

Ocean impact on the intensification of cyclone Titli

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Abstract:

Tropical cyclones are the most devastating weather events which still needs to understand much due to the uniqueness in their paths and intensification locations. One such recent very severe cyclonic storm Titli is perfectly fit for the individual case study. The cyclone Titli originated from a low-pressure area formed over the southeast Bay of Bengal (BoB) and adjoining north of the Andaman Sea on 7 th October 2018 and intensified into a very severe cyclonic storm on 10th over a region of low saline water pool in the western Bay of Bengal. The addition of low salinity water in this region is from the lower Mahanadi basin and surroundings that received excess rainfall in September 2018. The low saline waters developed high stratification and suppressed the upwelling at the cold-core eddy center and restricted to 50m. Persistent high heat content and high internal energy are the primary sources of intensification of cyclone Titli. Generally, intense cyclones enrich biomass's enhancement in the ocean's surface layer after their passage. But in the case of Titli, biomass enrichment did not happen due to persistent high stratification, which is about 3-4. Even the 80knots (150km/hr) winds cannot break up the upper layer stratification, suppressing the cyclone-induced upwelling. Observations show only a 0.2-0.4 mg/m³ rise in chlorophyll on the surface and it may be due to the land drove nutrients and lightning. Data analyzed from the high-resolution global NEMO model also shows the intrusion of low saline waters off India's east coast. Though the model is slightly overestimating the upwelling in the cold core eddy's surface layers, it represents the barrier caused by stratified waters. Both the observations and model data sets are well correlating, daily analyzed model data is well capturing the seasonal stratification caused by the low saline waters in the northern Bay of Bengal. These high-resolution global ocean model data sets are useful and essential for the accurate forecast of cyclones over the Bay of Bengal.

Introduction:

Generally, about 6-7 percent of the global tropical cyclones form over the Indian ocean (Nuemann 1993). In the Indian Ocean Bay of Bengal, it is much prone to storms than the Arabian sea because of freshwater input. This freshwater occupies the top layers and holds high heat content. whereas in the Arabian Sea, strong winds ~~that~~ cause mixing and distribution of heat take place which may not support the formation and intensification of more cyclones (Shenoi et al. 2004, Vinay Chandran et al. 2008). We are now experiencing several climate changes all over the globe B in the recent climate-changing era, such changes are also evident in the Indian Ocean region. Those increase the risk of extreme weather events like cyclones to certain areas unexpectedly due to ocean warming in many areas. Those include the recent 2014-2018 cyclones over the northern Indian ocean. One of such cyclones at present we are discussing in this paper is Titli. Titli was the most destructive cyclonic storm to strike the Indian coast in 2018. The genesis of Very Severe Cyclonic Storm (VSCS), Titli over the Bay of Bengal, took place 45 hours after VSCS, Luban, over the Arabian Sea. It was one of the rarest of rare events that simultaneously two VSCSs developed over the Arabian Sea and Bay of Bengal. Titli originated as a low-pressure area over the southeast Bay of Bengal (BoB) and adjoining the north Andaman Sea on 7 th October 2018. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over east-central BoB on 8th October and further into a cyclonic storm (CS) "Titli" around noon of 9th October 2018. Later it moved north-westwards and intensified into a severe cyclonic storm (SCS) in the early hours of 10th, further moved north-north westwards and intensified into a very severe cyclonic storm (VSCS) on 10th. It crossed near Palasa (18.80N/84.50E) on 11th as a VSCS with a wind speed of 140-150 gusting to 165 kmph (www.imd.gov.in). An increase in the intensity and frequency of storms in recent years (2014-2018) indicates that we are already facing climate change. Even though there are many improvements in observation methods during cyclones, the past studies are not reliable with today's weather. There is a need to work on recent individual storms since the cyclone formation, intensification is a highly complex phenomenon and is an interaction between ocean and atmosphere. Similarly, Cyclone Hudhud occurred in the year 2014 was also intensified over the northern Bay of Bengal during the post-monsoon season but the reasons behind the stratification are different from Titli So, for each cyclone, the model has to work differently and making the prediction more complex. So it is necessary to understand the recent high-resolution coupled models and it has to be verified how best they help to analyze the individual tracks.

The present study is on the cyclone Titli in which we utilized the in-situ satellite and model data for analysis.

Data and methods:

Cyclone track data has been taken from the IMD website. The ocean data has been taken from ARMOR 3D data, which provides temperature-salinity vertical profiles to build a global 3D weekly temperature, salinity fields at a Spatial Resolution of 0.250 x 0.250 grid resolution. Atmospheric data has been taken from NCEP -NCAR reanalysis data sets. Daily rainfall statistics have been taken from IMD. Stratification(S) has been estimated from the stratification factor which is derived from the maximum and reference Bruntvaisala frequencies (N). The maximum frequency is estimated from the vertical profile and the reference frequency is 3cph.

$$S = \sqrt{\frac{N_{\max}}{N_0}} \quad \text{where} \quad N = \sqrt{-\frac{g}{\rho} \frac{d\rho}{dZ}}$$

The model data has been taken from CMEMS global weakly coupled ocean-atmospheric data assimilation, using 3D-var, which utilized GLO-CPL for 3d ocean forecast at 1/4th degree met office unified model coupled to an hourly NEMO v 3.4 (Lea et al. .2015). NEMO run in ORACA025 configuration (Blockley et al. 2014) with a tripolar grid of 1/4th degree resolution and 75 vertical levels with 1 m resolution in the top 10m of the ocean, decreasing resolution in deeper parts. Ocean observations include satellite SST data, daily in-situ Argo, moored buoys and gliders. Ocean heat content data is extracted from BHUVAN which is computed from Artificial Neural Network models by utilizing remote-sensing sea-surface temperature and sea surface height anomaly data. Atmospheric instability is calculated from equation $\omega = Dp/Dt$.

Results and discussions:

Tropical cyclone formation and intensification are under the control of both atmospheric and ocean parameters jointly. The percentage of possession of each may vary from cyclone to cyclone. Cyclone Titli is one of the best case studies to show the exact ocean role in the intensification. In the present study, we had taken the spatial data up to 500 m depth just 15 days before the formation of cyclone Titli and overlaid the track. It is observed that a freshwater plume off the Orissa coast near the landfall of cyclone Titli and this plume extended up to 150 km offshore. This freshwater plume is due to the high river discharge caused by the excess rainfall near Mahanadi during the monsoon season of the year 2018. During the monsoon season (2008- 2018), the annual rainfall graph under the lower Mahanadi basin, mainly in the Bhubaneswar and Paradeep regions, clearly shows the excess rainfall in 2018. This may be the reason behind why the high freshwater discharge off the east coast near Orissa (fig.1).

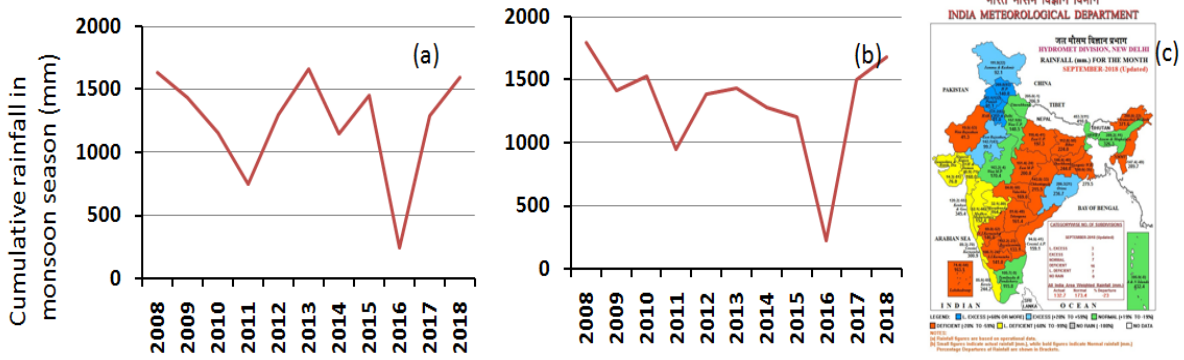


Fig.1. Cumulative rainfall during monsoon season under lower Mahanadi river basin (a) Bhubaneswar (b) Para deep and (c) Spatial rainfall pattern during Sep 2018 in mm over Orissa.

Generally, this freshwater plume acts as a barrier for mixing and traps heat in the ocean's surface layers. The summer floodwaters of the Ganges and Brahmaputra rivers discharging into the Bay of Bengal plus the Irrawaddy and Salween rivers emptying into the Andaman Sea combine to influence the salinity of the surface waters over thousands of kilometers offshore (Tomczak and Godfrey, 1994). This fact was confirmed during the summer 2001 Bay of Bengal Ocean Process Studies cruise. The copious amounts of rainfall and river runoff freshened the Bay's upper 30 m by 3-7 PSU compared to the central Arabian Sea (Prasanna Kumar et al. 2002). Similarly, in the western Bay of Bengal, the freshwater discharge due to excess rainfall from August -September 2018 over the lower Mahanadi basin (fig.1c), caused a high stratified layer that holds high heat content favorable formation and intensification of post-monsoon cyclones in this region.

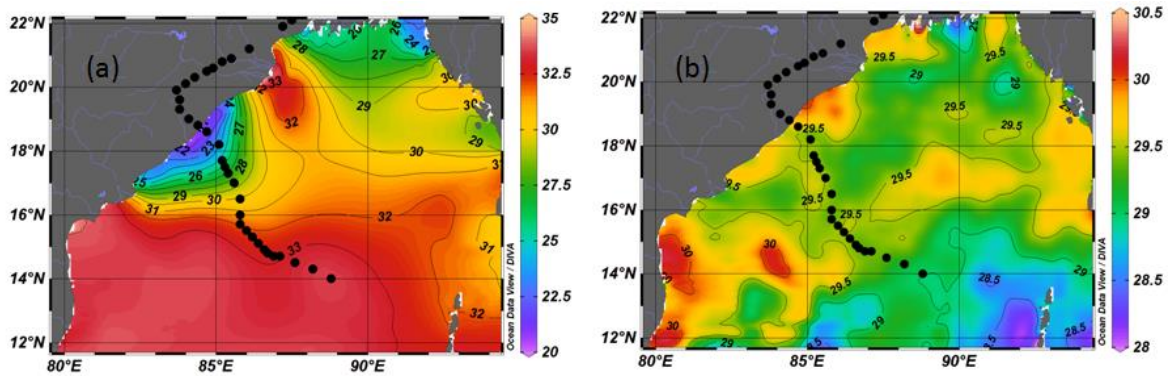


Fig.2. Spatial map of Sea surface (a) Salinity and (b) Temperature over the Bay of Bengal before (26/09/2018) cyclone Titli.

Fig.2. Shows the pool of lower salinity water along the east coast of India beyond the Godavari and after Mahanadi confluence into the Bay of Bengal. Salinity decreased from 28 PSU at 150km offshore to 22 PSU near the coast and this low salinity pool extended from 16.5 °N to 20°N along the coast up to the longitudinal belt of 86°E.

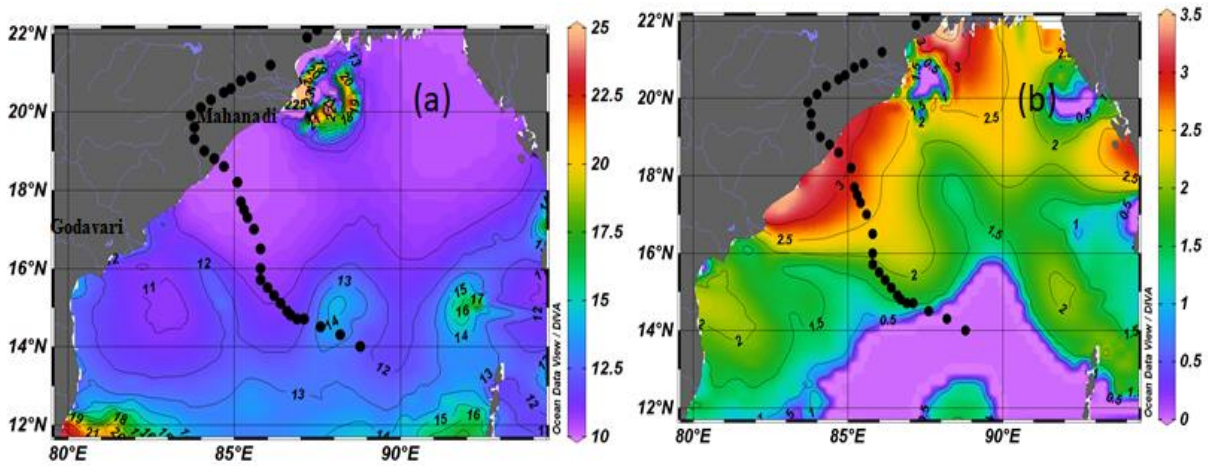


Fig.3. Spatial map of mixed layer depth (density threshold equivalent to 0.2°C) and (b) stratification factor(S) over Bay of Bengal prior to (26/09/2018) cyclone Titli.

High stratification has been observed over north and northwestern parts of Bay of Bengal, i.e., almost more significant than 3 where the central Bay S varies from 1-2. Shallow mixed layer depths below 10 m depict low entrainment due to this high stratified layer before cyclone Titli (fig.3).

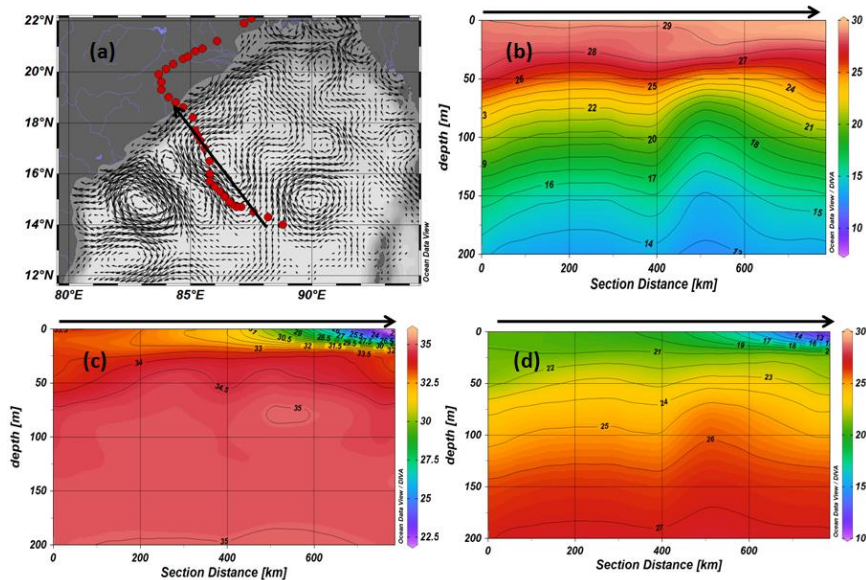


Fig.4. (a) Surface circulation over the Bay of Bengal and along-track vertical sections of (b) Temperature (°C) (c) salinity (psu) (d) density (kg/m^3) prior to Titli.

During the last week (27th) of September of 2018, the flow of EICC is towards the south with a speed of nearly 0.8m/s and also the flow is divided into several mesoscale eddies due to its instability. One such cold-core vortex is situated at the center of the cyclone track before the cyclone (fig.4a), which is also evident through the vertical section's observation along the path. Fig.10b shows the upwelling of

isotherms at the center of the cold-core eddy and the subsidence of isotherms at the eddy's peripheral. But this upwelling could not reach the surface and it has been suppressed below 50m. This is due to the strong stratification in the top layers, which strongly inhibits the subsurface waters to mix with surface layers. The surface warm water layer with temperatures greater than 28°C is due to the intrusion of fresh waters from coast to offshore, the low saline water tongue extended up to 250 km offshore (fig.4c). As the surface layer stratification reduces the strength of upwelling (Prasanna Kumar et al. Carine G. Van et al., 2019), the density section clearly shows the suppressed upwelling above 50m (fig.10d). This phenomenon opposes cooling, which generally happens at the center of the cold-core eddy. So the top layers are warming up, showing high internal energy in the upper 50 m and the conditions before the cyclone are highly favorable for the formation and intensification.

The cyclone Titli formed on 8th October 2018 and started with a translation speed of 2.6 m/s and became a deep depression under a translation speed of 1.4m/s. Later on, it continued with a high translation speed of 5.6 m/s up to 10th October 2018 and after reaching the western part again, it slowed down to 3.2 m/s under high stratified waters (fig.5).

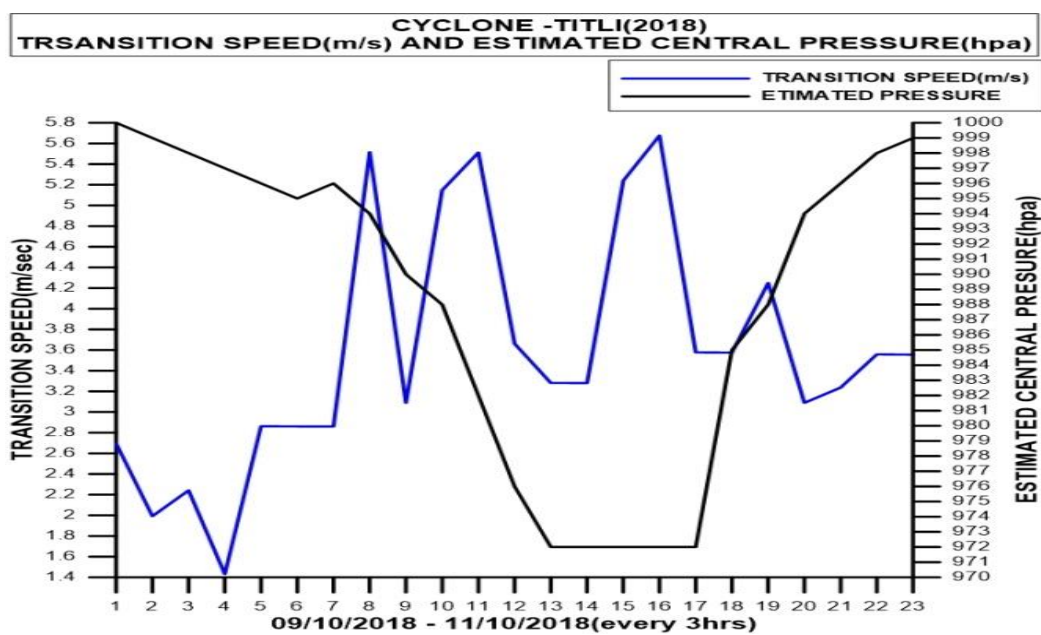


Fig.5. Translation speed (m/s) and the corresponding pressure drop during Titli Cyclone.

The interaction of the cyclone with the ocean during intensification on the 10th has been shown in fig.6. The cyclone circulation has been identified from fig 6a. It has undergone rapid intensification over the high temperatures greater than 30°C and stratification greater than 3 at a distance of 200km from the coast (fig.6b,c). The along-track section clearly shows the upwelling signature at the center of the cold-

core. It could not reach the upper layers due to persistent high stratification due to low salinity water cap, evident from fig 6b and f. Also, these results are compared with the ocean-atmospheric coupled model with NEMO 3.4

multiple layer ocean configuration simulated on daily intervals with 0.25 resolution. The model could able to catch the low salinity patch very well though it is slightly overestimating. It clearly shows the low salinity water along the coast at 18°N, higher SST's around 31°C and cold-core eddy off 16°N has been observed along the track (fig7.a,b,c).

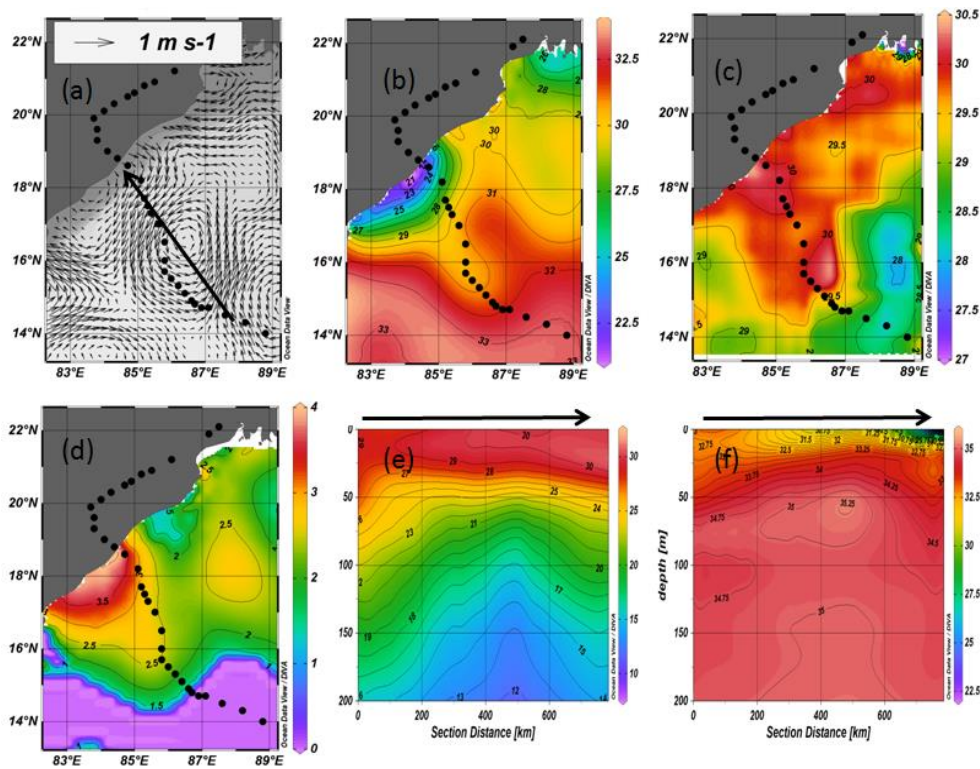


Fig.6. (a) Surface circulation (m/s) (b) Surface salinity (PSU) (c) sea surface temperature (°C) (d) stratification and along-track vertical sections prior to cyclone Titli.

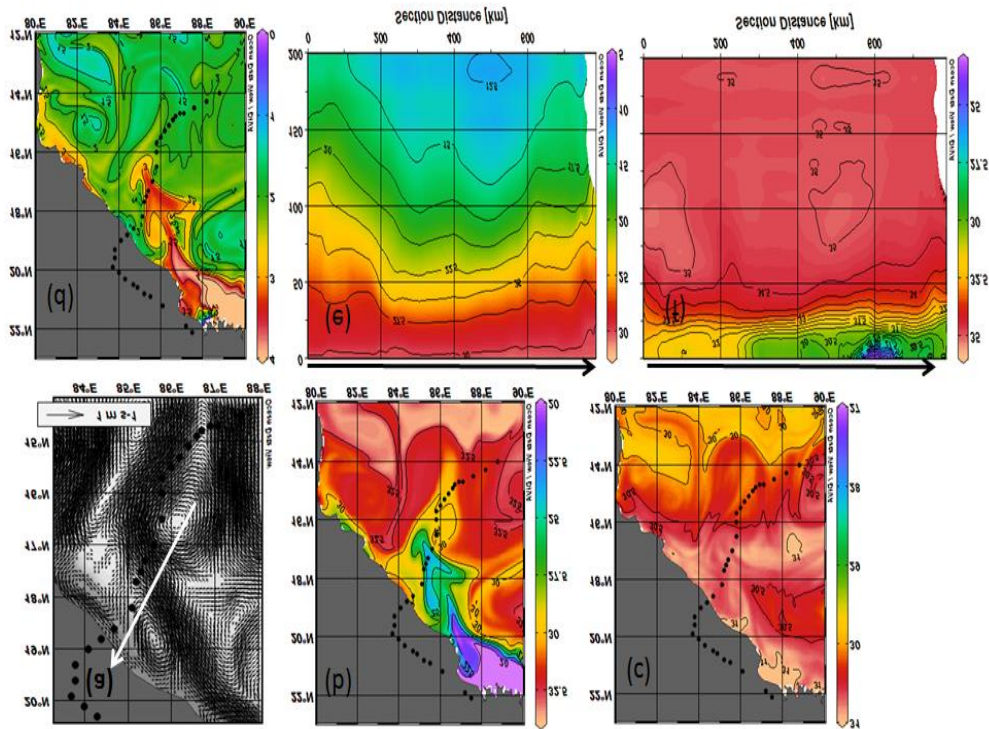


Fig.7. (a) Surface circulation (m/s) (b) Surface salinity (PSU) (c) sea surface temperature ($^{\circ}\text{C}$) (d) stratification and along-track vertical sections of (e) Temperature ($^{\circ}\text{C}$), (f) Salinity (PSU) before cyclone Titli using model data.

The stratification factor has been underestimated by the model with high stratification on the track's north right side. In contrast, the observations show the maximum stratification on the left side. Both represent the stratified waters off 18°N and along-track vertical sections from model data, clearly illustrating the upwelling signatures in the cold core eddy and the intrusion of low saline water from the coast (fig 7 e,f), which prohibited the upwelling to surface layers. Higher temperatures in the top 50 m have been observed from the model data and are favorable for cyclone's intensification.

Out of 100m, the top 50 m layer contains high heat content (estimated from remote sensing), crucial for cyclone formation and intensification (fig.8).

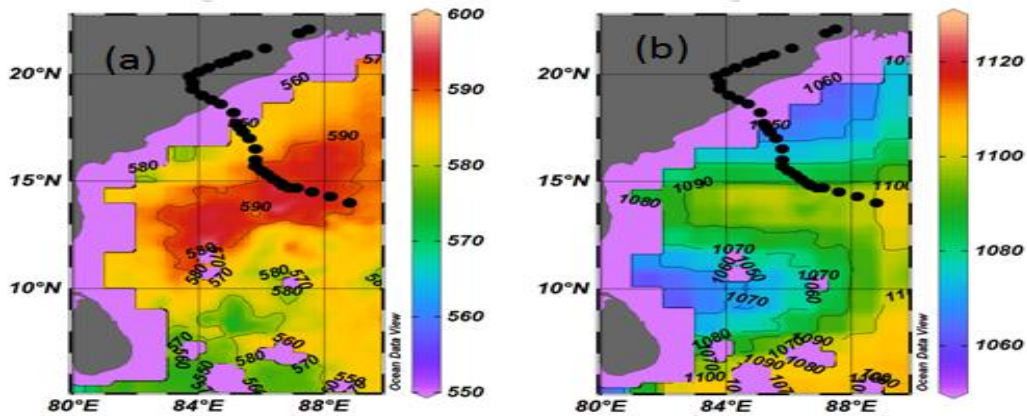


Fig.8. Spatial Heat content (W/m^2) at (a) 50 m and (b) 100m over the western Bay of Bengal before the cyclone Titli.

In the present cyclone, Titli started with low translation speed up to deep depression and the translation speed increased at the time of rapid intensification. There is a large drop in translation speed at the location of high heat content. The surface waters with high heat content are responsible for the instability, ascending motion in the atmosphere, and accumulation of high relative humidity (fig.9a) at different atmospheric levels.

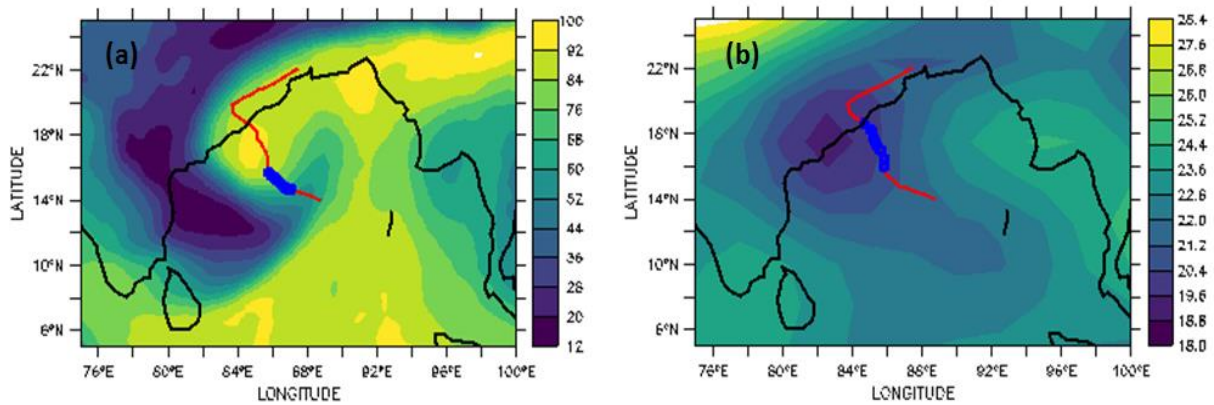


Fig.9. Atmospheric (a) Relative humidity(%) (b) Instability (pa/s) during cyclone Titli intensification.

These are helpful for the release of latent heat, reduces the temperature contrast between the ocean and atmosphere (fig.9b) and helps the development of cyclone further during and after the passage of cyclone along-track observational as well as model data has been observed and not found many changes in the upwelling along the track fig.10. The observed size of the cold core eddy along the track is 2.5×4 ; it is extended up to the coast due to strong EICC, whereas the model data underestimates the speed of the EICC and the size of the eddy (3×2.5). Both the model and observations show a stable upwelling

signature, which is suppressed above 50 m. There is no negative impact of the cold-core eddy on a cyclone; this may be due to the substantial intrusion of low saline water from the coast, which is evident through observations and model data. Model results show the low saline (<30psu) water intrusion up to 300km from the coast, whereas the observation shows 150km(fig.11efgh). The model is underestimating the temperatures and overestimating the salinity in the top 50 m layer(fig.10abcd).

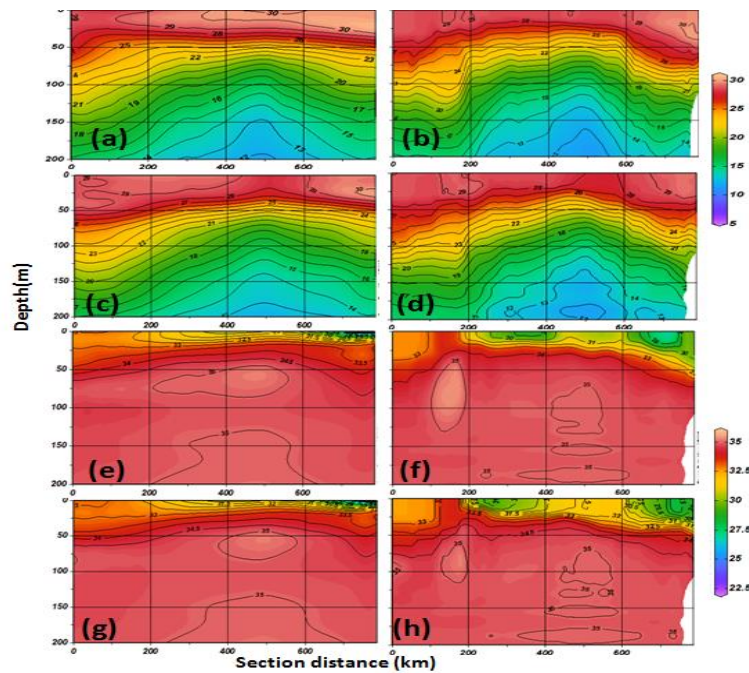


Fig.10. Along track vertical section of Temperature ($^{\circ}\text{C}$) (a,b,c,d) and salinity (PSU) (e,f,g,h) from observational (a,c,e,g), model (b,d,f,h) data sets during (a,b,e,f) and after (c,d,g,h) passage of cyclone.

Biological response: Generally, in the Bay of Bengal coastal and open-ocean, biogeochemistry was influenced by the cold-core eddies, rainfall events and cyclones. Tropical cyclones (also known as hurricanes or typhoons) can have devastating effects on human lives when passing over land. Still, they can enormously enhance another form of life - ocean primary (phytoplankton) production (Lin et al., 2003). Once the cyclone is passed along the cyclone's track, there will be cooling due to the wind forced upwelling at the center. Such physical changes are expected to impact marine biogeochemistry. The cool, nutrient-rich water will come to the surface, which reduces the surface temperatures. It may vary from 1-10 $^{\circ}\text{C}$ depending on the strength of the cyclone. Injection of nutrients from the subsurface will increase the production. After the cyclone departure, cold wakes, typically more evident to the right of the cyclone tracks (Chang and Anthes, 1978; Price, 1981; Cornillon et al., 1987; Bender and Ginis, 2000; Monaldo et al., 1997; Wentz et al., 2000; Lin et al., 2003; Maneesha et al., 2011) are left behind. These cold wakes can

exist in the ocean for days to weeks and generate continual feedback with the atmosphere (Emanuel, 2001; Lin et al., 2005). After the landfall, the land-driven material from the rainfall and the currents along the coast will affect coastal biogeochemistry. Storms occurring in the world oceans typically have a duration of only a few days. Still, these perturbations in physical and biological effects can last up to several weeks (Madhu et al., 2002; Maneesha et al., .2011).

The biological response of several recent cyclones has been studied over the Bay of Bengal. But in the present for the cyclone Titli the condition is different; though the winds were much more robust, i.e., greater than 80 knots, they cannot break the stratification in the western Bay of Bengal. This results in the suppression of upwelling in the surface layers significantly less rise in the surface chlorophyll levels over the Bay of Bengal. The minor variation i.e., from 0.1-0.2 mg/m³ in chlorophyll, may be due to the land drove nutrients and nitrogen fixation due to lightning during the cyclone (fig.11).

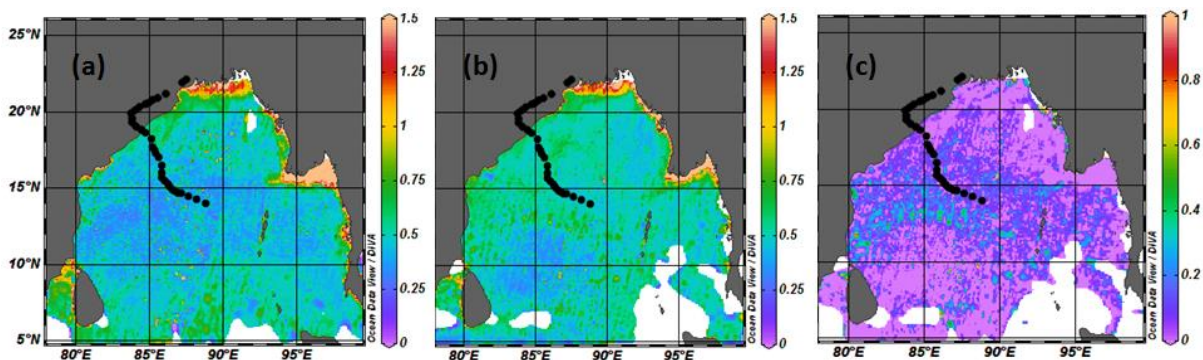


Fig.11.Surface chlorophyll (mg/m³) variations over the Bay of Bengal (a)before (01/10/2018) (b) after (20/10/2018) the cyclone Titli and (c) difference.

Conclusions:

A tropical cyclone is one of the devastating weather events which still needs to understand a lot due to their uniqueness in tracks and intensification locations. The recent cyclone Titli is a perfect fit for an individual case study because of its rapid intensification and biological response. It dictates the ocean's role in the sudden intensification. The cyclone Titli started in the central Bay of Bengal and moved northwestwards the highly stratified, low saline water pool and intensified rapidly. This low saline water results from the freshwater influx caused by the heavy rainfall near the lower Mahanadi basin in September 2018. So, highly stratified upper layers in the western Bay of Bengal having high heat content in the top 50m layer gave positive feedback for the cyclone Titli's rapid intensification. Even 80-knot cyclonic wind cannot break the surface layer stratification, which can be evident through surface chlorophyll levels after the cyclone. High-resolution model results are well comparable with the observations and these models are helpful for better prediction of cyclone track and intensity.

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Author Statement:

K. Maneesha conceived the idea, made all the calculations and interpretation, V.Siva Prasad and K.Venkateswararao helped in the arrangement of data, figures and interpretation of physical, biological aspects, all the authors contributed to the development of the final manuscript.

References:

Bender M A and Ginis I 2000 Real-case simulations of hurricane–ocean interaction using a high resolution coupled model: effects on hurricane intensity; *Mon. Wea. Rev.* **128** 917–946.

Blockley E W and Coauthors 2014 Recent development of the Met Office operational ocean forecasting system: An overview and assessment of the new Global FOAM forecasts; *Geosci. Model Dev.* **7** 2613–2638 doi:10.5194/gmd-7-2613-2014.

Carine G. van der Boog, Julie P, Henk D and Caroline A K 2019 The Impact of Upwelling on the Intensification of Anticyclonic Ocean Eddies in the Caribbean Sea; *Ocean Sci. Discuss.* <https://doi.org/10.5194/os-2019-51>.

Chang S W and Anthes R A 1978 Numerical simulations of the ocean's nonlinear, baroclinic response to translating hurricanes; *J. Phys.Oceanog.* **8** 468–480.

Cornillon P, Stramma L and Price J F 1987 Satellite measurements of sea surface cooling during hurricane Gloria; *Nature* **326** 373–375.

Emanuel K A 2001 The contribution of tropical cyclones to the oceans' meridional heat transport; *J. Geophys. Res.* **106** 14771–14781.

Lea, D J, Mirouze I, Martin M J, King R R, Hines A, Walters D and Thurlow M 2015 Assessing a new data assimilation system based on the Met Office coupled atmosphere-land-ocean-sea ice model; *Monthly Weather Review* **143** 4678-4694.

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 2003 New evidence for enhanced ocean primary production triggered by tropical cyclone; *Geophys. Res. Lett.* **30** 1718 doi:10.1029/2003GL017141.

Lin I I, Wu C C, Emanuel K A, Lee I H, Wu C R and Pun I F 2005 The interaction of supertyphoon maemi (2003) with a warm ocean eddy; *Mon. Wea. Rev.* **133** 2635–2649.

Maneesha K, Sarma V V S S, Reddy N P C, Sadhram Y, Murty T V R, Sarma V V and Kumar M D 2011 Meso-scale atmospheric events promote phytoplankton blooms in the coastal Bay of Bengal; *Journal of Earth System Sciences* **120** 773–782 <http://dx.doi.org/10.1007/s12040-011-0089-y>.

Monaldo F M, Sikora T D, Babin S M, and Sterner R E 1997 Satellite imagery of sea surface temperature cooling in the wake of hurricane Edouard (1996); *Mon. Weather Rev.* **125** 2716–2721.

Neumann C J 1993 "Global Overview" - Chapter 1" Global Guide to Tropical Cyclone Forecasting; WMO/TC-No. **560** Report No. TCP-31 World Meteorological Organization Geneva Switzerland.

Prasanna kumar S, Muraleedharan P M, Prasad N, Madhupratap M 2002 Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea?; *Geophys Res Letters* **29** 2235, doi:10.1029/2002GL016013.

Prasanna Kumar S, Nuncio M, Jayu Narvekar, Ajoy Kumar, Sardesai S, Desouza SN, Mangesh Gauns, Ramaiah N and Madhuprat 2004. Are Eddies nature's trigger to enhance biological productivity in the Bay of Bengal?; *Geophysical Research Letters* **31** L07309 doi:10..1029/ 26 2003GI019274.

Price J F 1981 Upper ocean response to a hurricane; *J. Phys. Oceanogr.* **11** 153– 175.

Shenoi SSC, Shankar D and Shetye S R 2004 Why is Bay of Bengal warmer than Arabian Sea during the summer monsoon?; Proceedings of the National Symposium METOC - 2004 on Emerging Trends in the Fields of Oceanography and Meteorology, 05-06 February 2004. (Natl. Symp. *METOC - 2004* on Emerging Trends in the Fields of Oceanography and Meteorology; Kochi; India; 5-6 Feb 2004 87-93.

Tomczak M, and Godfrey J S, 1994 Regional Oceanography An Introduction; *Pergamon Press*, Oxford.

Vinayachandran P N and Saji N H 2008 Mechanisms of south Indian Ocean intraseasonal cooling; *Geophysical Research Letters* Vol. 35 L23607 doi:10.1029/2008GL035733.

Wentz F J, Gentemann C, Smith D and Chelton D 2000 Satellite measurements of sea surface temperature through clouds; *Science* **288** 5467 847–850.