CHAPTER III
Advection is the process by which heat is transported from one place to another. Advection of water due to wind and density currents plays an important role in deciding thermal structure profile in the upper layer and the MLD. The local exchange of heat altering the thermal structure, largely depends on the horizontal advection and diffusion of heat (Reed and Halpern, 1974). Joyce et al. (1980) observed that the dominant low frequency variability in the seasonal thermocline accounting to 60% of the observed temperature changes during JASIN experiment in north Atlantic was due to horizontal advection by currents. Vertical advection of cold waters during the upwelling period affects MLD especially in the coastal areas.

Divergence and convergence of waters due to surface currents cause vertical movements in MLD. Convergence causes sinking of the MLD and associated thermal and density structure while divergence causes upwelling or shoaling of MLD and associated structures (La Fond, 1954). Convergence/divergence can be semipermanent or vary at short time intervals with the periodicity of changes in surface wind and tides in an area. According to Mazeika (1960) each individual geographic area (of 5\degree or less square) possesses certain geographic characteristics which affect the formation of MLD and where permanent convergence
or divergence exists, these characteristics may be sufficiently strong to preclude conventional mixing processes. Apart from such extreme cases, local conditions due to changes in convergence/divergence will influence local MLD values.

Convergence/divergence can be estimated from local wind currents. But this method can be subjective (Laevastu and Hubert, 1965). A realistic approach is to derive the surface divergence from surface current data. The surface divergence is calculated following Hela (1954), reviewed by Laevastu and Hubert (1965).

Internal oscillations with periods ranging from about 10 seconds to months related to atmospheric pressure changes, current shears and tidal forces are found to influence time variations of MLD. The lower limit of the period of these oscillations is set by the Brunt-Vaisala frequency. Internal waves occur at the boundary between density layers and vary widely in amplitude and period (La Fond, 1954; Mazeika, 1960).

The annual variation of surface current speed, direction and its east-west and north-south components as well as surface current divergence for the 8 subareas of study are presented in this chapter. The characteristics of internal waves in the Arabian Sea are discussed only in respect to the time series data at S1 for a sample strength of 64 observations. Fig. 3.1 shows the monthly circulation pattern over the Arabian Sea after Varadachari and Sharma (1967).
FIG. 3.1 MEAN SURFACE CIRCULATION IN THE ARABIAN SEA (AFTER VARADACHARI AND SHARMA, 1967)
3.1 Subarea 1 (Fig. 3.2)

3.1.1 Surface currents (Figs. 3.2 a to d)

Surface currents in the subarea at the mouth of Gulf of Oman is westerly during January with speeds up to 25 cm sec\(^{-1}\). During February a major easterly flow is apparent with diminished speeds. By March a southerly flow with speeds of about 14 cm sec\(^{-1}\) is present. In April current speeds are maximum (30 cm sec\(^{-1}\)) in the south-easterly direction. Currents with speeds 16-22 cm sec\(^{-1}\) continue to be present in the subarea during May-October. In October southwesterly currents with minimum speeds (about 13 cm sec\(^{-1}\)) are observed. The surface current speeds increase during winter due to the intensified westerly flow.

From an examination of the surface current components, easterly components are more apparent from April to October and from December to January while westerly components are dominant during January, March and November. The southward components are maximum during April and minimum during December.

3.1.2 Surface current divergence (Fig. 3.2 e)

Maximum negative values of surface divergence (about 40 units) are observed in January suggesting convergence and sinking for the surface mixed layer. A moderate positive value of surface divergence during February/March is followed by weak converging tendency in April. Upwelling tendency is indicated from May to July.
reaching a maximum divergence in June (-25 units). Convergence of the surface current from August to October is conducive for sinking of the surface layer. The trend is reversed in November with divergence at surface. But increased convergence starts from December to January during which the winter deepening of MLD is observed (Fig. 2.9). This observed deepening may be the combined result of sinking and cooling. A decrease in the surface divergence during May/June is also supplemented by the increased surface heat gain (Fig. 2.1 c) resulting in shoaling tendency of MLD observed. The deeper layers observed during August-October (Fig. 2.9) can be attributed to the convergence apparent during this time.

The patterns observed especially of convergence in December/January, divergence in February-March and divergence in June-July and September-October are in agreement with the earlier observations of Varadachari and Sharma (1967).

3.2 Subarea 2 (Fig. 3.3)

3.2.1 Surface currents (Figs. 3.3 a to d)

The surface currents are southerly and generally weaker near the Indus Cone and off Gujarat during January-February (greater than 10 cm sec\(^{-1}\)). The flow changes to a southeasterly direction from March to October attaining a maximum speed in July (about 27 cm sec\(^{-1}\)). The wind speed decreases in July (12 cm sec\(^{-1}\)) and increases to a second peak in August (23 cm sec\(^{-1}\)). From November the wind speed
decreases with a mean southerly flow. The mean flow in this area is fairly agreeable with the previous observations (Varadachari and Sharma, 1967; Duing 1970), except in January and December. This can be due to the errors in averaging of sparse current data from mean 2° quadrangles from Wooster et al. (1967) for the subarea.

From February to October easterly components are predominant while during November to January southerly components are present.

3.2.2 Surface current divergence (Fig. 3.3 e)

Weak convergence (-4.9 units) is indicated in the subarea from January to March. This is reflected in the sinking tendency of MLD (Fig. 2.9) up to February. A strong divergence is seen during April (26 units) as confirmed by the circulation pattern during the period (Duetsches Hydrographisches Institut, 1960). This is reflected in shoaling of MLD observed up to May (Fig. 2.9). Convergence is indicated from July to November with a maximum in August (-32 units) which agrees with the observations of Varadachari and Sharma (1967). A slight increase of MLD (Fig. 2.9) from June to November is the consequence of the convergence-induced sinking exceeding the shoaling effects due to the secondary warming in September (Fig. 2.2 c). Divergence is indicated in December which may oppose the MLD deepening to a limited extent.
3.3 Subarea 3 (Fig. 3.4)

3.3.1 Surface currents (Figs 3.4 a to d)

This subarea in the western half of the central Arabian Sea has strong average currents during May to September (23-26 cm sec\(^{-1}\)) flowing in the easterly direction. During October and November the mean currents turn southeasterly and southerly with reduced speeds. During winter months, the currents are southwesterly and weaker. In February the surface current becomes stronger (21 cm sec\(^{-1}\)) in the southwesterly direction. During March-April the currents again become weaker flowing towards south and southwest.

Easterly components are present during January and March-October while westerly components are present from February to April. Northerly components are prevalent during June-September, January-May and southerly components are active during October-December. The circulation pattern agrees with the results of Colborn, (1975).

3.3.2 Surface current divergence (Fig. 3.4 e)

January is marked by convergence in the subarea resulting in sinking of the surface layer which is already deepened due to convective mixing during winter cooling. The divergence of February is maximum (26 units) and continues up to March. Sinking tendency for MLD is indicated during April-July by the convergence with a
maximum in May (-19 units). The observed deepening of MLD for the subarea (Fig. 2.9) during this month may be the result of the net heat loss upto June supplemented by the convergence upto July. This convergence is also seen in the circulation pattern reported by Varadachari and Sharma (1967). After a short spell of divergence in August the convergence trend reappears again in September. Divergent and convergent tendencies are alternatively indicated from October to December. The weak divergence in December is not sufficient to balance the convective deepening of MLD during the month (Fig. 2.9).

3.4 Subarea 4 (Fig. 3.5)

3.4.1 Surface currents (Figs. 3.5 a to d)

The surface current direction in January is southeasterly, with low speeds (less than 15 cm sec$^{-1}$). The surface current becomes southwesterly in February and stronger (22 cm sec$^{-1}$). The speed decreases in March and again increases from April to June (22 cm sec$^{-1}$). During April-May the currents are variable. By June the current direction is set to northeasterly and remains so till June. It becomes easterly/southeasterly in August-October with a maximum surface speed (28 cm sec$^{-1}$) in August. From November the average current is westerly with high speed in December (19 cm sec$^{-1}$).

Easterly components are predominant during May to October while westerly components are dominant in November-December and February (Fig. 2.9). During June-July the northerly components are active and from January to
May and from August to November southerly components are predominant. The general pattern excepting for transitional periods agrees with that given by Varadachari and Sharma (1967).

3.4.2 Surface current divergence (Fig. 3.5 e)

The surface divergence indicated for January and February is not sufficient to shoal the MLD as the winter cooling and the convective deepening are stronger during this time (Fig. 2.9). The reversing trend in March also does not have any deepening effect as the spring heating and shoaling of MLD is already at the maximum, making the mixed layer shallow. The divergence indicated in April is also supplementing the shoaling of MLD upto May resulting from secondary warming. The maximum convergence in August (-13 units) coincides with the mid-summer deepening of MLD, when the effects of both cooling and convergence seems to be active during the month. The shoaling of MLD after September shows correlation with the maximum divergence (14 units) for the month. The low values of convergence estimated for October and November supplement the deepening of MLD due to cooling (Fig. 2.9). However, the divergence indicated during December is in contrast to the deep layers observed and hence may be erroneous due to the data scarcity. The surface divergence pattern is in agreement with the results of Varadachari and Sharma (1967) except for the period in December-January.
Figure 3.2: Annual cycle of (a) surface current, (b) surface current direction, (c) E-W current component, (d) N-S current component, and (e) surface divergence (Subarea 1).

Figure 3.3: Annual cycle of (a) surface current, (b) surface current direction, (c) E-W current component, (d) N-S current component, and (e) surface divergence (Subarea 2).

Figure 3.4: Annual cycle of (a) surface current, (b) surface current direction, (c) E-W current component, (d) N-S current component, and (e) surface divergence (Subarea 3).

Figure 3.5: Annual cycle of (a) surface current, (b) surface current direction, (c) E-W current component, (d) N-S current component, and (e) surface divergence (Subarea 4).
3.5 Subarea 5 (Fig. 3.6)

3.5.1 Surface currents (Figs. 3.6 a to d)

During January a weak westerly flow (13 cm sec\(^{-1}\)) is present which changes to southeasterly during February-March. The surface current speed increases from March. The current direction changes to southwesterly in May to southeasterly in June-September with maximum speed (30 cm sec\(^{-1}\)) in August. The surface currents weaken towards November through January. During November and December the surface current direction changes to southwesterly.

The variation of the current components indicates the prevalence of easterly component from February to March and June to September. Westerly component is apparent during November-January. Throughout the year only southerly component is observed in this area. The present observations on surface currents in this area closely resemble the patterns presented by U.S. Navy Hydrographic Office (1960).

3.5.2 Surface current divergence (Fig. 3.6 e)

From January to July divergence is indicated for the subarea with a maximum (about 13 units). Basil Mathew (1982) observed weak to moderate divergence in the same area except in April. The convergence and divergence are indicated in alternation from August to December. The divergence during January is not reflected in the deepening of MLD from November onwards in the subarea (Fig. 2.10).
Divergence from March to May supplements the shoaling of the surface layer due to spring heating. Diminished deepening of MLD during the mid-summer cooling in June/July can be attributed to the divergence during this month. Weak convergence in August observed in the present study has not resulted in any increase of MLD because of the counteracting influence of the secondary warming during the month. However, Basil Mathew (1982) has reported moderate upwelling in this area during this time. A possible reason for this may be due to difference in data sets and averaging. Secondary warming in unison with divergence observed in September seems to cause shoaling of MLD after November. Maximum convergence indicated in December (about -10 units) coincides with the deepening of MLD (Fig. 2.10). Divergence in September and convergence in October observed in this area are also apparent from the results of Varadachari and Sharma (1967).

3.6 Subarea 6 (Fig. 3.7)

3.6.1 Surface current field (Figs. 3.7 a to d)

Western areas of the southcentral Arabian Sea falling under this subarea is characterised by southwesterly and westerly flows during northeast monsoon and northeasterly to easterly flows during southwest monsoon period. Southwesterly flow in January becomes weaker towards March and April (about 12 cm sec\(^{-1}\)) with directions changing to southeasterly. The northeasterly flow starts from June reaching a maximum (30 cm sec\(^{-1}\))
in July. A decrease in current speed from August to September is followed by a change in the current direction to southeasterly with very low speeds (less than 9 cm sec\(^{-1}\)) in October. Southwesterly currents attain maximum values (about 15 cm sec\(^{-1}\)) during December/January.

Easterly components are predominant during March to September while westerly components are active from October to December/January. Southerly components in the flow are observed during March-May and September-January and northerly components are observed during February and June-August. These observations are in general agreement with the pattern presented in the atlas of Deutsches Hydrographisches Institut (1960) except for March and April.

3.6.2 Surface current divergence (Fig. 3.7 e)

During January weak convergence is indicated resulting in the sinking of MLD during January due to winter cooling. Weak divergence is indicated in February. Convergence during March increases to moderately high values in April (-13 units). This may be due to the presence of the anticyclonic system in the central Arabian Sea by March (U.S. Navy Hydrographic Office, 1960). However, the MLD has not deepened significantly during this time. The divergence in May is reflected in shallower layers observed, though it may also be caused by net heating. From June to July high convergence is
correlated with maximum layer depths (Fig. 2.10). This agrees with the observations by Bruce (1981) and Sastry and Ramesh Babu (1979) of negative wind stress curl and convergence. Moderate divergence in August increases in September and is reflected in the shoaling of MLD. This is also the result of the secondary warming. During October and November weak convergence indicated has agreement to the pattern discussed by Varadachari and Sharma (1967), though a shoaling of MLD is observed during this time in the present analysis due to positive heat transfer. The weak divergence indicated in December also is not reflected in the MLD value as it appears to be mainly controlled by the convective process during this time (Fig. 2.10).

3.7 Subarea 7 (Fig. 3.8)

3.7.1 Surface currents (Figs. 3.8 a to d)

The southeasterly flow indicated in January from the present analysis for the subarea is not realistic. In February southwesterly flow is present. Southeasterly and southwesterly flow indicated in March and April respectively are also indicated by Varadachari and Sharma (1967) and may be explained as the irregular features of the transitional months. The surface flow is mainly southeasterly and easterly during March-October with maximum speeds (41 cm sec\(^{-1}\)) in October. During November and December the surface currents are northwesterly with moderate speeds (about 20 cm sec\(^{-1}\)).
Easterly components are prominent during March and May-October and westerly components in February, April, November and December. Northerly components are indicated only in December while for the rest of the year southerly components are prevalent.

3.7.2 Surface current divergence (Fig. 3.8 e)

In January weak convergence is indicated. This can also be associated with the sinking motion observed in the offshore areas of southwest coast of India as a result of convergence of westerly flowing northeast monsoon drift and southerly flow in the beginning of formation of the anticyclonic circulation (Colborn, 1975). The large MLD values in January are in correlation with the convergence and convective deepening during this month. However, the persistence of a maximum MLD through February is not explained by the divergence during this time. The divergence observed in this subarea in February has also been reported by Basil Mathew (1982). From March to April convergence increases to moderate intensity (13 units), which closely agrees with the convergence zone due to the presence of an anticyclonic circulation (clockwise) formed in the subarea during March/April (U.S. Navy Hydrographic Office, 1960; Varadachari and Sharma, 1967). But shoaling of MLD during this period is caused by the intense heating (Fig. 2.7 c). The weak convergence indicated in June/July in the present study seems to augment the convective deepening during the mid-summer cooling active by this time. The moderate
divergence appearing from August to September is reflected in the shoaling of MLD. This shoaling is related to the divergence of southerly flow in the area (Varadachari and Sharma, 1967) similar to an upwelling motion, assisted by the secondary warming during the period. In October a weak convergence is present and it remains up to November, though the secondary heating starting from August through October is still active in shoaling the MLD against the sinking influence of the convergence. The divergence indicated during December is not supported by any evidence in the present analysis as a thickening of MLD is observed indicative of sinking during the month. This disparity may be on account of the sparse current data set.

3.8 Subarea 8 (Fig. 3.9)

3.8.1 Surface currents (Figs. 3.9 a to d)

From February to October southeasterly flow is indicated. Speeds are maximum in August (36 cm sec\(^{-1}\)) under the influence of southwest monsoon. During winter speeds are stronger (28 cm sec\(^{-1}\)) in January. Flow pattern agrees well with Varadachari and Sharma (1967) except for December and January. Easterly and southerly components show an extensive coverage in the annual cycle.

3.8.2 Surface current divergence (Fig. 3.9 e)

Weak to moderate convergence observed from January to April is indicative of sinking during this period. However, deepening of MLD is reflected only up to February.
The reverse trend observed later indicates the dominant influence of the net heating from February onwards (Fig. 2.10). The moderate divergence indicated during May-July with a maximum (about 25 units) does not contribute to deepening of MLD till June. Moderate convergence (-12 units) is found to act in unison with the convective deepening (Fig. 2.10) from June to August. The weak convergence apparent in the present analysis from September to October is not reflected in the shoaling of MLD observed during that period (Fig. 2.10). Basil Mathew (1982) has reported similar moderate weak convergence near the west coast of India derived from surface currents during the period. The divergence indicated during November does not seem to affect the layer as the observed mixed layer deepening due to winter cooling is more. A weak convergence is indicated during December which may supplement the layer deepening in winter (Fig. 2.10). The pattern of sinking due to convergence is also indicated by the north flowing coastal currents in this area during the month (Varadachari and Sharma, 1967).

3.9 Internal waves (Fig. 3.10)

The spectrum of the internal waves during the southwest monsoon (June) periods in the central Arabian Sea comprises several harmonic oscillations with periods ranging from 6 hrs to 192 hours. Following Roberts (1975) they may be categorised under two viz., short period (less than 12 hrs) and long period (greater than 12 hrs) internal waves.
FIG. 3.10 SPECTRAL CHARACTERISTICS OF MIXED LAYER DEPTH OSCILLATION AT 10° 30' N, 66° E

SAMPLE STRENGTH = 64
SAMPLING INTERVAL = 3 HRS
MAXIMUM AMPLITUDE = 9.8 M
3.9.1 Short period internal waves

The predominant periods of the short period internal oscillations in MLD are around 6.9 hrs (maximum) and 11.3 hrs with amplitudes around 3 m in the central Arabian Sea. The lower modes of short period internal oscillations have periods of 6 hrs, 7.7 hrs and 10.1 hrs with amplitudes between 1.5 m and 3 m. Using time series 3 hourly data sets, Ramam et al. (1979) reported short period oscillations with periods ranging from 5 to 11 hrs at a depth of 50-60 m in the central Arabian Sea during May–June with the internal wave height varying from 3 to 4 m (corresponding to amplitudes of 1.5–7 m). This agrees well with the present amplitudes of the short period internal oscillations in MLD. The variability of short period internal waves for the other months of the year is not available.

3.9.2 Long period internal waves

The long period components of MLD oscillations show increased amplitudes at the higher periods. The predominant peaks of energy occur at harmonics with periods of 64 hrs (near inertial), 48 hrs, 24 hrs, 17.5 hrs and 16 hrs. The near inertial oscillations exhibit an amplitude range of about 6 m. The overall distribution of amplitude of the long period oscillations shows a range of 4-10 m. The range of amplitudes is of the same order of magnitude (4-5 m) of internal tides of both diurnal and semidiurnal periods (12 hrs and 24 hrs) reported by
La Fond and Rao (1954) in the Bay of Bengal.

The amplitudes inferred from the present study fall within the range 1.5–10 m and a combination of one or more of these components may occur simultaneously with large amplitudes of layer depth.

The variability of internal waves is related to the variability in the causative factors like wind and air pressure fluctuation (Schott, 1971) and storms (Pollard, 1972) and currents (Roberts, 1975) and bottom irregularities. Seasonal and spatial variations of these in the Arabian Sea have profound influence on the internal oscillation which could not be examined from this data set. However, under short time scales up to inertial periods the MLD variability can be up to about ±10 m during the intense southwest monsoon regime over the mean observed layer for a duration up to 8 to 10 hrs as observed from this analysis.