CHAPTER V
CHAPTER V

PREDICTIVE CHARACTERISTICS OF THE MIXED LAYER DEPTH

On account of the relevance of mixed layer depth (MLD) to applications in fisheries, naval warfare and planetary boundary layer modelling, it is pertinent to evolve techniques of forecasting MLD from easily observable data such as, wind and air/sea temperatures. A number of one dimensional models have been developed to give time dependent estimates of the surface mixed layer depth using parameterisation of surface fluxes of heat, momentum (wind stress) and buoyancy. The model developed by Kraus and Turner (1967) does not take into account horizontal motion (advection) and assumes that kinetic energy is generated at surface, a constant fraction of which is used for entrainment across the interface below the mixed layer. Their expression for potential energy does not take into account frictional dissipation. Giesler and Kraus (1969), Denman (1973), Niiler (1975) and Kim (1976) have developed variants of Kraus-Turner model. Niiler (1975) showed that turbulent kinetic energy (considered earlier by Denman (1973)) dominated the energy generated by the mean shear which was taken into account by Pollard et al. (1975) for mixing a day or more. Gill and Turner (1974) pointed out that the convective release of turbulent energy is essential in addition to the energy generated by wind stress. Kim (1976) generalised the Kraus-Turner model to include both wind generated and convective release of turbulent energy.
isolating non-penetrative and penetrative convection depending upon the magnitude of surface cooling. These models failed to predict the features of the thermocline and also the variation of MLD above it, over longer periods. This shortcoming arises out of ignoring advection effects in the models.

A simple one dimensional scheme is evolved incorporating methods of Laevastu and Hubert (1965) and James (1966) to give short term prediction of the MLD in deeper and shallow zones where advection effects can be assumed negligible. Earlier evaluation of this model using data from coastal waters off Cochin (Joseph, 1980) indicated that for short term predictions up to 6-10 hrs the error between the predicted and observed values of MLD was small and within the variability of diurnal and semidiurnal internal oscillations in the sea, even though advection effect had not been considered. In the present study, this scheme is evaluated for predicting MLD at the deep water station 51 (10°30' N, 66°E and 2000 m depth) and at the shallow water station 52 (10°15' N, 75°48' E and 200 m depth). In the first case 3 hourly BT and salinity data along with the meteorological data collected on board R.V. PRILIV from 7 to 19 June 1977 (92 observations) during Monsoon-77 programme, are utilised. In the second case BT and salinity data along with meteorological data (near-hourly) collected on board M.V. PRASIKSHANI on 19 January 1983 are utilised.
5.1 Description of the scheme

In a slab (continuous density model) of sea water, the change in temperature in the slab is effected mainly through the top surface of the mixed layer. Considering the lateral heat advection to be negligible, heat budget at the surface can be written as,

\[ Q_N = \left( Q_s - Q_r - Q_b - Q_e - Q_h \right) \] \hspace{1cm} \text{(5.1)}

where

- \( Q_N \) : the net heat gain at the surface
- \( Q_s \) : incoming solar and sky radiation
- \( Q_r \) : reflected radiation at the surface
- \( Q_b \) : back radiation (long wave)
- \( Q_e \) : evaporative/condensation heat transfer
- \( Q_h \) : sensible heat transfer.

The incoming solar and sky radiation is evaluated following Lumb (1964),

\[ Q_0 = 1.93 \sin \alpha (0.61 + 0.2 \sin \alpha) \] \hspace{1cm} \text{(5.2)}

where

- \( Q_0 \) : clear sky radiation in cal cm\(^{-2}\) min\(^{-1}\)
- \( \alpha \) : solar altitude in degrees.

A correction introduced by Reed (1977) is applied to obtain an equation for insolation for cloudy sky.

\[ Q_s = Q_0 (1 - 0.62 C + 0.0019 \alpha) \] \hspace{1cm} \text{(5.3)}

where

- \( Q_s \) : insolation under cloudy conditions in cal cm\(^{-2}\) min\(^{-1}\)
- \( C \) : cloud cover in tenths
- \( \alpha \) : noon solar altitude in degrees.
It appears appropriate to use the above formula suggested for higher values of cloudiness in the tropics and subtropics.

The reflected radiation is calculated using relationship after Laevastu and Hubert (1965),

\[ Q_r = \frac{3Q_S}{\alpha} \quad \cdots (5.4) \]

where \( Q_r \) = reflected radiation in cal cm\(^{-2}\) min\(^{-1}\).

Following Laevastu and Hubert (1965), the back radiation (long wave) is obtained as,

\[ Q_b = \left( \frac{297 - 1.867 T_S - 0.95 U}{1440} \right) (1 - 0.765 C) \quad \cdots (5.5) \]

where \( Q_b \) = back radiation in cal cm\(^{-2}\) min\(^{-1}\)

\( T_S \) = sea surface temperature in degree centigrade

\( U \) = relative humidity in percentage.

Following James, (1966) the evaporative loss is calculated.

\[ Q_e = 2.46 (0.26 + 0.04W) (E_w - E_a) \text{ for } E_w > E_a \quad \cdots (5.6) \]

where \( Q_e \) = evaporative loss in cal cm\(^{-2}\) hr\(^{-1}\)

\( W \) = wind speed in knots

\( E_w \) = saturated vapour pressure at sea surface in millibars

\( E_a \) = vapour pressure in the air in millibars.
The sensible heat loss $Q_h$ is obtained from

$$Q_h = 1.5 \times (0.26 + 0.04 W)(T_s - T_a) \text{ for } T_s > T_a \quad \ldots \ldots (5.8)$$

where $Q_h$ : sensible heat loss in cal cm$^{-2}$ hr$^{-1}$

$T_a$ : air temperature in degree centigrade

When $T_s < T_a$, a modified equation can be used,

$$Q_h = 0.036 W (T_s - T_a) \quad \ldots \ldots (5.9)$$

5.1.1 Positive heat transfer

The change in temperature $\Delta T$ in a layer of thickness $L$ due to heat transfer $Q$ over a time step $\Delta t$ is given by,

$$\frac{\Delta T}{\Delta t} = \frac{QA}{100 \cdot C_p \rho L} \quad \ldots \ldots (5.10)$$

where $T$ : the change in temperature in degree centigrade

$Q$ : the net heat gain at the surface in cal cm$^{-2}$ min$^{-1}$

$A$ : percentage absorption of heat for the layer

$C_p$ : specific heat of sea water (taken as 0.955 cal g$^{-1}$°C$^{-1}$)

$L$ : thickness of the layer in centimetres

$\rho$ : the density of sea water in g cm$^{-3}$

When the heat transfer from air to sea is positive at the surface, absorption of heat takes place in the surface and subsurface layers.

If $Q_0$ is the initial heat energy available at the top of layer thickness $L$ and $Q_L$ the heat energy available
at the bottom of the layer after absorption within the thickness, the ratio of the heat energy at the top to that at the bottom of the layer is obtained by,

\[
\frac{Q_0}{Q_L} = e^{-kL} \quad \ldots \quad (5.11)
\]

where \( Q_0 \) = heat gain at the top of the layer in cal
\( Q_L \) = heat available at the bottom of the layer in cal
\( k \) = extinction coefficient
\( L \) = layer thickness in centimetres.

Depending on the optical characteristics of water masses, extinction coefficients have been classified by Jerlov (1951). Tables 5.1 and 5.2 are based on these data, reproduced after Laevastu and Hubert (1961), giving percentage absorption values for different water masses and depths.

Heating of the layers is considered taking into account first the net heat gain available at the surface of the different layers from surface to 150 m namely 2.5, 5, 10, 20, 30, 40, 50, 75, 100 and 150 m by distributing the net heat gain available at the surface to the different subsurface layers using the appropriate percentage absorption values obtained from Table 5.2. Using equation 5.10, change in temperature at the respective levels is calculated and the change in the thermal structure due to positive heat transfer is accounted.
<table>
<thead>
<tr>
<th>Category No.</th>
<th>Optical water mass</th>
<th>Characteristics</th>
<th>Colour (Forel scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oceanic, clear</td>
<td>&quot;Old&quot; clear oceanic waters in productive areas (especially in low latitudes)</td>
<td>0 - 2</td>
</tr>
<tr>
<td>2</td>
<td>Oceanic, normal</td>
<td>Medium-productive oceanic waters in medium and low latitudes</td>
<td>2 - 5</td>
</tr>
<tr>
<td>3</td>
<td>Oceanic, turbid and coastal, clear</td>
<td>High productive oceanic areas, especially during plankton bloom. Tropical coastal waters, especially over sheep shelves</td>
<td>5 - 8</td>
</tr>
<tr>
<td>4</td>
<td>Coastal, normal</td>
<td>Normal, medium-productive coastal waters and waters over shallow shelves</td>
<td>8 - 10</td>
</tr>
<tr>
<td>5</td>
<td>Coastal, turbid</td>
<td>Estuarine and coastal waters during intensive plankton bloom and waters close to the coast where much sediment has been whirled up by wave action</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>
# Table 5.2

Absorption of total energy (%) in various layers of the sea

(After Laevastu and Hubert, 1965)

<table>
<thead>
<tr>
<th>Layer in metres from surface</th>
<th>Optical water mass</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 2.5</td>
<td></td>
<td>71.4</td>
<td>78.2</td>
<td>84.8</td>
<td>89.6</td>
<td>95.1</td>
</tr>
<tr>
<td>2.5 - 5</td>
<td></td>
<td>6.8</td>
<td>9.1</td>
<td>8.1</td>
<td>6.5</td>
<td>4.0</td>
</tr>
<tr>
<td>5 - 10</td>
<td></td>
<td>7.2</td>
<td>7.2</td>
<td>4.7</td>
<td>3.2</td>
<td>0.9</td>
</tr>
<tr>
<td>10 - 20</td>
<td></td>
<td>6.6</td>
<td>3.7</td>
<td>2.0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>20 - 30</td>
<td></td>
<td>3.0</td>
<td>0.9</td>
<td>0.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>30 - 40</td>
<td></td>
<td>1.3</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 - 50</td>
<td></td>
<td>1.1</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 - 75</td>
<td></td>
<td>0.9</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 - 100</td>
<td></td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 - 150</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.1.2 Wind/turbulent (mechanical) mixing

Mechanical mixing is the result of wind and wave action causing turbulent mixing and drift currents. Wind mixing does not always produce deeper layer depths. The effect of wind mixing is to redistribute the heat gain by the surface layers. As the mixing is inversely proportional to the stability of the water column it is desirable to introduce stability factor while considering the wind mixing (James, 1966). However, in the present schedule both shallow and deep water thermal structures are found to have deeper mixed layers with negligible stability in the surface few metres, and hence the stability effect is ignored. Following Laevastu (1960) who assumed that mixing ceases where the diameter of the orbital path is less than 10cm, and the depth of wind/wave mixing is calculated as

\[ D_M = 12.5 H_s \quad \text{.... (5.12)} \]

where \( D_M \) = depth of wind mixing in metres
\( H_s \) = significant wave height in metres.

The significant wave height is obtained from a relationship (Laevastu and Hubert, 1965).

\[ H_s = \frac{0.0008 W^2 50 + (T_W - T_a)}{(1 + 5 W)} \left(1 + \frac{W}{3 t} \right) \quad \text{... (5.13)} \]

where \( W \) = wind speed in m sec\(^{-1}\)
\( T_W \) = sea surface temperature in degree centigrade
\( T_a \) = air temperature in degree centigrade
\[ F = \text{fetch in kilometres} \]
\[ t = \text{duration in hours} \]

The wind mixed layers thus obtained are adjusted such that equal areas of heating and cooling with respect to the initial structure are obtained by the new position of the wind mixed layer in the final structure.

5.1.3 Negative heat transfer and convective mixing

In case of negative heat transfer (heat loss) from the surface, the increase in surface density will induce convective mixing and the depth of convective mixing is calculated from the relationship given by James (1966),

\[ D_C = \left( D_0 + \frac{2Q_L}{C_P \rho \Delta T} \right)^{\frac{1}{2}} \quad \ldots \quad (5.14) \]

where

- \( D_C \) = convective mixing depth in metres
- \( D_0 \) = initial MLD in metres
- \( Q_L \) = heat loss for the period of forecast in cal
- \( C_P \) = specific heat of sea water in cal g\(^{-1}\) \( ^{\circ}\)C\(^{-1}\)
- \( \rho \) = average density of sea water in the mixed layer in g cm\(^{-3}\)
- \( \Delta T \) = average gradient of temperature in 30 m below MLD.

Heat loss for the time interval of forecast is calculated from the heat budget equation using inputs from observations at the beginning of the interval and the layer deepening is calculated.
5.1.4 **Salinity effects**

The salinity effects are assumed minimal and negligible. Hence, only temperature gradient is considered for stability in both cases as applicable to isohaline condition. However, average salinity data are used to compute density for using in equations 5.10 and 5.14 following standard equations given by National Oceanographic Data Centre (1974).

5.1.5 **Advection and convergence/divergence**

Horizontal and vertical advection becomes relevant only when wind currents of long duration and intensity are present. Geostrophic currents are semi-permanent and do not affect the thermal structure. Hence the final layer depth is computed assuming no advection. As a result, the effect of convergence/divergence due to the horizontal currents are also not taken into account in the present scheme.

5.1.6 **Internal waves**

The effect of internal waves is to generate periodic functions of MLD. The predicted MLD is assumed to be the average on which internal wave amplitude is superimposed to give the current position. However, in the evaluation, the predicted values of MLD are without the internal wave amplitudes.

5.1.7 **MLD prediction routine**

For the deep station S1,92 vertical thermal structures beginning at 1355 hrs on 7th June 1977 and
ending at 0200 hrs (IST) on 19th June 1977 along with data on wind, sea surface temperature, dry and wet bulb temperatures and cloudiness are utilised for the prediction run. For the shallow station S2, 21 vertical thermal structures beginning at 1015 hrs (IST) and ending at 2130 hrs (IST) on 9th January 1983 along with the supplementary meteorological observations as in the deep water case are utilised. In each prediction run the first thermal structure is initialised from the observed and MLD and SST are predicted at the end of the time step. The thermal structure is again initialised from the observed for prediction of the structure after the next time step and the process is repeated till the end of the series. In this manner forecast runs were made for 3 hourly and 6 hourly steps for both deep water and shallow water cases. In each case the predicted values of SST and MLD are compared with the observed values.

5.2 Deep station S1 (10°30'N, 66°E)

5.2.1 Observed characteristics (Figs. 5.1 and 5.2)

Deep station S1 is in the central Arabian Sea. The observed variations in the air-sea transfer parameters, MLD with the associated thermal structure and the average salinity profile for the period from 1355 hrs (IST) on 7 June to 0200 hrs (IST) on 19 June 1977 are presented in Figs. 5.1 and 5.2.

The general distribution of wind (Fig. 5.1) during the period was predominantly easterly with speeds ranging from 12 to
Fig. 5: Observed time variation of air-sea transfer parameters during June 1974 at 1000 km.

- O: Sea surface temperature (°C)
- D: Cloud cover (1/10)
- ---: Vapor pressure difference (mb)
- ---: Net heat gain (cal/cm²/min)
32 kts in the beginning, decreasing to nearly 15 kts by 10 June and then stabilising around 25 kts towards the end of the series between 16 - 19 June, 1977.

The net heat gain variation (Fig.5.1) exhibited cyclic changes with maximum values ranging from 0.23 to 0.36 cal cm\(^{-2}\) min\(^{-1}\) occurring between 1100 to 1400 hrs (IST) in the beginning of the run upto 10 June and afterwards increasing to values between 0.6 - 0.8 cal cm\(^{-2}\) min\(^{-1}\). A further increase to 0.7 cal cm\(^{-2}\) min\(^{-1}\) was observed after 12 June. The night time cooling ranged between -0.4 and -0.9 cal cm\(^{-2}\) min\(^{-1}\) through out the period.

Vapour pressure difference was positive and showed variation in the beginning between about 2 to 11 mb upto 9 June and then decreased to lower values ranging between -1.7 and 1.5 mb till the end. Till 10 July the sky was overcast and after that the cloudiness decreased upto 14 July. Sky was overcast again towards end of the period. The sea surface temperature was higher in the beginning (29.8\(^{0}\) C) which progressively decreased from 11 July reaching the lowest (28.9\(^{0}\) C) towards the end as a result of cooling in the central Arabian Sea (Rao et al., 1981). The corresponding sea-air temperature was positive throughout the period ranging from 0 - 3.5\(^{0}\) C.

The observed MLD variation (Fig.5.2a) shows a progressive increase of average MLD towards the end of a 11 day period from 40 m to about 75 m which corresponds to a progressive cooling period in the area. The MLD variation is superimposed by the internal oscillation of
FIG. 5.2 (a) TIME SECTION OF OBSERVED MIXED LAYER DEPTH AND ASSOCIATED THERMAL STRUCTURE (b) AVERAGE SALINITY PROFILE DURING JUNE 1977 AT 10°30'S, 66°E
predominantly 6 and 10 hrs period with a maximum amplitude of about 10 m. The below layer gradient in thermocline exhibited similar amplitudes of oscillation, but the gradient thickness does not change throughout even after the MLD deepens.

The observed average salinity structure (Fig.5.2b) for the period of observation at the deep station shows vertical positive gradients of 0.13 ppt in 50 m (0.003 ppt in 10 m) up to a depth of 50 m. There is a subsurface maximum corresponding to 95-100 m (36.35 ppt). Between 50-100 m and 100-150 m, the salinity gradient is approximately 0.027 ppt in 10 m, positive and negative respectively. Below this the gradient is negative and more.

5.2.2 Station constants

For the deep water station a fetch of 1000 km is taken for calculating the wind mixing. Average duration of 12 hrs is considered for the average winds of the same duration. The subsurface radiation absorption (percentage) appropriate for different levels was based on the optical water mass type 1 representing "oceanic, clear" (Tables 5.1 and 5.2).

5.2.3 Results and discussion (Figs. 5.3 to 5.10)

Figs. 5.3 to 5.10 presents the characteristics of the predicted SST and MLD for 3 hourly and 6 hourly intervals.

5.2.3.1 3 hourly series

The 3 hourly prediction run initialised at 1355 hrs (IST) on 7 June (fig. 5.3) shows a night cooling in excess
of the observed by having predicted SST values lower by around 1°C for each diurnal cycle. A positive difference (increase) of predicted SST from the observed in the afternoon hours on 8, 9, 10 and 14 June with a maximum difference of about 0.5°C is noticed. The excess cooling has resulted in corresponding deeper MLD. Similarly shoaling of MLD occurs whenever SST increase is noticed. Maximum difference of MLD coincides with shoaling events due to afternoon increase in SST on 10, 14 and 15 and 17 June upto about 30 m from the observed.

Figs. 5.4 and 5.5 presents the error evaluation of the 3 hourly run. In about 61.4% of the intervals the difference between predicted and observed SST is within 0.5°C (Fig. 5.4). The difference increase to 0.6 - 1.0°C for 37.4% of the intervals. For about 1.2% intervals the difference is highest between 1.1 - 1.5°C. Fig. 5.5 shows the corresponding error evaluation for MLD. The difference in MLD between the predicted and observed is upto 5 m for 54% of the intervals while for 28.6% of the intervals the difference is between 6 - 10 m. Higher differences in MLD ranges from 8% of the intervals having differences between 11 - 15 m, 4.6% having 16 - 20 m, 3.8% with 21 - 25 m and 1% with 26 - 30 m.

A comparison of the wind mixing and convective mixing computed for 3 hourly run is presented in Fig.5.6. Till the end of the prediction the wind mixing length is less throughout the run by 5 - 50 m than the convective mixing which is closer to the predicted. The
FIG 5.3 COMPARISON OF PREDICTED AND OBSERVED (a) SEA SURFACE TEMPERATURE AND (b) MIXED LAYER DEPTH FOR 3 HOURLY TIME STEPS DURING JUNE 1977 AT 10°30’N, 66°E

FIG 5.4 DIFFERENCE BETWEEN PREDICTED AND OBSERVED SEA SURFACE TEMPERATURE (°C) FOR 3 HOURLY TIME STEPS AT 10°30’N, 66°E

FIG 5.5 DIFFERENCE BETWEEN PREDICTED AND OBSERVED MIXED LAYER DEPTH (m) FOR 3 HOURLY TIME STEPS AT 10°30’N, 66°E

FIG 5.6 COMPARISON OF WIND AND CONVECTIVE MIXING DEPTHS FOR 3 HOURLY TIME STEPS DURING JUNE 1977 — AT 10°N, 66°E
anomalous increase in wind mixing from 2000 hrs on 13 June to 1100 hrs (IST) on 14 June and from 2300 hrs (IST) on 17 June to 0800 hrs (IST) on 18 June are only due to errors in the wind force introduced by gaps in wind data on 13 June (2005 hrs, IST) and on 17 June (2300 hrs, IST).

5.2.3.2 6 hourly series

The result of the 6 hourly prediction run initialised at 1355 hrs (IST) (Fig. 5.7) shows that the predicted cooling was in excess by maximum 1.5°C upto 16 June. But from 0200 hrs (IST) on 17 June to 0600 hrs (IST) on 18 June, the predicted SST is lower by more than 3°C which corresponds to the error in wind forcing and the resulting errors in heating due to the gaps in wind data on 17 and 18 June, referred earlier. The predicted SST is slightly in excess of the observed by about 0.1 to 0.5°C on 13, 14, 15, 16, 18 and 19 June. Predicted MLD is closer to the observed with differences ranging from 0 to 25 m, except for great differences in deepening corresponding to the gaps on wind data on 17 and 18 June.

Histograms (Figs. 5.8 and 5.9) present the error evaluation for the prediction run with 6 hourly time steps. The difference between predicted and observed SST is upto 0.5°C for 54% of cases and 0.6 - 1°C for 34.2% cases, between 2.6 - 3.0°C for 3.8% cases and between 3.6 - 4°C for 1.8% cases. The difference in MLD between the predicted and observed is upto 5 m for 32.8% cases, 6 - 10 m for 38.2% cases, 11 - 15 m for 13.4% cases, 16 - 20 m for 4% cases, 21-25 m for 2% cases and 26 - 30 m for
FIG. 5.7 COMPARISON OF PREDICTED AND OBSERVED (a) SEA SURFACE TEMPERATURE AND (b) MIXED LAYER DEPTH FOR 6 HOURLY TIME STEPS DURING JUNE 1977 AT 10°30′N, 66°E

FIG. 5.8 DIFFERENCE BETWEEN PREDICTED AND OBSERVED SEA SURFACE TEMPERATURE (°C) FOR 6 HOURLY TIME STEPS AT 10°30′N, 66°E

FIG. 5.9 DIFFERENCE BETWEEN PREDICTED AND OBSERVED MIXED LAYER DEPTH (m) FOR 6 HOURLY TIME STEPS AT 10°30′N, 66°E

FIG. 5.10 COMPARISON OF WIND AND CONVECTIVE MIXING DEPTHS FOR 6 HOURLY TIME STEPS DURING JUNE 1977 AT 10°30′N, 66°E.
A comparison of the wind mixing and convective mixing for 6 hourly time steps is presented in Fig. 5.10. The wind mixing shows shallower extent with a difference from convective mixing ranging from 8-15 m. The convective mixing is closer to the predicted throughout the run.

5.3 Shallow station 52 (10°15'N, 75°48'E)

5.3.1 Observed characteristics (Figs. 5.11 and 5.12)

This station is in the continental slope off Cochin and the evaluation period represents the winter regime. The observed variation in the air-sea transfer parameters and the MLD with the associated thermal structure and average salinity structure are presented in Figs. 5.11 and 5.12.

The distribution of air-sea transfer parameters (Fig. 5.11) from 1015 hrs (IST) to 2115 hrs (IST) on 19 January 1983 at the shallow site is presented in Fig. 5.11. The wind speed ranges from 0 to about 5 kts for the entire duration. The wind direction was predominantly southeasterly, but changing to southerly towards the end with a short spell of northeasterly weak winds during 1600-1800 hrs (IST).

The net heat gain is positive from 1015 hrs (IST) to 1600 hrs (IST). The negative phase of cooling is prevalent from 1600 hrs (IST) to 2150 hrs (IST) till the end of the duration. The maximum heat gain was at the beginning from about 1030 hrs (IST) (nearly 1.2 cal cm⁻² min⁻¹) and maximum cooling was towards the end of the duration.
FIG. 5.11 OBSERVED TIME VARIATION OF AIR-SEA TRANSFER PARAMETERS DURING JANUARY 1963 AT 10°S N, 75°48'E
at around 2130 hrs (IST) (nearly -0.2 cal cm\(^{-2}\) min\(^{-1}\)). Variation of vapour pressure difference from sea surface to air shows a range between 0-3 mb. Cloud cover was very low between 0 - 1 (one tenth) for the duration. The sea-air temperature difference was positive (0 - 1.5\(^{\circ}\)C) indicating the sensible heat loss. The temperature of sea surface was highest (28.6\(^{\circ}\)C) at around 1350 hrs (IST), which decreased to a minimum (28\(^{\circ}\)C) from 1700 to 2130 hrs (IST).

The MLD (Fig. 5.12a) varied from about 70 m at 1030 hrs (IST) to shallower depths of 60 m at 1445 hrs (IST) and 1600 hrs (IST). This was followed by a deepening to the previous depth and then back to a shallowest position of 58 m by about 1800 hrs (IST). The layer further deepened to the end of the observation period. The oscillations in the MLD during the length of the observation are related to periods of about 3 and 6 hourly durations with average amplitudes of 5-12 m. The thermal gradients below the mixed layer show an average range from about 4\(^{\circ}\)C/10 m in the beginning to 2.5\(^{\circ}\)C/10 m afterwards.

The observed average vertical salinity structure (Fig.5.12b) at the shallow station indicates a slight negative gradient up to 30 m (about 0.03 ppt in 10 m). From 30 to 75 m the salinity increases to a subsurface maximum 35.62 ppt) with a gradient of 0.3 ppt in 10 m. The salinity change is very weak between 100 and 150 m. From 150 m to 180 m the gradient is negative and more (0.2 ppt in 10 m).
FIG. 5.12 (a) Time section of observed mixed layer depth and associated thermal structure. (b) Average salinity profile during January 1983 at 10°15'N 75°48'.
5.3.2  **Station constants**

For the shallow station a fetch of 35 km is used with 12 hourly average wind speeds for wind mixing calculations. Percentage absorption values for different levels relevant to type 4 "Coastal, normal" water mass (Tables 5.1 and 5.2) are used for obtaining the temperature changes due to heating.

5.3.3  **Results and discussion**

The results of the prediction run for the 3 hourly and 6 hourly time steps at the shallow station are presented in Figs. 5.13 to 5.20.

5.3.3.1  **3 hourly series**

Predicted SST is slightly less (Fig. 5.13) in the beginning at 1300 hrs (IST) which becomes more than the observed with increasing difference at 1600 hrs (IST). The difference in predicted MLD remains the same, but the values become less than observed towards the end. The predicted MLD is deeper with a difference of 25 m from the observed at 1300 hrs (IST) which decreases to nil at 1600 hrs (IST). At 1900 hrs (IST) the predicted MLD is slightly less by about 5 m and towards the end the difference disappears.

Figs. 5.14 and 5.15 present the error evaluation of SST and MLD between the predicted and observed situations, for 3 hourly time steps. For 66% cases the difference in predicted SST from the observed is upto 0.5°C and for 34% cases the difference ranges between 0.6 - 1°C. For predicted
Figure 5.13 Comparison of predicted and observed (a) sea surface temperature and (b) mixed layer depth for 3 hourly time steps during January 1983 at 10°15'S, 75°4E.

Figure 5.14 Difference between predicted and observed sea surface temperature (°C) for 3 hourly time steps at 10°15'S, 75°4E.

Figure 5.15 Difference between predicted and observed mixed layer depth (m) for 3 hourly time steps at 10°15'S, 75°4E.

Figure 5.16 Comparison of wind and convective mixing depths for 3 hourly time steps during January 1983 at 10°15'S, 75°4E.
MLD the difference is upto 5 m in 77% cases and 21-25 m for the rest.

A comparison of wind and convective mixing values (Fig. 5.16) indicates wide difference between both ranging from about 22 m to 50 m. The low wind mixing profiles are due to the low wind forcing and the predominance of convective mixing is indicated for the predicted MLD.

5.3.3.2 6 hourly series

Fig. 5.17 presents the distribution of the predicted and observed SST and MLD resulting from the prediction run for 6 hourly time steps at the shallow station. The predicted SST is slightly more than the observed for the first interval. The difference increases to 1600 hrs (IST) when predicted SST values are lower and the trend remains somewhat same till 1900 hrs (IST). The trend changes reversing the difference towards the end of the series. The predicted MLD shows maximum difference of about 20 m at 1300 hrs (IST) when the predicted MLD is deeper. The predicted layer coincides with the observed at 1600 hrs (IST). The predicted layer depth is shallower by about 5 m at 1900 hrs (IST) and the difference vanishes towards the end.

The error in prediction for 6 hourly time steps at the shallow station is presented in Figs. 5.18 and 5.19. For equal numbers of 6 hourly intervals (50% each) the difference between the predicted and observed SST is upto 0.5°C and 0.6 - 1°C respectively. The difference
between the predicted and observed MLD is up to 5 m for 50% cases. However, for the other 50% cases, the difference is between 16-20 m.

The wind mixing is shallower than the convective mixing for the 6 hourly series at the shallow station (Fig. 5.20). This difference is maximum in the beginning (about 80 m) and decreases to near 70 m at the end. The wind mixing decreases from 70 m in the beginning to about 5 m at the end. The predicted convective mixing shows a decrease towards the end while the maximum negative heat transfer and observed MLD for the same period (Figs. 5.11 and 5.12) are suggestive of convective deepening. This contrast in the predicted shallowing of the MLD is due to the perturbation of the internal oscillation making the MLD input at 1630 hrs (IST) shallower up to about 60 m. This results in the deepening of predicted MLD due to negative heat transfer to an extent less than the observed deepening.

5.4 Conclusions

The predictive scheme which does not take into account advection and salinity effects is found to be sensitive to both wind forcing and heating. In fact the model equations used predict more cooling and corresponding deepening of MLD during night time. The prediction run for 3 hourly and 6 hourly time steps is more sensitive to the wind forcing which may result in errors due to data gaps. However, the differences are found to be well within the range of internal wave variability in the Arabian Sea.
FIG. 5.17 COMPARISON OF PREDICTED AND OBSERVED
SEA SURFACE TEMPERATURE AND
MIXED LAYER DEPTH FOR 6 HOURLY TIME
STEPS DURING JANUARY 1983 AT 10°15'S, 75°48'E

FIG. 5.18 DIFFERENCE BETWEEN PREDICTED AND OBSERVED
SEA SURFACE TEMPERATURE (°C) FOR 6 HOURLY
TIME STEPS AT 10°15'S, 75°48'E.

FIG. 5.19 DIFFERENCE BETWEEN PREDICTED AND OBSERVED
MIXED LAYER DEPTH (m) FOR 6 HOURLY TIME STEPS
AT 10°15'S, 75°48'E.

FIG. 5.20 COMPARISON OF WIND AND CONVECTIVE MIXING DEPTH
FOR 6 HOURLY TIME STEPS DURING JANUARY 1983 AT
10°15'S, 75°48'E.
and within the limits imposed by this, the scheme is satisfactory for predicting short term variations from 3-6 hrs in the deep site during June (southwest monsoon) and in the shallow site during winter regime.

As the MLD parameterisation is based on the average criterion of Wyrtki (1971) the scheme is unable to take into account the formation of transient thermoclines. The use of averaged fluxes for (3 hourly and 6 hourly) predicting the SST and MLD may result in the excess cooling and heating and corresponding deepening or shoaling of MLD as has been observed by Elsberry et al. (1984) who omitted advective and salinity effects in their one dimensional model for short time scale. The non-inclusion of salinity effects in accounting stability during turbulent and convective mixing can be a setback for cases where sharp salinity gradient exists (Miller, 1976).