

Seasonal cyclogenesis and the role of near-surface stratified layer in the Bay of Bengal

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Abstract

The role of the near-surface stratified layer developed due to the spread of low salinity waters under the influence of freshwater influx on the cyclogenesis over the Bay of Bengal is addressed. The seasonal variation of the Effective Oceanic Layer for Cyclogenesis (EOLC) and the associated effective heat potential, the parameters that represent the thermo-haline regime of the near-surface stratified layer, is discussed in relation to the seasonal cyclogenesis over the Bay. It is found that the zones of cyclogenesis during May and November, representing the pre- and post-southwest monsoon seasons respectively, over the central Bay and the southeastern Bay fairly coincide with the zones of higher EOLC, possessing higher percentage of effective heat potential. The climatological mean-cyclone tracks closely align with the contours of higher EOLC and suggest that the surface flow associated with the EOLC guides the movement of the weather disturbance. Also, the percentage of effective heat potential increases in the direction of cyclone track. This study reveals that one should consider the EOLC parameter for identifying the zones of cyclogenesis and for better prediction of cyclone tracks in the Bay of Bengal.

1. Introduction

Recently, Varkey et al. (1996) reviewed the Physical Oceanography of the Bay of Bengal and the Andaman Sea and documented the seasonal variability in the freshwater influx along the coastline, evaporation and precipitation over these water bodies and discussed the associated variability in the upper ocean hydrographic characteristics. The upper ocean thermo-haline variability in the northern Bay during the southwest monsoon season (June-September) leads to an increase of static stability with depth to a maximum value at subsurface depths (~ 30 m) due to the existence of intense halocline (Sastry et al., 1985; Murty et al., 1992; Murty et al., 1996). The depth of halocline (zone of sharp variations in salinity) changes from one location to the other in the Bay. The stable stratification near to the sea surface due to halocline leads to minimum vertical mixing which in turn helps maintaining warmer waters in the near-surface layer by net heat gain at the sea surface due to heat exchange across the air-sea interface and horizontal advective processes. The association of warmer SSTs with the low salinity waters in the northern Bay during monsoon season is also documented (Rao et al., 1981; Murty et al., 1996). Murty et al. (2000), further, show that the static stability maximum due to seasonal thermocline occurs well below the halocline stability maximum. Realizing the importance of the upper ocean stratification characterised by the subsurface stability maximum on the air-sea interaction and air-sea coupling processes in the Bay of Bengal and the Andaman Sea, Murty and Sarma (2000) have proposed a new oceanic parameter called

the "Effective Oceanic Layer for Cyclogenesis (EOLC)" that is related to the upper ocean stratification. A good example of air-sea coupling processes in the Bay of Bengal is the cyclogenesis and the associated organised convection. It is well documented that the number of weather systems (monsoon depressions, cyclones and severe cyclones) formed over the Bay of the Bengal in a year is 3-4 times higher than from those in the Arabian Sea (Anon, 1977; Obasi, 1997). The percentage of number of cyclones is more in May (pre-southwest monsoon) and November (post-southwest monsoon) based on 100 years (1877-1976) data on the storms and cyclones in the Bay of Bengal (Fig. 1). The tracks of cyclonic storms during pre- and post-southwest monsoon season for the recent period 1987-1994

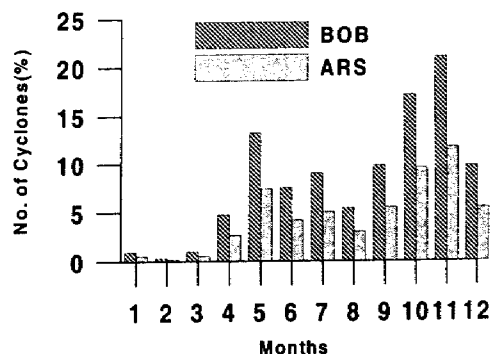


Fig. 1. Annual variation of percentage of number of cyclones over a period of 100 years (1877-1976) in the Bay of Bengal (BOB) and Arabian Sea (ARS) (After, Anon, 1976).

(Desai and Waikar, 1997) follow closely with the 100 year-mean climatological tracks (Anon, 1977). In this paper, the seasonal variability of EOLC and the associated upper ocean heat potential are discussed in relation to the pre- and post- southwest monsoon cyclogenesis and cyclone tracks in the Bay of Bengal.

2. Data and Methods

The climatological monthly mean temperature and salinity data (Conkright et al., 1994) in the upper 200 m have been used to compute the static stability parameter, $E (=N^2/g)$, where N is the Brunt-Vaisala frequency (rad/s) and g is the acceleration due to gravity ($9.8 \text{ m}^2/\text{s}^2$), following Pond and Pickard (1983). Since the depth variation of near-surface stability maximum varied narrowly around 30 m depth, we have computed the geopotential thickness ($\Delta D = \int \alpha dp$, where α is the mean specific volume anomaly over the pressure interval, dp). The integration is carried out from sea surface to 30 m depth. This geopotential thickness (m^2/s^2), within the near-surface stratified layer, is termed as the EOLC. This parameter takes into account both temperature and salinity in the near-surface layer, thus represents the real oceanic conditions, in contrast to the Cyclone Heat Potential (CHP), the heat content of the water column relative to and up to the depth of 26°C isotherm. Earlier researchers (Rao et al., 1981; Sarma et al., 1990; Rao et al., 1998) proposed that the zones of higher CHP are energetically active wherein the genesis of the weather disturbance takes place. However, it is not certain that the moving weather disturbances would follow the higher CHP zones in the presence of intense upper layer stratification due to lower salinity waters. In other words, it is not known whether the path of the weather disturbances is modified /changed when it is moving over the highly stratified water column. In this article, we estimate the effective heat potential (EOLC-HP) in a similar way as that of CHP, but limited to the near-surface stratified layer whose mean temperature forms the effective temperature (EOLC-T). The EOLC-HP provides the necessary heat energy for the genesis / growth / development / sustenance of the weather disturbance. If the synoptic disturbance moves through the zone of large EOLC, the weather system would intensify/grow. If the movement of the synoptic system is through the zone of lower EOLC-HP, the weather system may not develop further, but weakens. The percentage of EOLC-HP to the CHP is also estimated and termed it as EOLC-%HP. Also utilizing the Comprehensive Oceanic and Atmospheric Data Set (COADS) of relative humidity (RH), SST and atmospheric pressure at sea surface for 12 years during 1982-93, the 12 year-mean monthly averages of relative humidity (RH) and specific humidity of air (Qa) are obtained. The monthly

distributions of SST, sea surface salinity (SSS), EOLC, EOLC-T, EOLC-HP, EOLC-%HP, RH and Qa have been examined. In this study, we restrict the presentation only to the distributions of EOLC, EOLC-%HP and Qa for the representative months of the two transition seasons – pre-southwest monsoon (May) and post-southwest monsoon (November). Based on the near-synoptic hydrographic data, we discuss the inter-relationship between EOLC, SST and SSS for the post-southwest monsoon (November) of 1985.

3. Results and Discussion

Fig. 2 represents a typical profile of static stability parameter in the central Bay and northern Andaman Sea during May and November respectively. One would see a large subsurface maximum at around 30-40 m depth with relatively larger value in the Andaman Sea under the influence of spread of low salinity waters. The stability maxima lie in the halocline zone. Similar hydrographic conditions with subsurface stability maximum may also be prevalent in the meso-scale anticyclonic eddies in which the low salinity waters are trapped. Sastry and Rao (1981) also show larger values of static stability around 30-40m depth coinciding with the halocline in association with the spread of low salinity waters (from freshwater influx and precipitation). The interaction of the tropical storms/cyclones with the sea surface of the Bay of Bengal is reported to be higher (with larger sea surface cooling up to 3°C) in the areas of weaker stratification with respect to spread of freshwater influx (Rao, 1987;

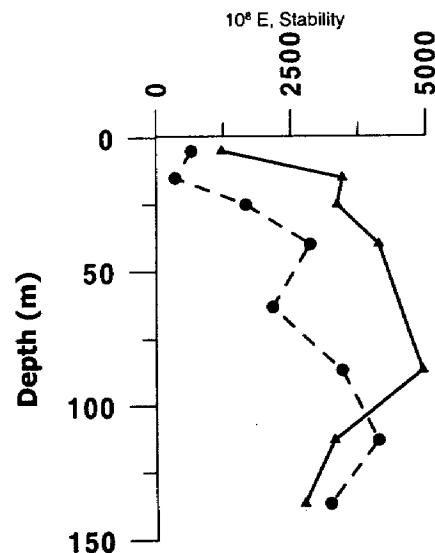


Fig. 2. Typical profiles of upper ocean static stability parameter (E) in the central Bay (•••••) during May and northern Andaman Sea (—) during November.

Gopaiakrishna et al., 1993). However, in the area of intense stratification due to freshwater influx, the sea surface cooling due to deep-depression is only up to 0.3°C (Murty et al., 1996).

3.1 Seasonal distributions of EOLC, EOLC-%HP and Qa

The seasonal variation of sea surface temperature (SST) shows that the surface waters are warmer (>28°C) from April to November in the entire Bay (Conkright et al., 1994; Murty et al., 1998). The seasonal freshwater influx is large during southwest monsoon period and drops the SSS to lower values (20-23) in the northern Bay and Andaman Sea (Rao et al., 1981; Murty et al., 1992; Murty et al., 1996; Varkey et al., 1996). In the Andaman Sea, the spread of freshwater takes place by the end of the southwest monsoon followed by the weakening of the southwesterly wind stress.

By definition, the dynamic parameter, EOLC would describe the flow field in the near-surface layer, assuming geostrophic balance. Then, in the Northern Hemisphere, higher values of EOLC occur to the right of the direction of flow and lower values to the left of the flow direction.

3.2 Pre-southwest monsoon (May)

During this period, the warm pool of the Bay is characterized with higher (30°C) SST and SSS (>33.5) in the central Bay (Figs. 3a-b). Relatively lower SST and SSS prevail in the northeastern Bay and northern Andaman Sea and the weak salinity variation (32.5 to 34.0) is due to the minimum freshwater influx. The EOLC varies from 1.95 m²/s² in the southwest to >2.2 m²/s² in the Andaman Sea and northwest of the Andaman Islands (Fig. 3c). From this region of higher EOLC, the EOLC decreases westward to a lower value of 2.05 m²/s² in the western Bay. The contours of EOLC indicate a westward flow in the southern Bay (<10°N) and its northeastward turning from north of 10°N. A northwestward flow emanates from the southeastern Bay/southern Andaman Sea. The superposition of the climatological cyclone tracks of this month on the EOLC shows two interesting features. Firstly, the zones of genesis of the cyclones (the base of each track in the Fig. 3c) fall between 10°-12°N and within the higher EOLC contours (2.10 - 2.15 m²/s²). Secondly, the cyclone tracks pass over the higher EOLC contours (>2.1 m²/s²). The alignment between the EOLC contours and the cyclone track suggests that the near-surface flow guides the movement of the cyclones. It is intriguing that the near-surface thermo-haline driven flow, without being influenced by the thermocline circulation, takes control on the movements of the

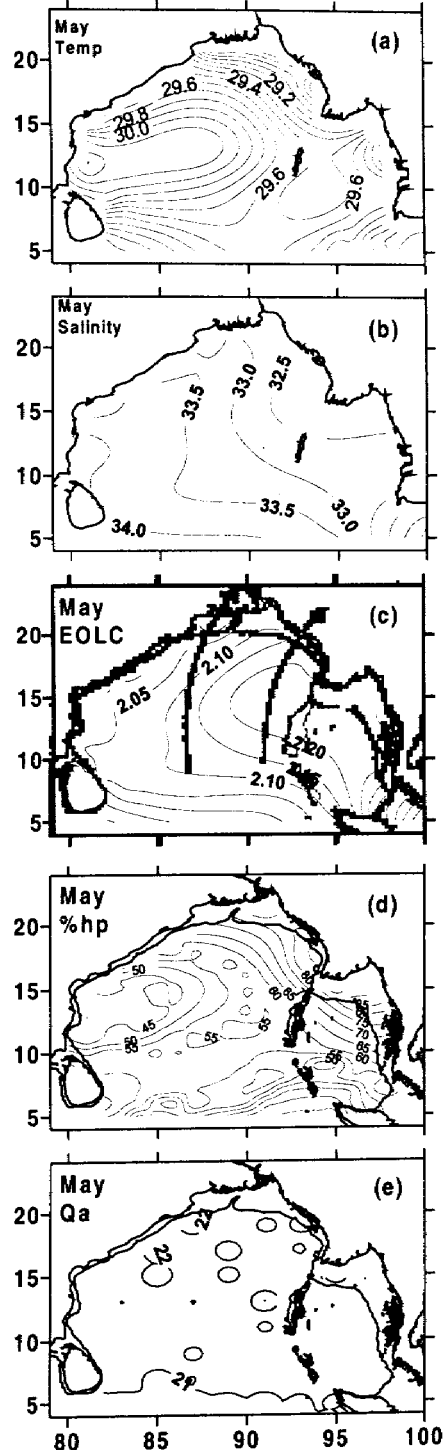


Fig. 3. Distributions of (a) SST, (b) SSS, (c) EOLC, (d) EOLC-%HP and (e) Qa during May, based on the climatological data.

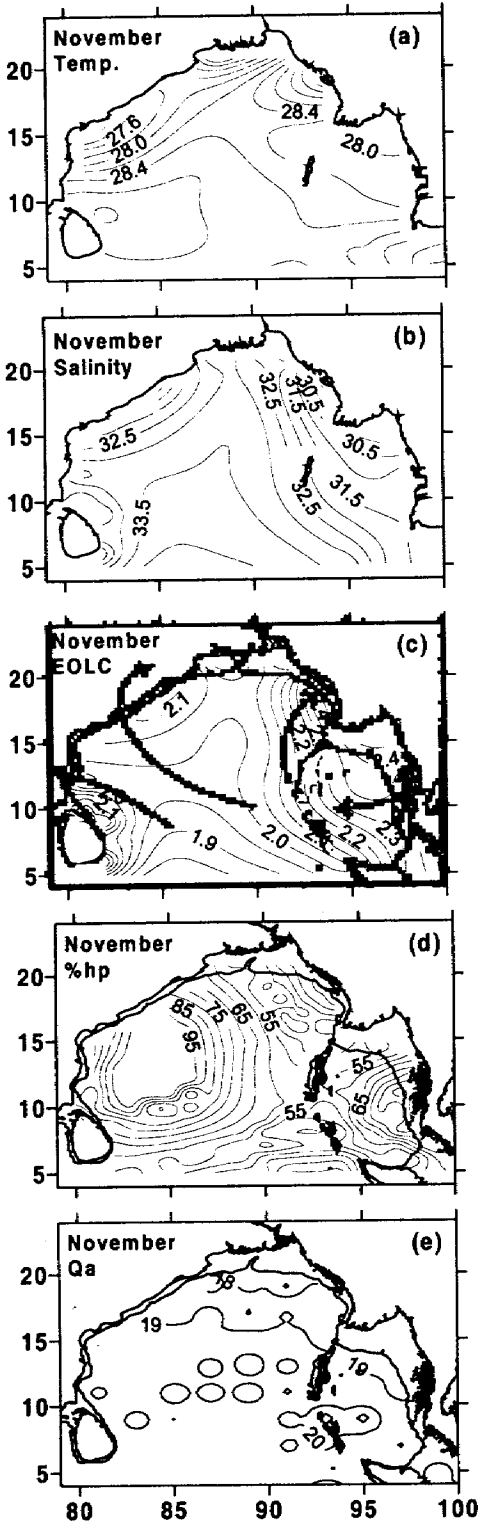


Fig. 4. Same as in Fig. 3, but for November.

cyclones/weather disturbances during this period. The EOLC-%HP exceeds 55% in the zone of cyclogenesis over the central Bay and increases towards northeastern Bay in the direction of cyclone track (Fig. 3d). It is surprising that the warm pool region (Fig. 3a) towards the western Bay is not supporting cyclogenesis due to its association with lower (<50%) EOLC-%HP. The specific humidity of air is around 22 g/kg over the zone of cyclogenesis (Fig. 3e) and along the cyclone tracks, indicating that the higher EOLC region acts as the source of moisture in addition to the source of effective higher heat potential.

3.3 Post-southwest monsoon (November)

The southwestern Bay possesses warmer SSTs ($>28.6^{\circ}\text{C}$) as the warm pool recedes southwards (Fig. 4a). Lowest SSS (<32.5) is noticed in the northeastern Bay, northern Andaman Sea (Fig. 4b) due the spread of low salinity waters from the Irravaddy and Salween river system. The EOLC attains higher values ($>2.2\text{ m}^2/\text{s}^2$) in the northern Andaman Sea and northeastern Bay and the contours are nearly parallel to coast line (Fig. 4c), suggesting a poleward flow along this coast. This coastal flow spreads the low salinity waters from the northern Andaman Sea towards northeastern Bay. Also along the east coast of India, the EOLC contours run parallel to the coast, suggesting a southerly flow constituting the East India Coastal Current (McCreary et al., 1996) and advecting the low salinity waters from the north Bay. South of 15°N , a westward flow emanating from the southeastern Bay can be seen. Again, as seen during May, the pattern and magnitude of the EOLC contours well support the zones of cyclogenesis and the tracks of the cyclones in the eastern Bay (Fig. 4c). The recursive nature of the tropical cyclones (Desai and Waikar, 1997) towards Bangladesh is closely related to the EOLC pattern (Fig. 4c). Further, the distribution of EOLC-%HP also supports the cyclogenesis and the path of the cyclone tracks (Fig. 4d). The specific humidity of air is around 19 g/kg at the zones of higher EOLC (Fig. 4e).

With the northward advancement of the monsoon trough during May and its southward retreat by October-November, cyclonic vorticity prevails in the lower troposphere over the central Bay up to the northern Andaman Sea. The prevailing atmospheric conditions (the cyclonic vorticity and wind shear) over the zones of higher EOLC and higher percentage of effective heat potential would trigger cyclogenesis over the central Bay and eastern Bay during May and November. It is surmised that once cyclogenesis takes place, the path and intensity of the cyclone are controlled by the surface flow (EOLC) and the effective heat potential (EOLC-HP) respectively.

3.4 Relationship between EOLC, SST and SSS

Murty and Sarma (2000) have examined the inter-relationships between EOLC, SST and SSS using the near-synoptic hydrographic data collected from various surveys in different seasons during which synoptic weather disturbances generated over the Bay of Bengal. They found a promisingly good inverse correlation between EOLC and SSS, but not with EOLC and SST. Figs. 5a-b present the scatter plots of EOLC vs SST and EOLC vs SSS for the November, 1985 based on time-series data at 11.5°N, 91°E, west of the Andaman Islands. The better correlation between EOLC and SSS suggests that the EOLC is primarily dependent up on SSS and higher EOLC values occur at low surface salinity. As the higher EOLC regions coincide with the zones of cyclogenesis, it is surmised that the regions/meso-scale plumes (~500 km size) of lower surface salinity have a potential control on the cyclogenesis. If the sea surface salinity is derived from the remote sensing satellite data (from the evaporation and the precipitation balance) to a greater accuracy, the EOLC distribution can be estimated. The pattern of EOLC further provides more information on the probable path of the cyclone / storm, once emanated from the zones of cyclogenesis.

Thus incorporation of surface salinity, through EOLC, into the numerical models for the prediction of cyclone tracks (Prasad et al., 1997) becomes necessary for the best results of prediction with reference to the Bay of Bengal and Andaman Sea. Our study clearly brings out that it is the plumes of freshwater of low salinity, rather than SST alone (Gadgil, 2000) and the associated upper ocean stratification that control the dynamic parameter EOLC and causes the genesis of weather disturbances (or convective systems). Murty and Sarma (2000) pointed out that a qualitative relationship exists between the EOLC and the satellite derived Outgoing Longwave Radiation (OLR). In conclusion, it can be expected that if the relationship between the oceanic parameter, EOLC and the atmospheric parameter, OLR is established through further studies, the air-sea coupling processes in the Bay of Bengal could be understood in a detailed way.

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