction in the RMSE from about 15 to 12 m in MLD at the buoy location after the inclusion of the seasonal chlorophyll data in the model run.

[20] Since seasonal mean chlorophyll data were used to model the effect of biological heating, it was thought appropriate to compare simulated MLDs with observed values on a monthly averaged basis. Figure 5 shows the time series of monthly averaged MLD_{insitu}, MLD_{cb}, and MLD_{wb}. As it can be seen, the maximum impact of biological heating is observed during August and September, and overall, there is a definite improvement in the model-simulated MLD when variable biology is used. The next section extends the study to the entire tropical Indian Ocean by examining the differences in the two simulations (MLD_{cb} and MLD_{wb}).

6.3. Seasonal Variations of the Differences of MLDs Simulated With Constant and Variable Biology

[21] In the previous section it was shown that at the WHOI data buoy location, MLD_{wb} is closer to MLD_{insitu} than MLD_{cb}. For this reason, it will be appropriate to investigate the temporal and spatial characteristics of the difference between the two MLD estimates in detail. In Figure 6, we present the difference between the two MLDs for 4 months (January, May, August, and November of 1994) representative of the winter, pre-monsoon, monsoon, and post-monsoon seasons. The most obvious characteristic is that the difference is less than 10 m at most of the places in tropical Indian Ocean. However, an exception to this is the Arabian Sea, where a large difference in the two estimates is seen. The differences are seasonally varying, being largest in August. During this season, the estimates differ by as much as 40 m in the central Arabian Sea and also near Somalia. In May also, the two simulated MLDs in the central Arabian Sea show large difference (>10 m). This implies that the impact of biological heating is quite significant in the Arabian Sea. In contrast, relatively small differences are obtained for the Bay of Bengal. Probably other processes, in particular fresh water discharge, control the MLD in this region more than the heating due to chlorophyll.

7. Summary

[22] In this paper an attempt has been made to study the impact of biological heating on mixed layer depth variations in the tropical Indian Ocean. The 1-D model, which simulates the response to local atmospheric forcing, is an excellent tool for evaluating the potential impact of biological heating on the upper ocean. A detailed analysis of 1-D simulations, which was forced with satellite-derived winds and chlorophyll data, has been carried out. The annual evolution of the mixed layer (e.g., at the mooring location in the Arabian Sea) has been simulated fairly well by the model. It is interesting to observe the competitive effect of the two parameters (winds and chlorophyll) on the model simulations. The maximum effect of biological heating on the surface mixed layer is found to be in the central Arabian Sea during August. Even though the winds are high during August, the mixed layer is shallow (~20–30 m). This is because of the enhanced stratification due to the chlorophyll

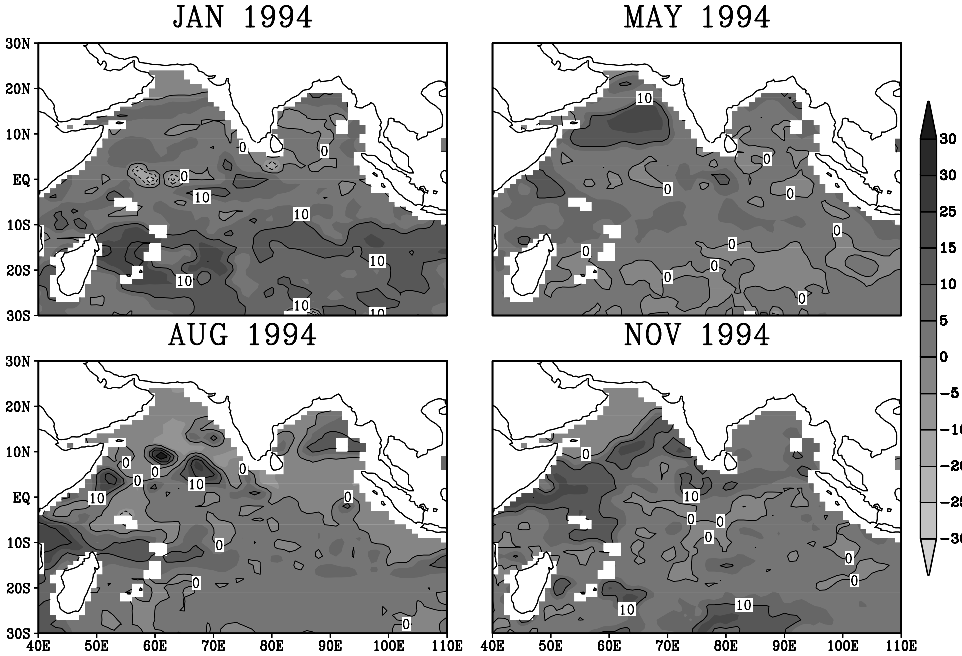

Figure 6. Distribution of difference of the two MLDs (simulated using constant and varying biology) over the study area during January, May, August, and November of 1994.

heating. At most of the places in the tropical Indian Ocean, the impact of biological heating on mixed layer depth variations is less than 10 m in all the seasons. This is the broad picture of the impact of biological heating on mixed layer depth variations that we could infer from our simulations, albeit, the model has an inherent lack of simulating the physics of advection. We do believe that the uncertainties in the model simulation may arise due to lack of advection, but our aim here has been to study the seasonal variations in the mixed layer depth under the effect of constant and variable biology, with the model being forced with satellite winds. This will also give us confidence in the usage of such winds in the forcing model, which has been found to be quite a realistic one, when compared with the buoy observations. Another learning experience with this study has been in defining the mixed layer depth using temperature and density criteria. The correspondence between the two depths was found to vary at large during February–March 1995. Because of these differences, care is warranted in selecting the criteria to be used for estimating the depth of mixed layer from in situ profiles. Finally, one of our purposes was to make use of yearlong buoy data to understand the local processes controlling the mixed layer depth variability. It should be kept in mind that limitations still exist as far as understanding the role of advection in controlling the MLD variations is concerned.

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