INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN: 2278 – 0211 (Online)

# Upper Ocean Thermal features during Tropical Cyclones over Bay of Bengal

**Ch. Venkata Ramu, Patnaik, K V K R K*., Prasad, K V S R., Arun Kumar, S V V., Acharyulu, P S N.**

Dept. of Meteorology & Oceanography; Andhra University; Visakhapatnam, India

* Indian Maritime University, Visakhapatnam, India

***Abstract:***

*The upper ocean is dramatically affected during tropical cyclones (TCs). Cyclones interact not only with the surface but also with the deeper oceans, the depth depending upon the strength of the wind mixing. Hence, it is necessary to consider the thermal structure of the upper ocean for cyclone studies. Rapid intensification of cyclone Nargis in the Bay of Bengal from category-1 to category-4 within 24 hours was attributed to the presence of a pre-existing warm SSHA evidenced by the insitu (Argo data) and altimeter observations. The warmer layers of 26$^0$C extended up to 100 m beneath the surface such as Isothermal layer depth (ILD) and barrier layer thickness (BLT) and Upper Ocean Heat Content (UOHC) during the cyclone progression were computed. The rate of intensification and final intensity of cyclones are sensitive to the initial spatial distribution of the mixed layer. The most apparent effect of TC passage is noted by the marked SST cooling, and the response of the ocean mixed layer temperature typically 1 to 6$^0$C towards the right of the storm track. In the present work, the response of Upper Ocean to the tropical cyclones over Bay of Bengal based on the satellite Altimetry, ARGO, RAMA buoys and QUICKSCAT forced (MOM-GODAS) data. The present studies suggest the use of sea surface height anomalies (SSHA) data derivable from satellite altimeters are more useful instead of sea surface temperatures in the atmospheric models, particularly, in the cyclone and coupled models.*

## 1.Introduction

The tropical cyclones develop and intensify by picking up energy from the oceans and they prefer to move to warm water regions. Generally, these storms in the Bay of Bengal move towards East Coast of India and a few of them take re-curvature and hit Myanmar, Bangladesh coasts. The frequency of tropical cyclones in the North Indian Ocean has registered increasing trends during November and May, which account for maximum number of intense cyclones (Singh, et al., 2001). The cyclones interact not only with the surface of the ocean but also with the subsurface down to 100–200 m (Gray, 1979; Holliday and Thompson, 1979; Emanuel, 1986; Shay et al., 2000; Goni and Trinanes, 2003; Lin et al., 2003a, b; Emanuel et al., 2004; Lin et al., 2009; Scharroo et al., 2005; Pun et al., 2007; Wu et al., 2007). Therefore, subsurface thermal structure is of vital importance for the prediction of tropical cyclone intensification.

In addition to atmospheric parameters, it is now realized that ocean parameters such as SSHA, TCHP/UOHC plays a vital role in the intensification of storms rather than sea surface temperature (SST). Ali et.al (2007) showed the importance of sea surface height anomalies (SSHA) in the storm intensification than SST, qualitatively. Recently Goni et al., (2011) reported that there is a decrease in UOHC during 2009-2010 in the Gulf of Mexico and the southwestern Pacific Ocean while there is an increase in the western Pacific Ocean, Arabian Sea and Bay of Bengal. In this paper, we quantify the importance of upper ocean thermal features such as SST, ILD, MLD, BLT, D26 and TCHP/UOHC includes SSHA during the time of SIDR and NARGIS cyclones.

## 2.Data and Methodology

A deep depression in the southeast Bay of Bengal intensified into a cyclonic storm "SIDR" on $12^{th}$ November 2007 at $10.5^{O}$N; $91^{O}$E. It further intensified to a very severe cyclone, slightly moved northwestwards and thereafter it moved northerly direction up to 1200 UTC of $15^{th}$ November 2007(IMD, 2008). In month of April 2008 a deep depression formed in Bay of Bengal and lay centered near $12^{O}$N; $86.5^{O}$E on $27^{th}$ April 2008 and subsequently moving northwestwards, further it's intensified to cyclonic storm "NARGIS" and re-curving northeastwards on $30^{th}$ April and crossed southwest coast of Myanmar between 1200 & 1400 UTC along $16^{O}$N on $2^{nd}$ May 2008 (IMD, 2009). The cyclone track information and CI or 'T' number has been downloaded from the best track information available in www.imd.gov.in website.

Argo data for the above periods was downloaded from INCOIS Argo page (www.incois.gov.in/argo/). This data was undergone quality checks to remove the spikes and insignificant data. The model results (Ravichandran, et al., 2012) are downloaded from the INCOIS Live Accesses server. The high resolution SST date is downloaded from www.esrl.noaa.gov/psd/. Daily averaged temperature profiles and D20 during the cyclone periods have been taken from the three RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) buoys in the Bay of Bengal (Locations shown in Fig.1). The values at every one-meter interval were interpolated using Spline interpolation technique. The data on SSHA are taken from the following web site http://www.aviso.oceanobs.com/en/data/products/sea-surface-heightproducts/global/index.html

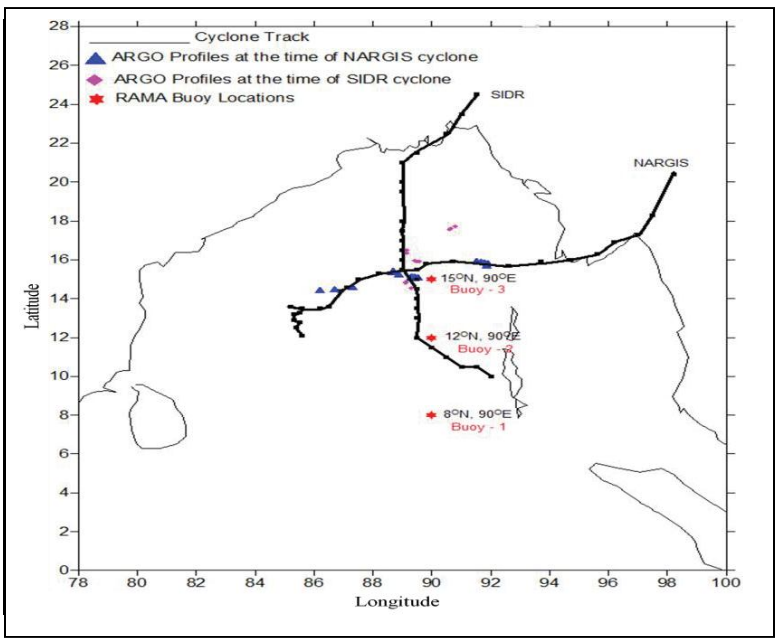


*Figure1: Location map of RAMA Buoys and SIDR, NARGIS cyclone tracks along with ARGO profiles locations during the cyclone time.*

## 3.Results and Discussions

The average monthly frequency of tropical cyclones in the North Indian Ocean in a year displays a bi-modal characteristic with a primary peak in November and secondary peak in May. Most of the severe cyclones in Bay of Bengal form during pre-monsoon (April-May) and post-monsoon (October-November) seasons. In this present study, we have considered two cyclones one is SIDR cyclone, which are formed in post monsoon season in the month of November 2007, and second one is NARGIS cyclone, which is formed in the end of 27th April, sustained up to 3rd May 2008 during pre-monsoon season. The range, mean and standard deviations of various parameters (SST, D26, D20, UOHC and SSHA) during pre monsoon (April- May) and post monsoon (Oct-Nov) seasons for the three RAMA buoy locations – 8$^{O}$N, 90$^{O}$E (buoy-1), 12$^{O}$N, 90$^{O}$E (buoy-2) and 15$^{O}$N, 90$^{O}$E (buoy-3) are computed and presented in Table 1.

| 8$^{0}$ N, 90$^{0}$E | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | SST ($^{0}$C) | | D26 (m) | | D20 (m) | | UOHC (kj/cm$^2$) | | SSHA (cm) | |
| | pre | Post | pre | post | pre | post | pre | post | pre | post |
| Range | 28.2-30.3 | 28.25-29.7 | 53-106 | 48-117 | 95-140 | 100-150 | 54-140 | 35-122 | -8.78-17.54 | -4.14-16.4 |
| Mean | 29.63 | 28.92 | 75.09 | 85 | 117.65 | 127.8 | 90.29 | 86.38 | 2.77 | 6.55 |
| Standard Deviation | 0.37 | 0.46 | 10.81 | 9.91 | 13.4 | 10.26 | 17.75 | 16.15 | 6.06 | 4.36 |
| 12$^{0}$ N, 90$^{0}$E | | | | | | | | | | |
| | SST ($^{0}$C) | | D26 (m) | | D20 (m) | | UOHC (kj/cm$^2$) | | SSHA (cm) | |
| | pre | Post | pre | post | pre | post | pre | post | pre | post |
| Range | 28.6-32.5 | 26.8-30.2 | 53-100 | 39-109 | 102-148 | 105-142 | 35-125 | 25-105 | -4.8-13.9 | -11-12.4 |
| Mean | 30.26 | 29.06 | 76 | 70.38 | 114.6 | 115.25 | 83.36 | 75.96 | 3.08 | 3.31 |
| Standard Deviation | 1.07 | 0.53 | 8.89 | 10.88 | 8.66 | 9.84 | 14.97 | 14.95 | 3.85 | 4.58 |
| 15$^{0}$ N, 90$^{0}$E | | | | | | | | | | |
| | SST ($^{0}$C) | | D26 (m) | | D20 (m) | | UOHC (kj/cm$^2$) | | SSHA (cm) | |
| | pre | Post | pre | post | pre | post | pre | post | pre | Post |
| Range | 28-32 | 28-30 | 53-100 | 60-106 | 110-146 | 100-160 | 42-121 | 50-126 | 0.5-17.7 | -9.5-20.48 |
| Mean | 29.96 | 29.21 | 83.2 | 76.06 | 128.5 | 124.45 | 91.90 | 86.13 | 6.31 | 5.02 |
| Standard Deviation | 0.68 | 0.42 | 7.97 | 9.45 | 7.44 | 11.55 | 12.61 | 14.46 | 4.51 | 5.98 |

*Table 1: Range, mean and standard deviation of SST, D26, D20, UOHC, and SSHA during pre monsoon and post monsoon seasons at the three locations.*
*(Source: Dr. K Maneesha, 2012." Role of upper Ocean in the Intensification and movement of tropical cyclones and their associated Biogeochemical response in the Bay of Bengal" Ph.D Thesis; Andhra University)*

*3.1.SIDR Cyclone*

At the time of SIDR cyclone, the SST shows 27.2 – 28.1$^{O}$C (fig. 2a) along the cyclone track. From the buoy observations, the annual SST is found to vary from 26 to 32.5$^{O}$C during pre and post monsoon season. During the post monsoon season, the mean temperatures are observed to be less than 30$^{O}$C (Table.1).

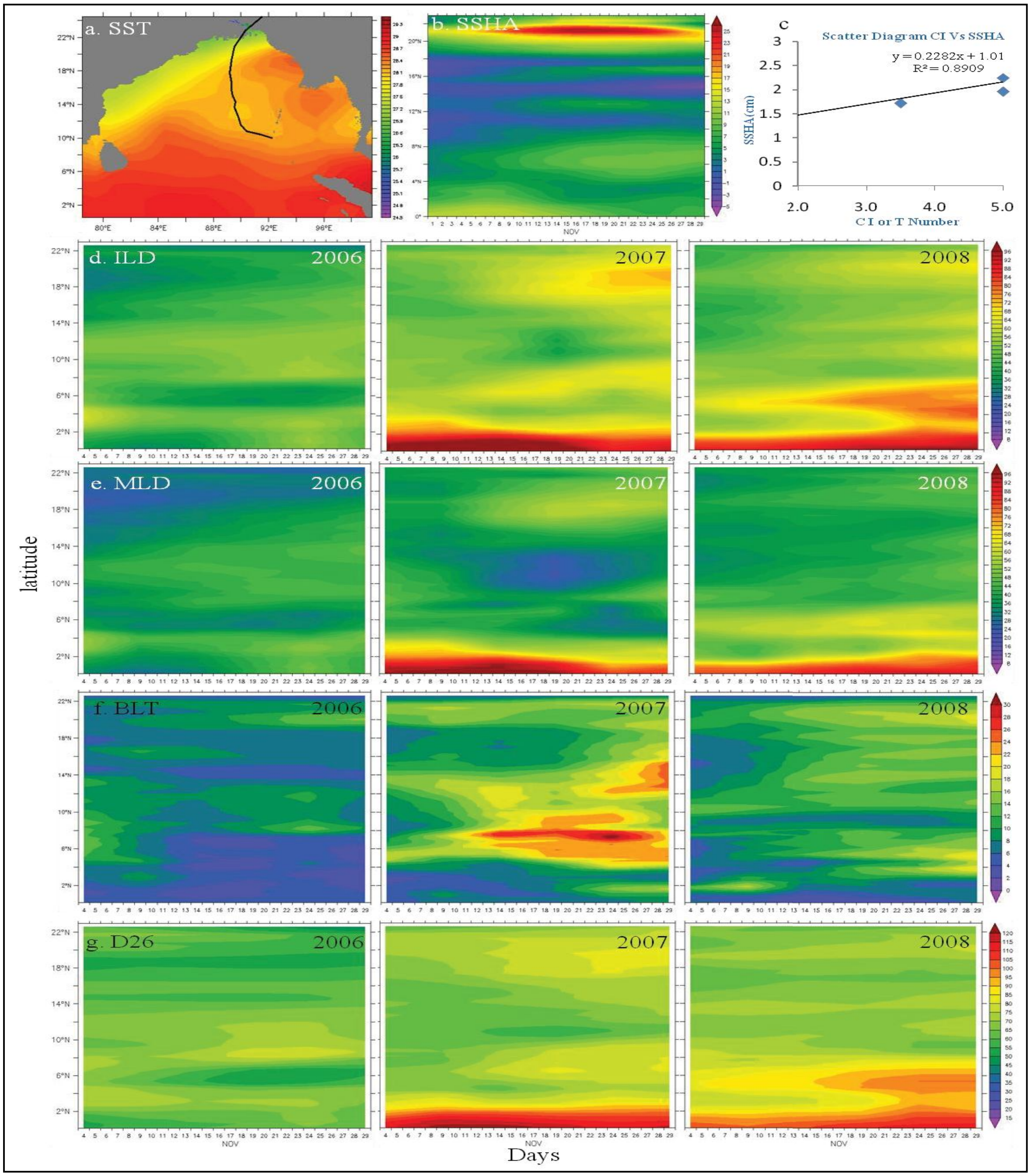


*Figure 2: Upper Ocean thermal features during the cyclone times, (a). NARGIS cyclone track overlaid by SST, (b). Sea surface Height Anomaly's (SSHA) in cm (c). Scatter diagram between CI and SSHA (cm). (d). Isothermal Layer Depth (ILD) in m (e). Mixed Layer Depth (MLD) in m (f). Barrier Layer Thickness (BLT) in m (g). Depth of 26$^{O}$C (D26) in m during the months of April and May for the years of 2006, 2007 and 2008, using QUICKSCAT MOM-GODAS data.*

This region was dominated by negative SSHA before the genesis of this storm, changed to positive and a peak value of 16 cm (Fig.2b). Highest range of 30 cm is found during post monsoon season at buoy-3 (Table.1). The SIDR cyclone was intensified while moving over the regions of high SSHAs. Good correlation 0.89 is observed with cyclone intensity (Fig. 2c). The distribution of ILD during the month of November 2007 along the latitudinal belt shows higher values 64 – 72 m (Fig. 2d) compare to the other years along the cyclone track derived from the model observations. The MLD climatology over the Bay of Bengal for this month varied from 5 – 30 m; while from the model observations it has been in the range of ~ 50 – 64 m (Fig. 2e) along the latitudinal belts and the ranges are much similar to that of RAMA and ARGO observations (see Fig. 3a to 3d).

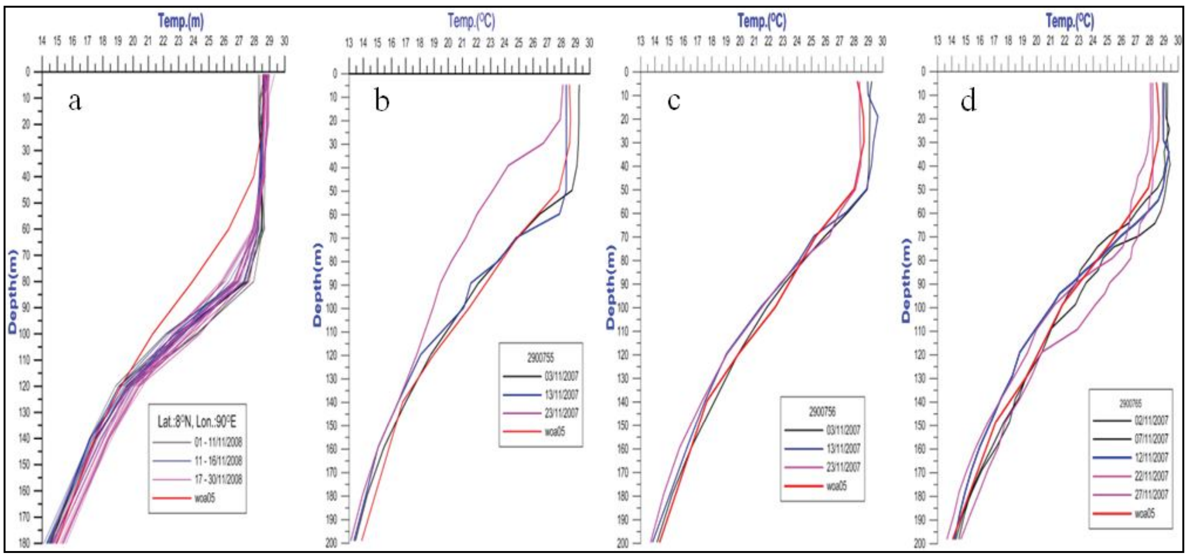


*Figure 3: Temperature profiles (a). RAMA buoy at 8$^O$N, 90$^O$E. (b). 2900755. (c). 2900756. (d). 2900765 using RAMA Buoy data and ARGO data before, during and after passage of SIDR cyclone*

The distribution of BLT for November 2007 shows higher values ~ 20 – 30 m with deepest observed on the latitudinal belt of 8$^O$N to 11$^O$N (Fig. 2f). During the period of SIDR cyclone, the D26 varies between 75 – 90 m (Fig. 2g) along the track and these values are higher compare to adjoining years. From the buoy observations, D26 is found to vary from 48-117 m at all the three locations with standard deviation 7 – 11 m. Higher values (>10 m) are observed at the buoy-1 during pre monsoon and at buoy-2 during post monsoon (Table.1). Sadhuram et al., (2004, 2006) has revealed that the UOHC with minimum threshold value of 60 kJ/cm$^2$ is necessary for the genesis and intensification of storms in the Bay of Bengal during the post monsoon (October-November) season.

D20 varied from 95-160 m at all the three locations during both pre and post monsoon seasons (Table.1). Highest range of 60m and lowest range of 36 m are observed at buoy-3 during post monsoon season and the pre monsoon season respectively. The ARGO profiles and RAMA individual profile shows the surface cooling and deepening of mixed layer after passage of cyclones (Fig. 4a to 4d). The north Bay of Bengal favours to intense cyclones during post-monsoon season (Oct-Nov), because of the high stratification due to the fresh water layer and sub surface inversions, help to store large amount of heat in the top few meters. Hence the top layer opposes the cooling due to a severe cyclone and result less cooling of SST (not more than $1^{o}C$ ), which helps to supply sufficient enthalpy flux for the intensity of storm (Senguptha et al., 2008).

*3.2.NARGIS Cyclone*

Overall, for the entire region covering the three buoy locations the annual SST is found to vary from 26 to $32.5^{O}C$ during pre and post monsoon season. Mean temperatures at buoy-2 are generally high with a maximum of $30.2^{O}C$ in the pre monsoon season (Table 1) and these ranges are equal to NOAA SST. The cyclone "SIDR" intensity increased after passing over warm SST to cooler SST (Fig. 2a), while in the case of "NARGIS" intensity increased from cooler SST to warmer SST (Fig. 4a). Sea Surface Height anomaly (SSHA) along the cyclone track and latitudinal belt of $12^{O}N$ to $16^{O}N$ varies from 11 – 17 cm (Fig. 4b). The cyclone intensity or 'T' number highly (0.99) co- related to the SSHA (Fig. 4c) and observed this, a less correlation is observed with SST. Sea Surface Height anomaly (SSHA) varies from -9.5 to 20.5 cm at all the three locations during both pre and post monsoon seasons. Mean SSHA varies from 2-7 cm in pre monsoon with maximum at buoy-1 and buoy-3. Lowest range of 9 cm is observed during the pre monsoon season at buoy-1.We have found that the ILD in the month of April and May 2008 on the latitudinal belt of $8^{O}N$ to $16^{O}N$ varies from 58 – 88 m (Fig. 4d) and this is the maximum range of connecting years excepted to the equatorial region. It is clearly observed that the cyclone interferes with the subsurface of the thermal structure.

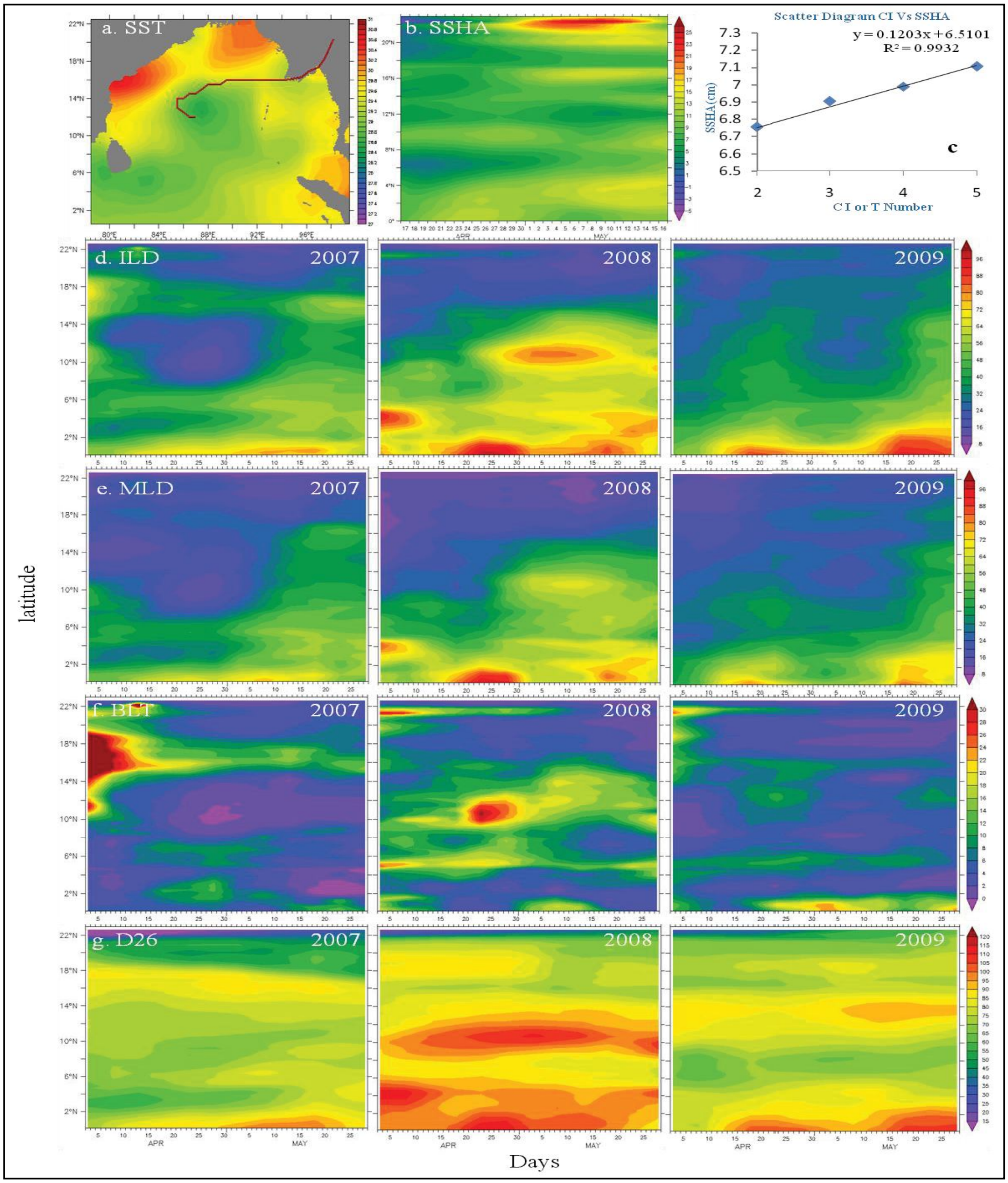


*Figure 4: Upper Ocean thermal features during the cyclone times, (a). NARGIS cyclone track overlaid by SST. (b). Sea surface Height Anomaly's (SSHA) in cm. (c). Scatter diagram between CI and SSHA (cm) (d). Isothermal Layer Depth (ILD) in m (e). Mixed Layer Depth (MLD) in m (f). Barrier Layer Thickness (BLT) in m (g). Depth of 26O C (D26) in m during the months of April and May for the years of 2007, 2008 and 2009, using QUICKSCAT MOM-GODAS data.*

In the months of April and May, MLD was shallower than 30 m (Climatology) in most part of the Bay except along the equator. However, in the case of "NARGIS" cyclone it varies from 48 – 72 m along cyclone passing latitudinal belt (Fig. 4e and Fig. 5a to 5e). A shallow MLD (8 – 20 m) was observed on northeastern part of the Bay. The BLT is abnormally varies in the month of April and May 2008 along the cyclone tack on the latitudinal belt of $10^{O}$N to $16^{O}$N varies from 20 – 30 m (Fig. 4f) and this is the maximum range of connecting years. Second peak of value ~ 30 m was noticed in April 2007, northern part of the Bay. When the tropical cyclones passes over the regions with barrier layers, increase in stratification and stability within the layer reduces the storm-induced vertical mixing and results in sea surface temperature cooling. This causes an increase in enthalpy flux from the ocean to the atmosphere and, consequently, an intensification of tropical cyclones. On average, the tropical cyclone intensification rate is nearly 50% higher over regions with barrier layers (Karthik et al 2012).

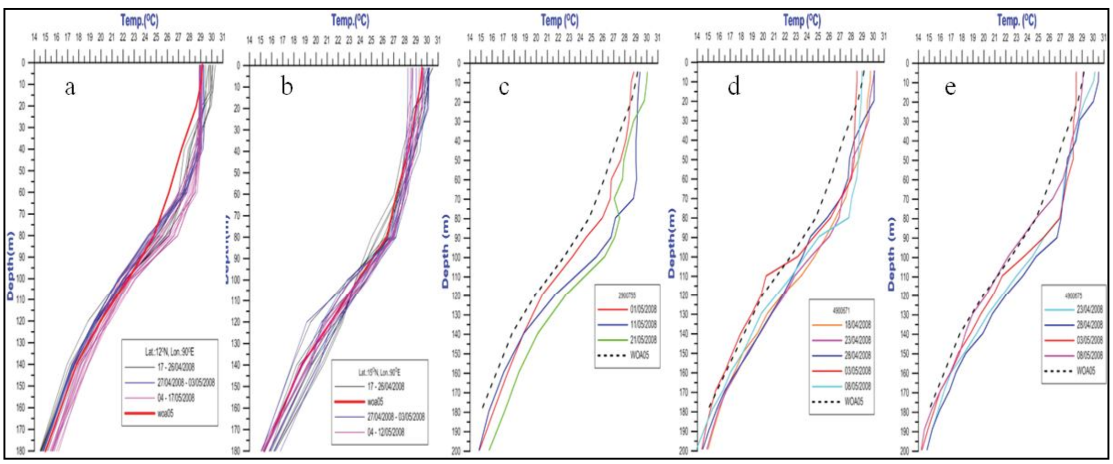


*Figure 5: Temperature profiles (a). RAMA buoy at $12^{O}$N, $90^{O}$E. (b). RAMA buoy $15^{O}$N, $90^{O}$E. (c). 2900755. (d). 4900671. (e). 4900675 using RAMA Buoy data and ARGO data before, during and after passage NARGIS cyclone*

The distribution of D26 along the cyclone track varies ~ 80 – 115 m (Fig. 4g) and it is found to vary from 48-117 m at all the three locations overall(Table – 1). At buoy-2 and buoy-3 locations mean D26 is found to be higher during pre monsoon season (>70m). Standard deviation of D26 is found to vary from 7 to11m with higher values (>10) at buoy-1 during pre monsoon (Table 1). UOHC varies from 35-140 kJ/$cm^2$ at all the three locations during both pre and post monsoon seasons. Mean UOHC is max (90 kJ/$cm^2$) in the post monsoon season at buoy-3 and lowest (<76 kJ/$cm^2$) in the post monsoon season at buoy-2 (Table.1). The results lead a strong support to the notation that subsurface temperature structure is more important predictor with greater sensitivity of the cyclones. However the cyclone intensity and track prediction based on oceanic parameters are not clearly understood due to its coupled phenomenon associated with atmosphere. In future studies, we will involve other critical meso scale features (eddies etc.), wind stress curl, fresh water fluxes, enthalpy flux from ocean to atmosphere etc.

**4.Acknowledgement**

The authors very much thankful to Ocean data providers such as INCOIS Live Accesses Sever for providing ocean analysis derived QUICKSCAT MOM-GODAS data, RAMA project, AVISO, NOAA and IMD etc., and FERRET using graphical presentation.

**5.Reference**


1. Ali,M.M., P.S.V.Jagadish, and S.Jain (2007), Effect of eddies on Bay of Bengal cyclone intensity EOS Trans , AGU, 88(8), doi: 10.1029/2007EO08001.
2. Emanuel, K. A., C. DesAutels, C. Holloway, and R. Korty, (2004), Environmental control of tropical cyclone intensity. J. Atmos. Sci., 61,843–858.
3. Emanuel, K. A., (1986), An air-sea interaction theory for tropical cyclones. Part I. J. Atmos. Sci. 43:585-504.
4. Goni, G.J., and J.A. Trinanes (2003), Ocean thermal structure monitoring could aid in the intensity forecast of tropical cyclones.EOS,Trans.Amer. Geophy.union, 84,573-580.
5. Gray, W.M., (1979), "Hurricanes: Their formation, structure and likely role in the tropical circulation", Meteorology Over Tropical Oceans. D. B. Shaw (Ed.), Roy. Meteor. Soc., James Glaisher House, Grenville Place, Bracknell, Berkshire, RG12 1BX, 155-218.
6. Holliday, C. R., and Thompson, A. H., (1979), Climatological characteristics of rapidly intensifying typhoons. Mon. Wea. Rev.,107, 1022–1034.
7. IMD, (2009), Report on cyclonic disturbances over north Indian Ocean during 2008, RSMC-Tropical cyclones, India Meteorological Department, New Delhi, India.
8. IMD, (2008), Report on cyclonic disturbances over north Indian Ocean during 2007, RSMC-Tropical cyclones, India Meteorological Department, New Delhi, India.
9. Karthik Balaguru et al., (2012). Ocean barrier layers effect on tropical cyclones intensification", Earth, Atm. & Plan. Sciences, www.pnas.org/cgi/doi/10.1073/pnas.1201364109.
10. Lin, I-I, Liu, W. T., Wu, C. C., Chiang, J. C. H., and Sui, C. H., (2003a), Satellite observations of modulation of surface winds by typhoon-induced upper ocean cooling. Geophys. Res.Lett., 30, 1131, doi:10.1029/2002GL015674.
11. Lin, I. I., Liu, W. T., Wu, C. C., Wong, G. T. F., Chen, C. Hu, Z., Liang, W. D., Yang, Y., and Liu, K. K., (2003b), New evidence for enhanced ocean primary production triggered by tropical cyclone. Geophys. Res. Lett., 30, 1718, doi:10.1029/2003GL017141.

12. Lin,I-I., Chen,C.H., Pun,I.F.,Liu,W.T., and Wu,C.C., (2009) Warm ocean anomaly, Air-sea fluxes and the rapid intensification of tropical cyclone Nargis, 2008., Geophys.Res.Letts., 36,LO3817,doi:10.1029/2008GL035815.
13. Pun, I. F., Lin, I-I., Wu, C. R., Ko, D. S., and Liu, W. T., (2007), Validation and application of altimetry-derived upper ocean thermal structure in the Western North Pacific Ocean for typhoon intensity forecast. IEEE Trans. Geosci. Remote Sens., 45 (6), 1616–1630.
14. Ravichandran M., Dave Behringer, S. Sivareddy, M. S. Girishkumar, Neethu Chacko, and R. Harikumar, (2012). Evaluation of Global Ocean Data Assimilation System at INCOIS: The tropical IO, submitted in ocean modeling. Ocean Modeling (in press).
15. Sadhuram,Y.,Rao.B.P.,Shastri,P.N.M and Subrahmanyam, M.V., (2004) Seasonal variability of cyclone heat potential in the Bay of Bengal, Nat.Hazards, 32,191-209.
16. Sadhuram,Y., T.V.Ramana Murthy and Y.K.Somayajulu., (2006) , Estimation of tropical cyclone heat potential in the Bay of Bengal and it's role in the genesis and intensification of storms , Ind.J.Mar.Sci., 35,2,132-138
17. Scharroo, R., Smith, W. H. F., and Lillibridge, J. L., (2005), Satellite altimetry and the intensification of Hurricane Katrina. Eos,Trans. Amer. Geophys. Union, 86, 366–367.
18. Senguptha,D., G.Bharath raj and G.S.Anitha., (2007), Cyclone induced mixing does not cool SST in the post-monsoon north Bay of Bengal , Atmos.Sci.Letts, Doi; 10.1002/asl.162
19. Shay, L.K., G.J.Goni and Black ,P.G., (2000), Effects of warm oceanic feature on hurricane Opal .Mon.Wea.Rev., 128,1366-1383
20. Singh, O.P., Ali Kahn, T.M., Rahman, S., (2001), Has the frequency of intense tropical cyclones increased in the north Indian Ocean? Curr Sci 80,575–580.
21. Wu, C. C., Lee, C. Y., and Lin, I-I ., (2007), The effect of the ocean eddy on tropical cyclone intensity. J. Atmos. Sci., 64, 3562– 3578.