

## **Impact of freshwater influx on the cyclogenesis, tracks of cyclones and air-sea coupling over the Bay of Bengal**

**V.S.N. Murty<sup>1</sup>, M.S.S. Sarma<sup>1</sup>, George V. Jenson<sup>2</sup> and P.J. Vidya<sup>1</sup>**

1. *National Institute of Oceanography, Dona Paula, Goa, India – 403 004*
2. *Department of Physical Oceanography, Cochin University of Science and Technology, Kochi – 682 016*

### **Abstract**

Over the Bay of Bengal weather disturbances of considerable seasonal variability in their zones of genesis, intensity, frequency and path across the Bay generate during May-November. This variability in the zones of cyclogenesis and paths of weather disturbances are well correlated with the proposed *new dynamic parameter* - the Effective Oceanic Layer for Cyclogenesis (EOLC) - defined as the geopotential thickness ( $\Delta D$ ) of the near-surface stratified layer formed due to spread of low salinity waters caused by freshwater influx and precipitation. It is found that the zone of higher EOLC, characterised by warmer temperature, lower surface salinity, higher heat potential and higher specific humidity in the surface air, couples with the zone of intense deep-organised convection (lower values of Outgoing Longwave Radiation) in the lower troposphere leading to the cyclogenesis. The surface flow in the stratified layer, decoupled from the thermocline processes, appears to guide the movement of weather disturbance into the region of increasing effective heat potential. Thus, the EOLC is a useful parameter, over the sea surface temperature, for better prediction of cyclone tracks, among many other potential applications.

The recently acquired upper ocean data from the Bay of Bengal Monsoon Experiment (BOBMEX) in 1999 and in November 2007 are found to be consistent with the above. Some results from these data sets will be presented.

## 1. Introduction

The Bay of Bengal together with the Andaman Sea is the semi-enclosed tropical oceanic body of the northeastern Indian Ocean with a unique oceanographic setup [warmer SST ( $>28^{\circ}\text{C}$ ), huge freshwater influx ( $70 \times 10^3 \text{ m}^3/\text{s}$ ), excess precipitation (230 cm/year) over evaporation (35 cm/year) and seasonally reversing monsoons (1-6)]. This setup affects the air-sea interaction and air-sea coupling processes (7,8) at diurnal, synoptic and seasonal time scales. A good example of air-sea coupling processes in the Bay is the cyclogenesis and the associated organised deep-convection. A number of weather disturbances generate and intensify from a synoptic low into various stages of a tropical cyclone during April-November (9). The number of weather systems and their percentage are 3-4 times higher, more so during May and November, over the Bay of Bengal compared to the Arabian Sea (9,10), the fact that is still puzzling the scientific community. The dramatic seasonal shift in the zones of cyclogenesis and a wide scatter in the tracks of these disturbances are the notable features. The genesis of these disturbances is associated with the advancement, persistence and retrieval of the Inter-Tropical Convergence Zone (ITCZ) over the Bay of Bengal from April through November. The genesis of cyclonic storms takes place over the central Bay during April-May (pre-southwest monsoon), monsoon depressions over the northern Bay ( $>17^{\circ}\text{N}$ ) during June-September, severe cyclonic storms of hurricane intensity over the Andaman Sea and southeastern Bay during October-November (post-southwest monsoon). In some years, the remnants of the western Pacific typhoons rejuvenate (11) over the Andaman Sea and intensify into depressions. The variability in the frequency and path of the post-monsoon weather disturbances is also correlated with the El Nino-Southern Oscillation (ENSO) events (12). Earlier studies considered the sea surface temperature (SST) of  $26^{\circ}\text{C}$  as the threshold value for the genesis of weather disturbances (13-14). During January-March, the SST is around/below the threshold value (4,15) and would not support cyclogenesis. For the rest of the year, the SST is  $2^{\circ}$ - $5^{\circ}\text{C}$  warmer than  $26^{\circ}\text{C}$  and would support the cyclogenesis, under favorable atmospheric conditions (extension of humidity up to 400 hPa and instability, upward motion or vertical temperature gradient in the atmosphere) due to the presence of ITCZ. Earlier investigators (16,

17) attempted relating the zones of higher Cyclone Heat Potential (CHP), estimated from the temperature profiles relative to and up to the depth of 26°C isotherm ( $D_{26}$ ), as the potential zones for cyclogenesis. The recent review on the Physical Oceanography of the Bay of Bengal and Andaman Sea (3) documents the seasonal variability in the water budget (freshwater influx + precipitation – evaporation) of the region. The associated upper ocean thermo-haline variability with a halocline (zone of sharp variations in salinity) in the depth range of 20-40 m leads to an increase of static stability with depth to a subsurface (~30 m) maximum value (2,3,6). This stable stratification in the surface layer in turn inhibits vertical mixing which helps maintaining warmer waters in this stratified layer by net heat flux across the air-sea interface and also by horizontal advective processes (6). The impact of the upper layer stratification on the air-sea interaction processes can be understood from the suppression of depression-induced-upwelling of cold waters reaching to sea surface causing mild lowering of SST (~0.5°C) followed by smaller (~20-30 m) mixed layer depth in the northwestern Bay during southwest monsoon (6). In contrast, a significant lowering of SST to 3°C followed by deep (~80 m) mixed layer due to severe cyclones is reported in the region of weaker stratification during pre-southwest monsoon (18,19). The recorded higher SSTs (29°-31°C) in the northern Bay during August 1998 by the Met-Ocean moored data buoys (20), in our opinion, could be related to processes associated with upper layer stratification. The association of warmer SSTs and low salinity waters is also documented earlier (6,16). The static stability maximum due to seasonal thermocline and the depth range of 26°C isotherm usually lies well below the depth of stability maximum due to halocline (17,21). Further, it is not certain whether the moving weather disturbances follow the higher CHP zones in the presence of intense upper layer stratification due to low salinity waters, in other words, whether the path of the weather disturbances is modified/changed when they move over the highly stratified water column. We, thus, realize that decoupling the near-surface stratified layer from the seasonal thermocline would have tremendous impact on the air-sea interaction and air-sea coupling processes in the Bay of Bengal and Andaman Sea. In order to understand the effective role of the upper layer stratification, we have defined a *new dynamic parameter*, the Effective Oceanic Layer for Cyclogenesis (EOLC)

which is derived from both temperature and salinity in the near-surface stratified layer, in contrast to the CHP parameter (13,14,16,17). The EOLC is defined as the geopotential thickness ( $\Delta D = \int \alpha dp$ , where  $\alpha$  is the mean specific volume anomaly over the pressure interval,  $dp$ ) of the stratified layer from the surface to the depth (~30 m) of subsurface stability maximum. The distribution of EOLC, having units of  $m^2/s^2$ , also describes the flow field in the near-surface stratified layer, if geostrophic balance is assumed, with higher EOLC to the right (left) of the flow direction in the Northern (Southern) Hemisphere. The mean temperature of the stratified layer and the associated heat potential estimated relative to  $26^\circ C$  then form the effective temperature (EOLC-T) and effective heat potential (EOLC-HP) respectively for the genesis/ growth /development / sustenance of the weather disturbance. The pattern and magnitude of EOLC-T are similar to those of SST, as the upper 30 m layer is isothermal. The contribution of EOLC-HP aids (weakens) the growth of the system if the weather disturbance moves through the region of large (smaller) EOLC, suggesting a critical value of EOLC for the genesis / growth of weather systems. The percentage of EOLC-HP to the CHP, termed as EOLC-%HP, is also computed.

In this paper, we have highlighted the usefulness of EOLC, EOLC-%HP parameters for identifying the zones of cyclogenesis as well as for predicting the probable path of the weather disturbances in the Bay of Bengal. Many other potential usages of EOLC are discussed.

## **2. Data and methods**

The parameters EOLC, EOLC-T, EOLC-HP and EOLC-%HP in the 0-30 m layer are computed using the  $1^\circ \times 1^\circ$  grid monthly climatological temperature and salinity data for the Bay of Bengal (22) and near-synoptic hydrographic data during 1984 for the northern Bay (2). The climatological (1877-1976) monthly-mean cyclone tracks (9) and the tracks of in situ generated weather disturbances in the northern Bay during 1984 (23) are superimposed on the respective EOLC maps. The maps of EOLC are also correlated with the monthly-mean maps of INSAT-1D derived Outgoing Longwave Radiation (OLR) during 1990-96 and specific humidity of air (Qa) computed from the Comprehensive Oceanic and Atmospheric Data Sets

(COADS) during 1982-93. In the following paragraphs, the results of the above analysis are presented for the months of southwest monsoon (July) and post-monsoon (October) seasons and as a case study during July, 1984.

### 3. Results and discussion

Figures 1a-b shows the typical profiles of upper layer temperature and salinity in the northern Bay and the Andaman Sea during August and October respectively. The temperature profiles indicate warmer SST and an isothermal ( $\sim 28^\circ\text{C}$ ) layer up to 30 m. Whereas the salinity profiles show the presence of halocline (rapid increase of salinity with depth) in the upper 50 m. These thermo-haline distributions lead to strong stratification (rapid increase of water density with depth) in the upper layer. The associated static stability parameter ( $E = N^2/g$ , where  $N$  is the Brunt-Vaisala frequency and  $g$  is the acceleration due to gravity) attains a subsurface maximum at around 30 m (Fig. 1c). The stability parameter,  $E$ , has the units of  $\text{m}^{-1}$ . Earlier studies (24) also show maximum stability around 30-40 m in the halocline in the northern Bay (July-August), Andaman Sea (September-October) and southeastern Bay (December-February).

Figures 2 and 3 represent the distribution maps of EOLC and EOLC-%HP for July and October respectively. The respective distribution maps of  $Q_a$  are shown in Figure 4. During July, the EOLC and EOLC-%HP attain higher values ( $>2.4 \text{ m}^2/\text{s}^2$  and  $>60\%$ ) in the northern Bay (Figs. 2a-b) where warmer SST ( $29^\circ\text{C}$ ) and lower SSS ( $<30$ ) prevail. The northern Bay is more favourable for cyclogenesis as the necessary cyclonic vorticity exists in the lower troposphere due to the prevailing monsoon trough. The higher values of  $Q_a$  (Fig. 4a), over the zone of higher EOLC supports moisture convergence in the atmospheric boundary layer. It is interesting to see that the zone of genesis of monsoon depressions lies within the zone of higher ( $>2.2 \text{ m}^2/\text{s}^2$ ) EOLC and higher (55-70%) EOLC-%HP. Their tracks follow the contours of higher ( $>2.2 \text{ m}^2/\text{s}^2$ ) EOLC and the upper stratified layer maintains higher effective heat potential for the genesis/sustenance of the monsoon disturbances (Lows and Depressions etc.). The surface flow in the stratified layer, associated with the EOLC, is directed westward and appears to guide the westward moving

monsoon disturbances. It is to note that *no cyclogenesis* occurs in the southwestern Bay ( $\sim 10^\circ\text{N}$ ) though EOLC-%HP is high ( $>80\%$ ) there (Fig. 2b). This is due to the fact that EOLC there is below the threshold value ( $2.2 \text{ m}^2/\text{s}^2$ ), i.e., the region of weaker salinity stratification, compared to the northern Bay ( $>17^\circ\text{N}$ ). This also suggests the absence of cyclonic vorticity in the lower troposphere over the zone of lower EOLC (weaker salinity stratification) compared to that over the zone of higher EOLC (intense salinity stratification). The higher EOLC and EOLC-%HP in the northwestern Bay during July 1984 and the genesis and path of deep-depressions (23) also show excellent correlation (Figs. 2c-d). The higher values of  $Q_a$  based on COADS data for July 1984 supports surface moisture convergence over the zone of higher EOLC (not shown).

It is more interesting to note that during October the zone of higher EOLC ( $>2.4 \text{ m}^2/\text{s}^2$ ) shifts to the northern Andaman Sea and northeastern Bay (Fig. 3a), so also the zone of cyclogenesis. The lowest sea surface salinity (SSS) due to the spread of freshwater from the Irrawaddy and the Salween rivers maintain warmer SST and leads to higher EOLC. The magnitude and pattern of EOLC contours, suggesting a poleward coastal flow along the eastern Bay, support well the genesis of the synoptic disturbances in the Andaman Sea with their tracks following the contours of higher EOLC (Fig. 3a). The recursive nature of the tropical cyclones towards Bangladesh during October can also be explained by the split in the EOLC contours (indicating surface flow in the stratified layer) bending poleward east of  $87^\circ\text{E}$  and north of  $15^\circ\text{N}$ . The higher EOLC-T ( $>29^\circ\text{C}$ ), EOLC-%HP ( $>55\%$ ) and  $Q_a$  ( $>20 \text{ g/kg}$ , in Fig. 4b) in the northwestern Bay, act as heat and moisture sources for the sustenance of the synoptic disturbances passing over this region. Similar distributions of the above parameters persisting through November highlight the occurrence of cyclogenesis in the Andaman Sea and southeastern Bay during November.

As the zones of higher EOLC contain the zones of cyclogenesis (Figs. 2 & 3), it is surmised that the meso-scale cells or plumes ( $\sim 100\text{-}500 \text{ km}$  size) of low salinity will act as the potential zones for cyclogenesis. The seasonal and interannual changes in SSS would lead to wide scatter in the zones of cyclogenesis and tracks of cyclones.

The unusual absence of monsoon depressions in the northwestern Bay in some years (eg., in July, 1990 and 1999) might be due to higher SSS (lesser EOLC below the threshold value) in this region in these years.

Scatter plots EOLC vs SST and between EOLC vs SSS show weaker correlation ( $r^2 = <0.05$ ) and a fairly good negative relation ( $r^2 = >0.6$ ) respectively (Fig. 5a). This interesting relation indicates that the EOLC parameter can be predicted if the salinity is known. The scatter plot between EOLC and RH (not shown) shows a band of higher RH (80-90%) at the threshold EOLC value indicating that the zone of higher EOLC is invariably the source of moisture for convective processes in the lower troposphere. Similarly, the scatter plot between EOLC and OLR (both representing to  $2.5^\circ \times 2.5^\circ$  grids) shows a negative linear relation with a higher ( $r^2 = >0.6$ ) correlation coefficient (Fig. 5b). As EOLC increases the OLR falls to a lower value, suggesting that the zone of higher EOLC support deep-organised convection (i.e. lower OLR,  $<200 \text{ W/m}^2$ ). At lower EOLC, the OLR is high (i.e., cloud free conditions and hence no convection). This suggests that the deep-organised convection leading to cyclogenesis take place over the zone of higher EOLC. The superposition of distribution maps of EOLC and OLR for July (Fig. 6) also confirms that the zone of lower OLR ( $<175 \text{ W/m}^2$ ) is overlying the zone of higher EOLC ( $>2.1 \text{ m}^2/\text{s}^2$ ). The NOAA satellite derived monthly-mean OLR data (25) also shows that the northern Bay is characterised by lower ( $\sim 180 \text{ W/m}^2$ ) OLR wherein higher EOLC prevails during monsoon season. The reported synoptic situation in the Bay with a marked synoptic 'LOW' in the Indian Daily Weather Maps and the associated intense cloud bands (derived from INSAT-1D satellite) over the 'LOW' within the zone of higher EOLC is a classical evidence for this study.

On the similar lines of this study, the seasonal cyclogenesis and the role of near-surface stratified layer in the Bay of Bengal during pre-southwest monsoon (May) and post-southwest monsoon (November) is examined and similar conclusions have been drawn (26). Our study clearly brings out that the genesis of convective systems, their intensification and propagation would depend on the pattern of EOLC

(both magnitude and orientation of contours) rather than on SST, its gradients and its maximum value (7,8,20) alone.

Thus, obtaining the field of EOLC through OLR in real-time would help identifying the zone of cyclogenesis and the path of the disturbance which improves the forecasting and prediction (27) capabilities on the probable landfall point of the disturbance. Also, it is envisaged that one could map (i) the SSS from the above inter-relationships between the parameters, without going into the details of freshwater influx, precipitation and evaporation (28) and (ii) the more-realistic near surface flow that is decoupled from the thermocline processes.

It is hoped that this study would open new gates for the future oceanic research to better understanding the air-sea interaction and coupling processes in the Bay of Bengal or similar water bodies such as Western Pacific.

**Acknowledgements:** The authors are thankful to Director, NIO for his keen interest in this study.

## References

1. K. Wyrtki, Oceanographic atlas of the International Indian Ocean Expedition. Washington, DC, National Science Foundation, USA. 531 plates (1971).
2. V.S.N. Murty, Y.V.B. Sarma, D.P. Rao, C.S. Murty, *J.Mar.Res.* **50**, 207 (1992).
3. M.J. Varkey, V.S.N. Murty, A. Suryanarayana, Physical Oceanography of the Bay of Bengal and Andaman Sea. *Oceanography and Marine Biology: an Annual Review (eds.) A.D. Ansell, R.N. Gibson & Margaret Barnes.* **34**, 1 (1996).
4. S. Hastenrath, and P.J. Lamb, Climatic atlas of the Indian Ocean. Part I. Surface climate and atmospheric circulation. Madison: University of Wisconsin Press. 93 Charts (1979).



5. A. Baumgartner, and E. Reichel, The world water balance: Mean annual global, continental and Maritime precipitation, evaporation and run off, Elsevier Scientific, 179 (1975).
6. V.S.N. Murty, Y.V.B. Sarma, D.P. Rao, *Proc. Indian Acad. Sci. (Earth Planet Sci.)*, **105**, 41 (1996).
7. S. Gadgil, P.V. Joseph, N.V. Joshi, *Nature*. **312**, 141 (1984).
8. S. Gadgil, *Current Science*. **78**, 309 (2000)
9. Anon, Tracks of storms and cyclones in the Arabian Sea and Bay of Bengal. India Meteorology Department, New Delhi. (1977).
10. G.O.P. Obasi, *Mausam*. **48**, 103 (1977).
11. S.K. Srivastav, *Proc. Indian Acad. Sci. (Earth Planet Sci)*. **105**,189 (1995).
12. A. Gupta and A. Muthuchami, *Mausam*, **42**, 257 (1991).
13. W.M. Gray, *Atm. Sci. Paper*, **234**, Colorado State University, 119 (1975).
14. V.N. Ivanov and A.P. Khain, *Izvestiya, Atmos. and Oceanic Phys.* **19**, 593 (1983).
15. V.S.N. Murty *et al.*, *Int. J. Remote Sensing*. **19**, 2361 (1998).
16. R.R. Rao *et al.*, *Mausam*, **32**, 85 (1981).
17. Y.V.B. Sarma *et al.*, *Indian J. Mar. Sci.* **19**, 102 (1990).
18. R.R. Rao, *Mausam*, **38**, 147 (1987).
19. V.V. Gopalakrishna, *Indian J. Mar. Sci.* **22**, 8 (1993).
20. S. Premkumar *et al.*, *Curr. Sci.* **78**, 323 (2000).
21. V.S.N. Murty *et al.*, *Deep-sea Res. I*, **47**, 859 (2000).
22. M.E. Conkright *et al.*, Atlas of the northwestern Indian Ocean. University of South Florida, U.S.A., NOAA, US Department of Commerce (1994).
23. A.A. Rama Sastry, M.R.M. Rao, N.C. Biswas, *Mausam*, **37**,1 (1986).
24. J.S. Sastry and D.P. Rao, *Mausam*, **32**, 159 (1981).
25. NOAA-Climatic Diagnostic Bulletins 1991-96. Mean and anomaly fields of OLR. Near real-time analysis, ocean/atmosphere. US Department of Commerce, Climatic Analysis Centre, Washington, D.C.

26. V.S.N. Murty, M.S.S. Sarma, and V. Tilvi, Seasonal cyclogenesis and the role of near-surface stratified layer in the Bay of Bengal. *In: Proceedings of PORSEC 2000 (A-092)*, to be held at NIO, Goa, India during 5-8 December, 2000. (In press).
27. K. Prasad, Y.V. Rama Rao, and Sen Sanjib, *Mausam*, 48,351 (1997).
28. V.S.N. Murty, Estimation of sea surface salinity in the Bay of Bengal from satellite OLR data – a new approach (abstract). Invited lecture at the National workshop on "Trends in Ocean Sciences – 21<sup>st</sup> Century" held at Regional Centre N.I.O., Visakhapatnam, India.