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Seasonal and diurnal variability of thermal structure in the coastal waters off Visakhapatnam

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Abstract. Seasonal and diurnal variability of thermal structure in the coastal waters off Visakhapatnam has been examined in relation to the flow field and surface winds utilizing the hourly data of temperature and currents taken at a fixed location over a tidal cycle at monthly intervals. The coastal currents in the pre-monsoon period and strong near-surface winter cooling processes affect the thermal structure of the coastal sea. Upwelling which is predominant during March to May with an intermittent relaxing event helps in the development of a strong layered thermal structure while convective mixing due to winter inversions during November to February causes weak thermal gradients in the water column.

Keywords. Thermal structure; upwelling; sinking; coastal currents; Visakhapatnam coast.

1. Introduction

The changes in the thermal structure of the coastal sea are generally attributed to the coastal current patterns. Earlier studies on the variability of water characteristics off Visakhapatnam coast mainly dealt with the temperature and salinity data (La Fond 1954; La Fond and Rao 1954; Varadachari 1958; Murthy and Varadachari 1968 and Rao *et al* 1986). A few studies have been attempted to describe the coastal circulation off Visakhapatnam based on the information derived indirectly either from density field (Rao 1956; Murthy and Sastry 1957) or by drift methods (Ramanatham *et al* 1967). These studies have indicated two different regimes of upwelling and sinking off the coast during pre-monsoon and autumn periods respectively under the influence of seasonally varying wind and current systems. On the shorter time scales, the oscillations in the thermal structure are related to surface tidal forces. Though Shetye (1984) investigated the thermal variability in the coastal waters off Kerala, studies relating to the actual observed flow field with the thermal variability off the Visakhapatnam coast are not generally available. We present here the seasonal and diurnal variabilities of the thermal structure of waters off Visakhapatnam coast which are discussed in relation to the observed current and surface wind fields.

2. Materials and methods

Data on temperature, currents and surface meteorological parameters were collected at an hourly interval over a semi-diurnal tidal cycle in a single day which

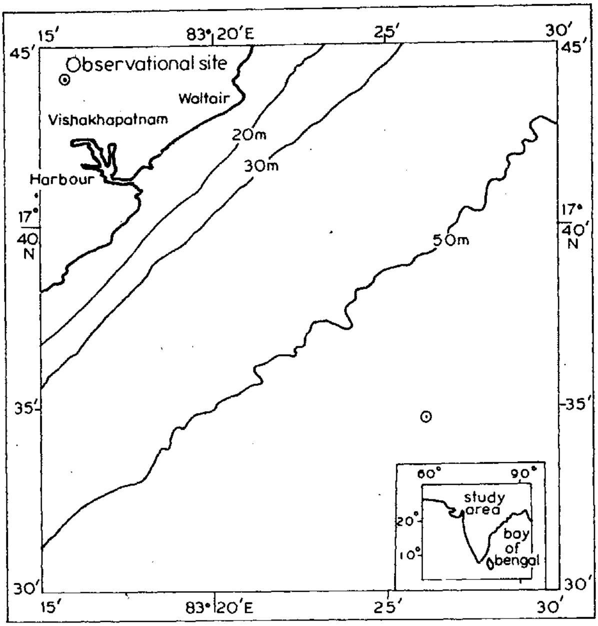

Figure 1. Observational location map.

was selected to represent every calender month. The observational site (figure 1) was located at a depth of 62 m. The mechanical bathythermograph (MBT) and a direct reading current meter (DRCM) (Model: DNC 3; accuracy: ±5 cm/sec; ±10°) were deployed from an anchored boat for collecting the temperature and current data respectively at every 10 m depth interval of water column. While the temperature data were obtained by digitizing continuous depth-temperature profile and thereafter by applying the necessary corrections, the currents were obtained by reading the display of the current meter which was held for a short time at every 10 m depth. Simultaneously, the wind data were obtained using an anemometer and a portable magnetic compass. The temperature data were collected over a semi-diurnal tidal cycle for every month from February 1980 to January 1981. During the monsoon season (July-August) the observations could not be carried out fully due to the prevailing rough sea conditions and limited MBT and the surface meteorological data were then collected. The current data were available upto June only and for subsequent period, no information on currents was obtained due to the failure of the current meter.

3. Results

3.1 *Surface meteorological conditions*

3.1a *Winds:* Table 1 presents the monthly surface wind data collected at the

Table 1. (I) Wind speed (m/sec) and (II) Direction (degrees true north).

Month/Time		0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000 IST	Average
Feb	I	–	–	–	4·3	–	4·3	4·3	5·0	5·3	4·3	4·0	5·2	5·5	5·2	5·2	4·8
	II	–	–	–	225	–	225	210	200	180	200	180	200	230	200	200	205
Mar	I	–	–	1·9	2·0	2·6	1·8	–	1·0	2·7	2·9	3·3	5·3	5·0	–	–	2·9
	II	–	–	10	10	20	80	–	150	150	150	160	180	185	–	–	110
Apr	I	–	6·7	7·5	8·0	8·0	8·3	8·3	–	–	–	–	–	–	–	–	7·8
	II	–	220	220	220	220	220	220	–	–	–	–	–	–	–	–	220
May	I	–	4·3	3·7	3·8	5·0	5·0	6·0	5·0	5·0	5·0	–	–	–	–	–	4·8
	II	–	210	210	210	210	210	170	210	180	200	–	–	–	–	–	201
Jue	I	–	2·2	2·8	4·0	3·0	2·0	2·3	4·0	2·7	2·7	1·9	–	–	–	–	2·8
	II	–	180	180	200	160	170	180	200	200	200	200	–	–	–	–	187
Jul	I	–	10·8	–	–	–	–	–	–	–	–	–	–	–	–	–	10·8
	II	–	200	–	–	–	–	–	–	–	–	–	–	–	–	–	200
Aug	I	–	–	4·3	5·5	5·6	–	–	–	–	–	–	–	–	–	–	5·1
	II	–	–	180	180	180	–	–	–	–	–	–	–	–	–	–	180
Sep	I	–	2·6	3·3	2·5	2·6	–	2·6	3·6	3·8	4·5	3·3	4·6	–	–	–	3·3
	II	–	45	45	45	45	–	180	180	180	180	180	160	–	–	–	126
Oct	I	–	6·3	6·3	6·7	6·7	6·0	6·0	6·0	5·0	5·0	4·2	–	–	–	–	5·8
	II	–	45	45	45	45	45	45	45	45	45	45	–	–	–	–	45
Nov	I	–	2·8	4·0	4·0	5·0	5·0	5·2	5·0	5·3	5·3	5·0	–	–	–	–	4·7
	II	–	40	40	40	40	40	40	40	40	40	40	–	–	–	–	40
Dec	I	3·0	3·0	4·8	4·3	5·0	5·0	4·2	4·2	2·5	2·2	2·0	3·6	–	–	–	3·7
	II	45	45	45	45	45	45	45	45	45	45	45	45	–	–	–	45
Jan	I	3·4	5·0	5·0	3·0	3·9	2·5	2·5	2·5	3·4	3·4	3·4	–	–	–	–	3·5
	II	50	50	50	50	60	60	40	40	50	50	70	–	–	–	–	52

Table 2. (I) Air temperature (°C) and (II) Sea surface temperature (°C)

Month/Time		0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000 IST	Average
Feb	I	–	–	–	25·5	–	26·0	27·0	27·0	27·5	29·0	28·5	27·0	26·5	26·0	26·0	26·4
	II	–	–	–	26·6	–	27·0	27·0	26·9	27·0	27·0	27·0	27·0	26·7	26·8	26·8	26·9
Mar	I	–	–	26·5	28·9	26·9	27·3	27·5	27·5	27·0	27·0	27·0	27·0	27·0	–	–	27·1
	II	–	–	26·3	26·4	26·6	26·6	26·8	26·8	26·9	27·4	28·0	27·6	27·6	–	–	27·0
Apr	I	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	II	–	28·5	28·7	28·5	28·5	28·5	28·5	28·5	28·5	–	–	–	–	–	–	28·5
May	I	–	28·5	28·5	29·0	29·2	29·5	29·5	29·0	29·0	29·0	29·0	–	–	–	–	29·2
	II	–	28·3	28·5	28·5	28·5	28·5	28·5	28·6	28·5	28·1	28·1	–	–	–	–	28·4
Jun	I	–	30·0	30·0	30·0	30·5	30·5	30·5	30·5	30·5	31·0	31·0	–	–	–	–	30·5
	II	–	29·8	29·7	30·1	30·2	30·4	30·5	30·6	30·5	30·6	30·7	–	–	–	–	30·3
Jul	I	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	II	–	27·5	–	–	–	–	–	–	–	–	–	–	–	–	–	27·5
Aug	I	–	29·5	29·5	29·5	–	–	–	–	–	–	–	–	–	–	–	29·5
	II	–	27·6	27·5	27·5	–	–	–	–	–	–	–	–	–	–	–	27·5
Sep	I	–	28·5	29·5	29·5	30·0	30·5	30·0	30·0	30·0	29·7	29·5	28·5	–	–	–	29·7
	II	–	29·4	29·7	29·4	29·5	29·7	29·3	29·7	30·0	30·0	30·1	30·0	–	–	–	29·6
Oct	I	–	28·0	29·5	30·0	30·0	30·5	31·0	30·5	30·5	30·0	30·0	–	–	–	–	30·0
	II	–	29·2	29·0	29·2	29·4	29·4	29·4	30·0	30·0	30·5	30·0	–	–	–	–	29·6
Nov	I	–	26·0	27·0	27·0	27·5	28·0	29·0	29·0	29·0	29·0	28·0	–	–	–	–	28·0
	II	–	26·4	27·1	26·7	27·1	27·1	27·5	27·1	27·6	27·6	27·1	–	–	–	–	27·1
Dec	I	24·5	24·5	24·5	25·0	25·0	26·0	26·0	27·0	27·5	26·5	26·0	26·0	–	–	–	25·7
	II	25·6	25·5	25·6	25·8	25·9	25·9	25·4	25·4	25·5	25·4	25·6	–	–	–	–	25·6
Jan	I	25·0	25·5	25·5	25·5	25·5	25·5	26·0	26·0	26·0	26·5	27·0	–	–	–	–	25·8
	II	24·6	24·7	24·7	24·6	24·6	24·9	25·4	24·8	24·7	24·8	24·8	24·8	–	–	–	24·8

Table 3. Surface meteorological conditions.

Calender period	Diurnal variation of winds Speed	Direction	Air temperature and SST	Diurnal SST range (°C)
Feb	Small	Small	Mean air temp. < Mean SST	0·4
Mar	High	High	Mean air temp. ≈ Mean SST	1·7
Apr	Small	Nil	—	0·2
May	Small	Small	Mean air temp. > Mean SST	0·5
Jun	Small	Small	Mean air temp. > Mean SST	1·0
Jul	–	–	–	–
Aug	–	–	Mean air temp. > Mean SST	–
Sep	Small	High	Mean air temp. ≈ Mean SST	0·7
Oct	Small	Nil	Mean air temp. > Mean SST	1·5
Nov	Small	Nil	Mean air temp. > Mean SST	1·2
Dec	High	Nil	Mean air temp. ≈ Mean SST	0·5
Jan	Small	Small	Mean air temp. > Mean SST	0·8

observational site. In February, the winds vary little diurnally and they are mainly from southwest and south directions with a speed of around 5 m/sec. In March, the wind data show a diurnal instability in both direction and speed. They are weak blowing from north-northeast and east directions before noon and are strong in the evenings blowing from southeast and south directions. In April, very steady and strong southwest winds with typical speeds around 8 m/sec prevail, while in May, the winds become weak again with moderate speeds around 5 m/sec and directed from south-southwest. In June, the winds are further lowered reaching an average value of 2·8 m/sec and are seen to rotate anti-clockwise. During July, the winds are strengthened (11 m/sec) with the onset of summer monsoon whereas in August, the wind speeds decrease to around 5 m/sec. The wind speeds weaken further (3 m/sec) during September and show a marked diurnal instability, especially in the direction as in March. From October to January, the wind speeds are mainly between 2 and 7 m/sec and the wind direction is predominantly from northeast. The diurnal stability in the wind field, especially the wind direction, is well pronounced during this period.

3.1b *Air and sea surface temperature:* The hourly values and the diurnal averages of both air (dry bulb) and sea surface temperatures (SST) at the observational site are presented in table 2. The air temperature is on an average lower than SST in February whereas during March, the difference between the averages of these two temperatures is considerably reduced. During the rest of the year, the air temperature in general is higher than SST. However, there is a tendency for the air temperature to be lower than SST at certain morning hours during post-monsoon and winter periods with an exception in January. These results are further summarized in table 3.

3.2 *Temperature variation*

3.2a *Diurnal time scales:* Figure 2 shows the diurnal variations of thermal structure depicted for every month except July. During February, the diurnal SST range (maximum minus minimum) for the observational period is 0·4°C. A positive

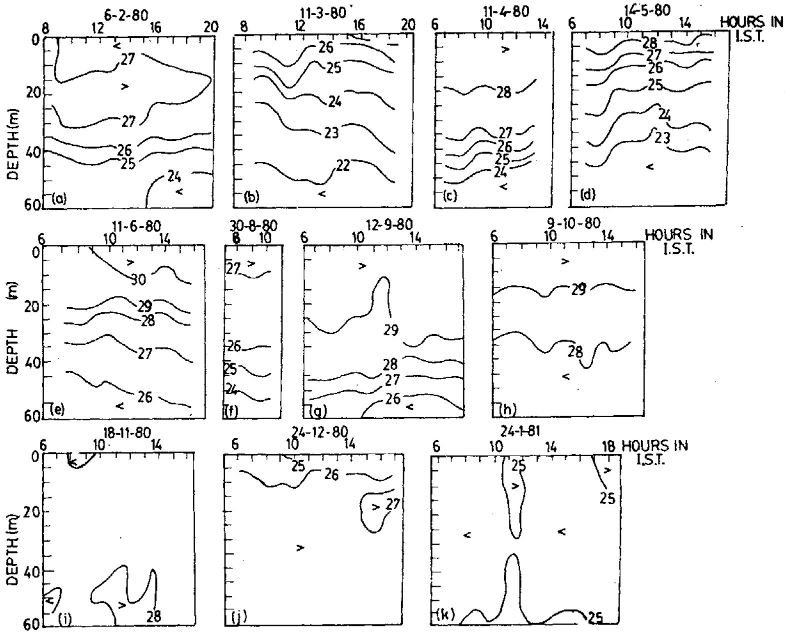

Figure 2. Diurnal variation of temperature(°C) in the coastal waters off Visakhapatnam for different months.

temperature gradient found in the depth range of 10–30 m continues to be present throughout the day (figure 2a). However, near the bottom, pockets of warm and cold waters are seen. During March, the diurnal SST range is well pronounced (1·7°C) and the positive temperature gradient as observed in the previous month completely disappears (figure 2b). The isotherms further exhibit the same mode of diurnal variation throughout the water column. In April, the mixed layer is conspicuously well developed (~35 m thickness) with an increase in temperature at all depths (figure 2c) while in May, the rising of isotherms is again seen throughout the water column (figure 2d) as in March. The mode of diurnal variation of isotherms in April is uniform depthwise whereas during May, its nature in the upper 20 m layer is in contrast to that in the near bottom layer where a dome in isotherms is seen around 1200 IST. During June, the surface layer gains heat and the diurnal SST range is about 1°C (figure 2e). The temperature of the water column lowers in July (diurnal SST range not presented here due to limited data) and August (figure 2f) with a simultaneous increase in the depth of thermocline. The diurnal SST range in September is more or less the same as that in the pre-monsoon period and the entire water column gains heat as seen from a general increase in temperature at all depths (figure 2g). In October, the temperature of water column further rises along with an increase in the diurnal SST range (1·5°C)(figure 2h). It is also to be noted that the thermal gradients are low in the water column, especially near the bottom layer in contrast to the structure in September. During November to December, cooling, in general, occurs resulting in the formation

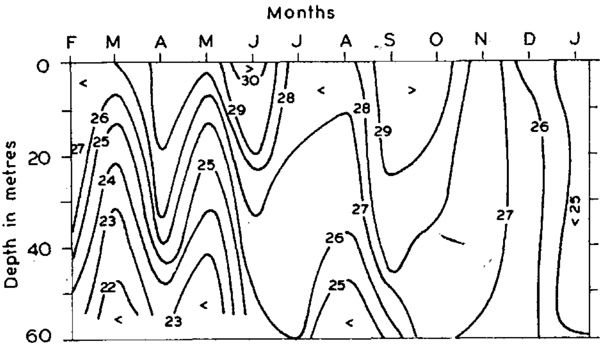

Figure 3. Seasonal variation of temperature(°C) in the coastal waters off Visakhapatnam.

of inversion layers near the surface (figures 2i and 2j) and the SST diurnal range is 1·2°C in November and it is 0·5°C in December (figure 2k). In January, the temperature of the water column reaches a minimum (around 24·8°C) and the inversions continue to be present.

3.2b *Seasonal time scales:* The temperatures observed at an hourly interval are averaged over each day to obtain daily averages which in turn represent the monthly values. The seasonal variation of thermal structure is presented in figure 3 which clearly shows the layered structure from February to September with a general weakening of thermal gradients with time. During November to January, the layered structure completely disappears leading to a strong mixed layer as seen from the vertical orientation of isotherms. In general, the thermal structure shows a very shallow thermocline during March and May with a conspicuous development of a strong intermittent mixed layer in April. A general lowering of isotherms takes place in the water column from May to June. During the summer monsoon season (July to August) again isotherms rise resulting in a zone of relatively cold waters (< 25°C) near the bottom. The seasonal cooling in the surface layer is found to be more than 1°C. A rapid increase in the temperature especially in the surface layers is observed during the post-monsoon season (September to October) and from November onwards, the temperature generally falls with time throughout the water column reaching a minimum value in January.

3.3 *Currents*

In February (figure 4a), the currents in the upper 30 m layer are steady and directed northward and northeastward while at deeper depths, currents vary considerably with time. During March (figure 4b) the flow is mainly between northeast and east with some off-shore drift in the upper layers in contrast to the longshore flow in February. From the data available in April (figure 4c), one could see that the flow is strengthened suddenly in the entire water column and is directed towards northeast with speeds around 1 m/sec. In May (figure 4d) the currents show a predominant off-shore direction in 0–10 m depth range as in March while below it, the currents are found oscillating. During June (figure 4e), the currents in

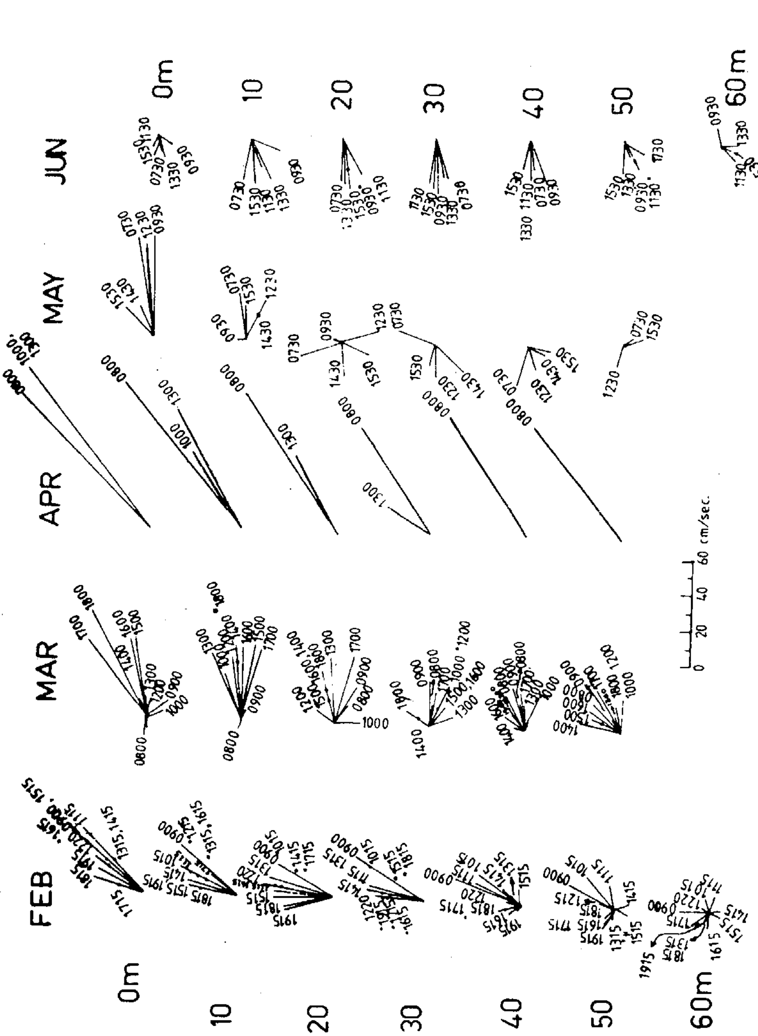

Figure 4. Coastal currents off Visakhapatnam.

general reverse in direction as seen from the presence of steady on-shore components in the upper 40 m water column while near the bottom they are slightly variable in direction.

4. Discussion

The maximum diurnal SST variation (range = 1·7°C) in March could be attributed to the stronger development of land–sea breeze system under which a high diurnal variation in wind field is seen (table 3). As the winds during the day time change their direction from north to south with a simultaneous increase in the speed (table 1) a wind drift is set up bringing more inshore warm waters into the observational location. The dry cold winds (table 2) during February cool the surface layer through an increase in both sensible and evaporative heat fluxes from sea to the atmosphere. This cooling in the surface layer as seen from the presence of inversions (figure 2a) leads to the formation of denser waters. The resultant convective mixing due to the sinking of denser waters is responsible for the development of weak gradients in the depth range of 0–15 m. Near the bottom (> 40 m), the presence of low and high temperature regimes indicates the effect of tides which can be inferred from the oscillatory nature of observed flow field.

The consistent occurrence of very cold waters (< 22°C) near the bottom in March (figure 2b) is due to the upwelling of waters in the coastal region as a result of increase in the off-shore components of currents compared to those in February. Although the near bottom currents do not show any on-shore flow tendency in this month, upwelling occurs in response to the presence of a vertical shear flow (stronger off-shore flow above the weaker one). It is not possible to examine the influence of the currents on the thermal structure in April due to limited current data. However, the strong surface winds (8 m/sec) which are conspicuously set during this month increase turbulent mixing in the upper layers resulting in weaker thermal gradients. Relatively, weaker off-shore components in the near surface flow field (figure 4c) during this month would also help in weakening the upwelling processes. When wind force is relaxed in May, the near surface currents (figure 4d) have become weak and are directed off-shore while below 10 m depth, they show some tendency of on-shore flow. This flow field revives upwelling in the water column.

It might be surprising to notice sinking under stronger winds blowing parallel to the coast situated on their left side and revival of upwelling accompanied by relaxation of winds. In shallow coastal regions where the angle of deflection between winds and the Ekman drift becomes smaller than 90°, upwelling is not expected to be intensive though winds are favourably blowing parallel to the coast, Moreover, some deviations from the Ekman theory are expected and the present set of observations need not follow the classical theory since the assumptions made in the theory cannot be approximated in a shallow coastal area. For the present study, the mean Ekman layer (depth of frictional resistance) is found to be about 40 m and the Rossby's radius of deformation is around 30 km. The reversal of surface currents in June from predominant off-shore components to on-shore components causes a cessation of upwelling and initiates sinking of waters which further helps in the development of surface layer and an increase in the

Table 4. Departures of dew point temperature from SST (°C).

Month	Mean dew point temperature	Departure from SST
Feb	25·2	−1·7
Mar	26·0	−1·0
Apr	–	–
May	28·3	−0·1
Jun	28·6	−1·7
Jul	–	–
Aug	27·7	+0·2
Sep	28·8	−0·9
Oct	28·5	−1·1
Nov	25·8	−1·3
Dec	22·0	−3·4
Jan	22·0	−2·9

temperature by about 3°C near the bottom from May to June. Thus, the upward motions in the water column seem to be mainly controlled by the off-shore/on-shore currents which are driven by factors other than wind. There is also a possibility of transient effects on sinking/upwelling processes caused by propagation of long period boundary waves which are trapped in the coastal regions. When a wave trough(ridge) passes over the area of study, it suppresses the upward (downward) motion of the thermocline intensifying the sinking (upwelling) processes in the water column.

The strong monsoon winds in July and August enhance the mixing processes resulting in a general cooling of water column (1°C). It is not possible to examine the influence of currents on the cooling processes in this period as there is no current data available after June. The absence of thermal gradients in the upper layer during September indicates the persistence of monsoonal wind effect. The homogeneous nature of the entire water column during November to January shows the influence of strong convective mixing as a result of inversions in the water column. The presence of thermal inversions could be related to net heat exchange between the sea and the atmosphere. Though sensible heat transport is directed towards the sea during November and January by virtue of higher air temperatures as compared to SST (table 3), the winter cooling is mainly effected through latent heat losses as seen from larger departures of dew point temperature from SST (higher evaporation rates) (table 4).

5. Conclusion

The present study gives some general characteristics of thermal variability in the coastal waters off Visakhapatnam based on a single year data. It is seen that the water column off Visakhapatnam coast is normally characterized by a layered thermal structure during spring and pre-monsoon (March to June) whereas during the later part of the year, this layered structure becomes weak and is absent by winter (November to February) due to an increase in the convective mixing. The seasonal variations in the depth of thermocline are rather controlled by current structure than by wind field alone.

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