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Tropical Cyclone Heat Potential (TCHP) from the NCMRWF NEMO based global ocean analysis and forecast system

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सार – इस अध्ययन में न्यूक्लियस यूरोपियन मॉडलिंग ऑफ ओशन (NEMO) पर आधारित वैश्विक महासागर विश्लेषण और NCMWRF की महासागर पूर्वानुमान प्रणाली का उपयोग 26° समताप रेखी द्रोणी जिसे उष्णकटिबंधीय चक्रवात ऊष्मीय विभव (TCHP) कहा जाता है, से उपरितन महासागरीय ऊष्मा की मात्रा की गणना करने के लिए किया गया है। NCMRWF में दैनिक वास्तविक समय पर उष्णकटिबंधीय चक्रवात ऊष्मीय विभव (TCHP) की निगरानी करने की क्षमता है। इसे वास्तविक समय में वैश्विक महासागर पूर्वानुमान प्रणाली में केवल महासागर मॉडल का उपयोग करके 10 दिनों तक का और युग्मित वायुमंडल-महासागर मॉडल का उपयोग करके 15 दिनों तक का पूर्वानुमान दिया जाता है। यह मुख्य रूप से उष्णकटिबंधीय चक्रवात (TC) के अनुसंधान के लिए तैयार किया जाता है। चक्रवाती तूफान से ऊपर की श्रेणी वाले चार मॉनसून पूर्व उष्णकटिबंधीय चक्रवात हैं जिसमें दो अरब सागर और दो बंगाल की खाड़ी से हैं जिनकी जाँच की गई है। समुद्री सतह के तापमान में गिरावट उन क्षेत्रों में बहुत अधिक है जहाँ सतही पवन प्रतिबल विसंगति प्रबल है। दोनों क्षेत्रों में, उष्णकटिबंधीय चक्रवात के दौरान भिन्न भिन्न छोटे पैमाने पर गर्म और ठंडे भंवर देखे जाते हैं। TCHP विसंगति उस क्षेत्र में सकारात्मक/नकारात्मक है जहां समुद्र सतह की ऊंचाई (SSH) विसंगति सकारात्मक / नकारात्मक है। TCHP से, यह पता चलता है कि TCHP विसंगति का परिमाण उष्णकटिबंधीय चक्रवातों के दौरान अरब सागर क्षेत्र की तुलना में बंगाल की खाड़ी में अधिक है।

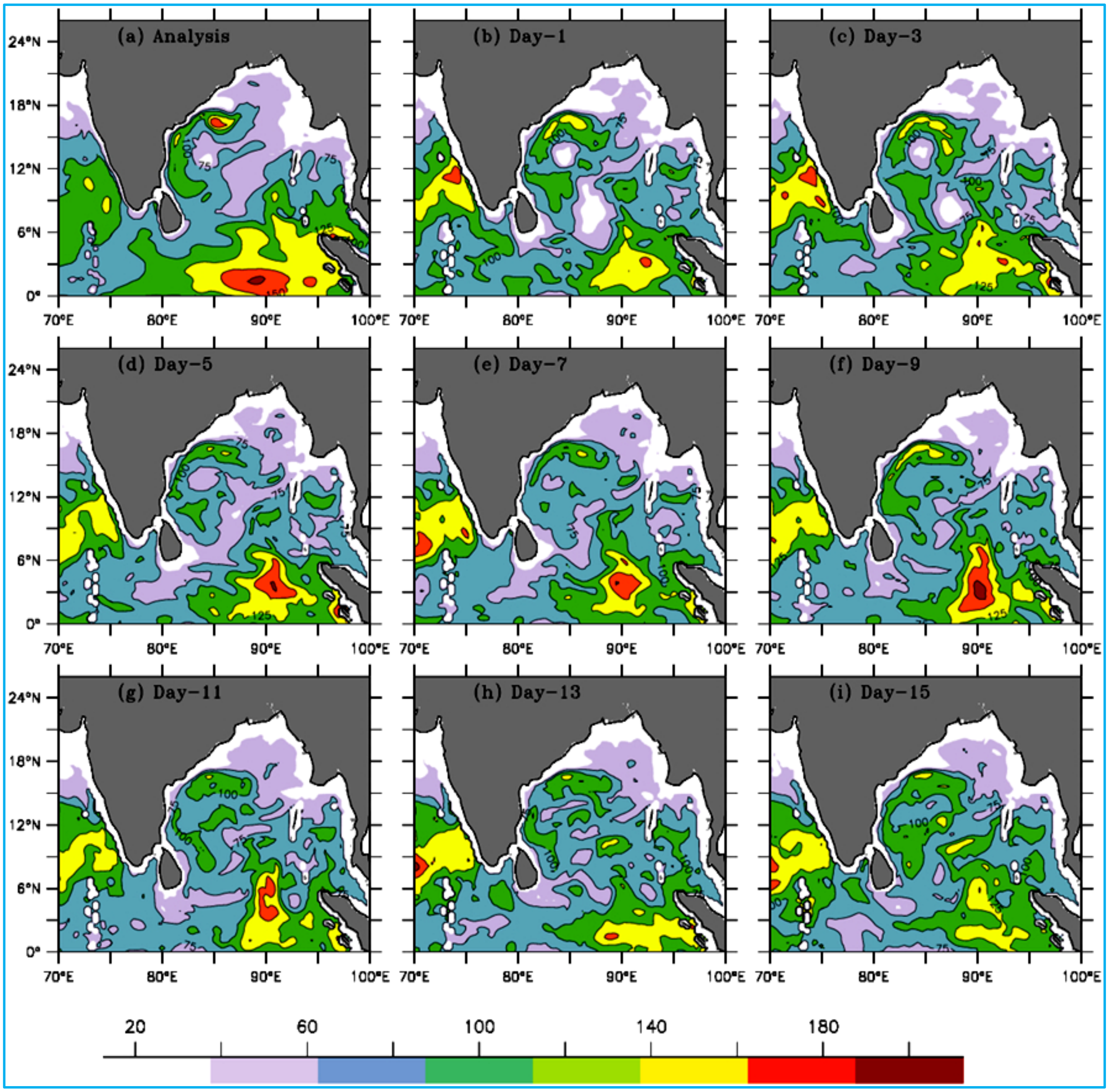
ABSTRACT. In this study, the Nucleus European Modelling of Ocean (NEMO) based global ocean analysis and forecast system configured at National Centre for Medium Range Weather Forecasting (NCMWRF) is used to compute the upper ocean heat content up to 26° isotherm depth called as Tropical Cyclone Heat Potential (TCHP). NCMRWF has the real-time TCHP monitoring capability on daily basis. It is produced in real time using the global ocean forecast system up to 10 days using the ocean only model and up to 15 days using the coupled atmosphere-ocean model for monitoring the upper ocean and also for research purpose mainly for Tropical Cyclone (TC) study. Four pre-monsoon TCs with category above cyclonic storms in which two from Arabian Sea and two from Bay of Bengal are also examined. The Sea Surface Temperature drop is much more over the regions where the surface wind stress anomaly is strong. In both regions, various small scale warm and cold eddies are observed during TCs. TCHP anomaly is positive/negative over the region where Sea Surface Height (SSH) anomaly is positive/negative. From TCHP, it is manifest that the magnitude of TCHP anomaly is higher in BoB than AS region during TCs.

Key words – NEMO, ODA, TCHP, AS, BoB.

1. Introduction

Tropical cyclones (TC) are characterized by the most potentially destructive extreme events associated with a low pressure centre and strong wind. They affect the coastal population as well as marine community with dangerous effects of strong wind, heavy rain and storm surge. As we know that the Sea Surface Temperature (SST) plays crucial role in the genesis of TC. Various studies show that the threshold value for the genesis of tropical cyclonesis more than 26 °C SST (Palmen 1956; Gray 1968; and Wendland 1977). Further, it controls the primary energy supply for TC through the upward latent heat fluxes. However, the intensification of TC is a very complex process which involves a combination of different favorable atmospheric conditions such as the boundary layers, barotropic instability, wind shear, convection, Rossby wave, upper ocean circulation and air-sea interaction. Emanuel (2003) described the dynamics, thermodynamics and air-sea interaction of tropical cyclone after the reviewing the structure, behavior, and climatology of various cyclonic storms.

The track and intensity prediction of tropical cyclones is vital for evacuation of densely populated coastal areas. Recently, Mohapatra and Sharma (2019) described the climatological characteristics (spatial and temporal distribution and intensity) of TC, damage



Figs. 1(a-i). TCHP (KJ cm^{-2}) forecast from the global coupled atmosphere-ocean model valid for 2 May, 2019 (FANI cyclone) along with its analysis

potential, modeling and prediction, Prediction skills, information dissemination mechanisms, and socio-economic impacts. However, the dynamical and statistical models are basically used with fixed SST as boundary/predictor for the prediction of track and intensity of tropical cyclones. Rai *et al*. (2018) used the regional model to examine the role of varying resolution of the sea surface temperature (SST) on the prediction of tropical cyclone (up to 72 hr lead time) and shows that the SST changes the size, intensity and track of tropical cyclone. They also show that the high resolution SST provides as useful input parameter for the regional model to improve the track and intensity of tropical cyclone. Dube *et al*. (2020) used the two different version of ensemble prediction system with an additional perturbation of SST, deep soil temperature and soil moisture content and shows that the high resolution ensemble prediction system improves the tropical cyclone forecast in terms of strike probability, mean tracks and position errors, Reliability Diagram, and Relative Operating Characteristic. However, Ali *et al*. (2013) used the satellite derived SST and tropical cyclone intensity (CI) to examine the relationship in the tropical Indian Ocean and shows that more than 50% of cyclones have no

TABLE 1

List of tropical cyclones over Bay of Bengal (BoB) and Arabian Sea (AS) regions during pre-monsoon (Category of Cyclonic Storms : Indian Meteorology Department Reports, http://www.rsmcnewdelhi.imd.gov.in)

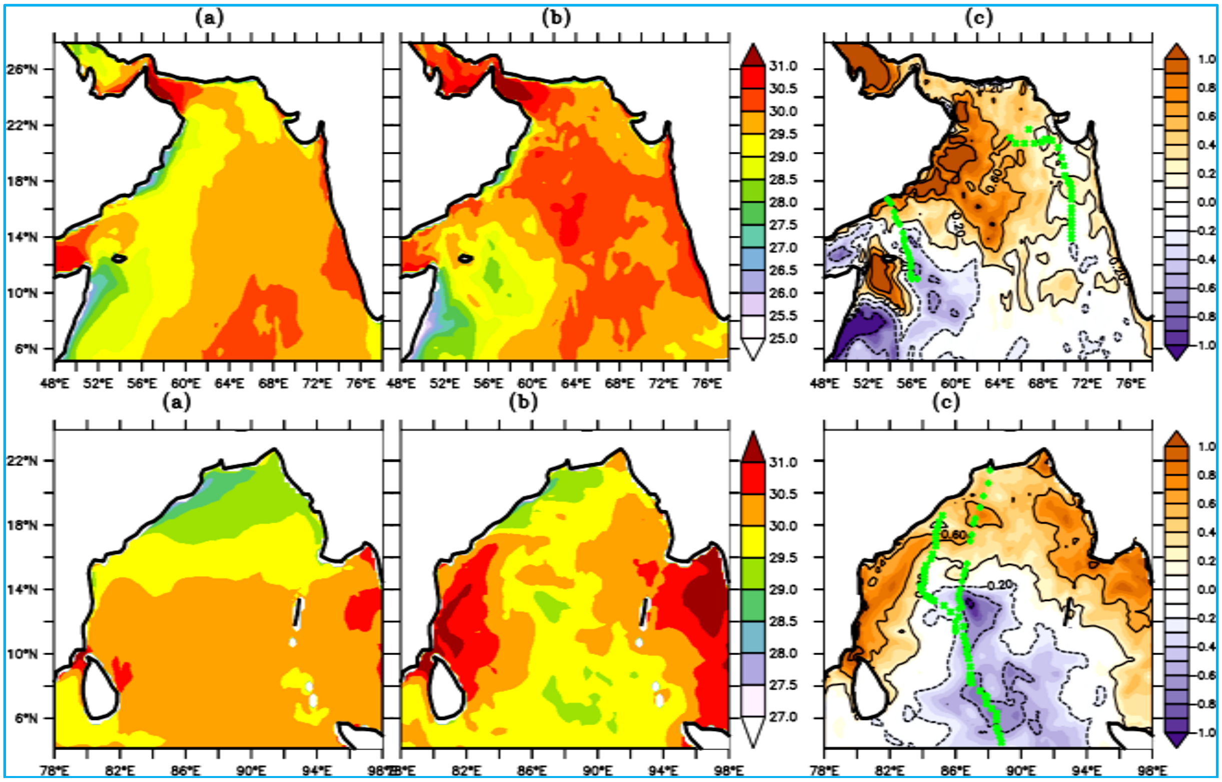
BoB			AS		
Name of cyclone	Date	Category of cyclonic disturbance	Name of cyclone	Date	Category of cyclonic disturbance
AMPHAN	16 May, 20	CS	MEKUNU	22 May, 18	CS
	17 May, 20	SCS & VSCS		23 May, 18	CS & SCS &VSCS
	18 May, 20	ESCS & SuCS		24 May, 18	VSCS
	19 May, 20	ESCS		25 May, 18	VSCS & ESCS
	20 May, 20	VSCS & SCS		26 May, 18	VSCS
	21 May, 20	CS			
FANI	27 Apr, 19	CS	VAYU	10 Jun, 19	CS
	28 Apr, 19	CS & SCS		11 Jun, 19	CS & SCS & VSCS
	29 Apr, 19	SCS		12 Jun, 19	VSCS
	30 Apr, 19	VSCS		13 Jun, 19	VSCS
	01 May, 19	VSCS & ESCS		14 Jun, 19	VSCS
	02 May, 19	ESCS		15 Jun, 19	VSCS
	03 May, 19	ESCS & VSCS & SCS		16 Jun, 19	VSCS & SCS & CS

significant correlation between SST and CI. They further shows that the SST leading the CI by maximum three days.

Upper Ocean plays a key role in the intensification of TC. Further, the various researchers show the intensification of TCs while passing through the deep upper ocean mixed layer [Shay *et al*., 2008; Ali *et al*., 2007; Lin *et al*., 2009; Goni *et al*., 2009]. Further, Sharma and Ali (2014) examined the thermal structure of the upper ocean during various TC phases such as pressure drop, track change, intensity and storm surge height and shows that the upper ocean is more critical and sensitive predictor for TC as compare to SST. In this study, we used the global ocean analysis and forecast system to compute the upper ocean heat content up to 26° isotherm depth called Tropical Cyclone Heat Potential (TCHP) during the TC. This TCHP data is also produced in real time using the global ocean forecast system up to 10 days using the ocean only model and up to 15 days using the coupled atmosphere-ocean model to monitor the upper ocean and also for research purpose. Figs. 1(a-i) shows the TCHP (KJ cm^{-2}) forecast valid for 02 May, 2019 during the FANI cyclone from the coupled atmosphere-ocean model along with its analysis. It shows that the coupled model predicts the high TCHP near the eastern coast of India very well but slightly less intense than analysis. We also examined the TCHP computed using the global ocean data assimilation system during the TCs for period of 2016-2020.

2. Model used

National Centre for Medium Range Weather Forecasting (NCMWRF) implemented the state-of-the-art modelling framework of Nucleus European Modelling of the Ocean (NEMO, Madec, 2008) for research activities, initialization of global coupled model and also for ocean state forecast. Momin *et al*. (2014) used the two different horizontal resolution of NEMO forced by climatological boundary fluxes and showed that the high resolution model simulated the annual cycle of upper ocean very well. The NEMO based variational data assimilation system called NEMOVar is a collaborative project with aims to develop and implement an advanced data assimilation techniques for multiscale applications. It is developed by number of partners such as Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS), European Centre for Medium-range Weather Forecast (ECMWF), Institut National de Recherche en Informatique et Automatique (INRIA), and Met Office. NEMOVar system was first implanted by ECMWF for non-operational and operational basis at ORCA1 configuration (Mogensen *et al*., 2012; Balmaseda *et al*., 2013) and by Met Office at ORCA025 configuration (Waters *et al*., 2014). Similar NEMOVar



Figs. 2(a-c). Sea Surface Temperature (°C) in AS (upper panel) and BoB (lower panel) during the TCs (a) Climatology (b) Observed and (c) Anomaly; Here, the wind stress anomaly (arrow length of 0.3 N/m^2) and TC tracks are overlaid in AS and BoB regions

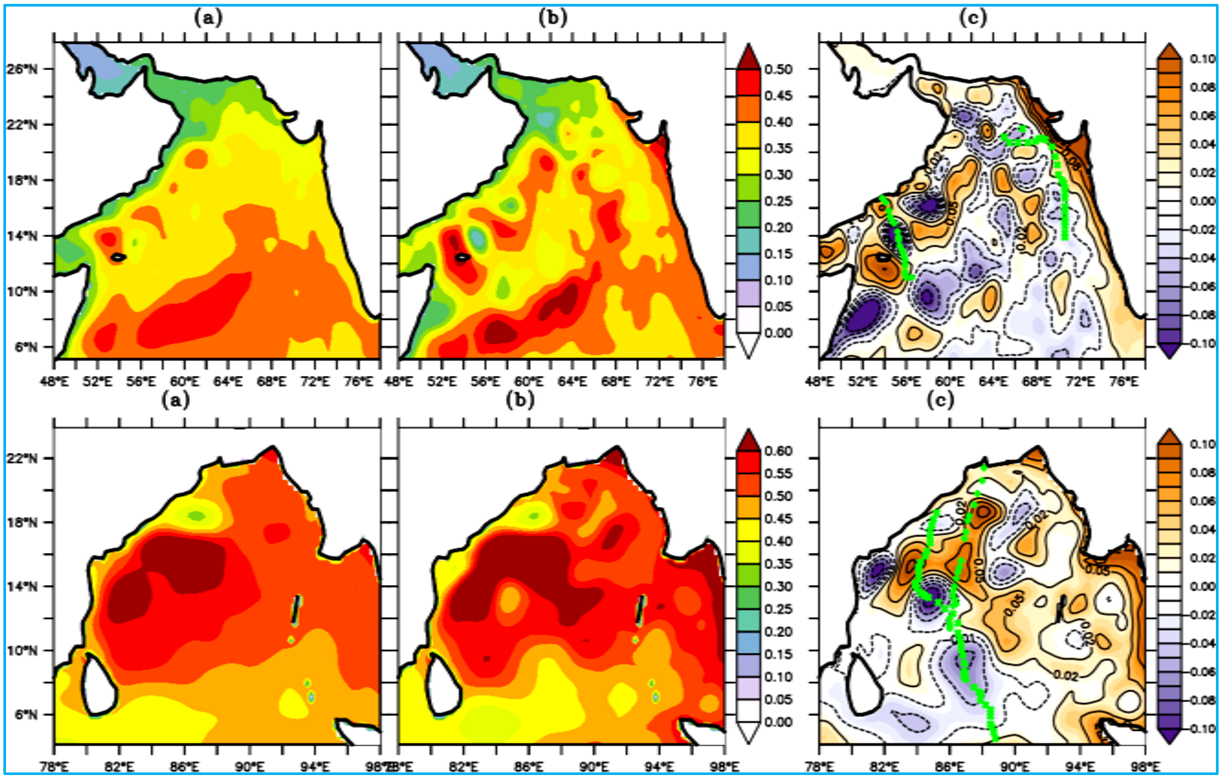
system at ORCA025 configuration is also implemented at National Centre for Medium Range Weather Forecasting (NCMWRF) in collaboration with Met Office for producing real time ocean analysis (Momin *et al*., 2020a). This analysis is further used to initialize the ocean component of the coupled atmosphere-ocean model configured at NCMRWF with aims to predict the weather and climate at different time scales such as short, medium, extended and seasonal (Gupta *et al*., 2019a; 2019b). The global ocean analysis has ¼ degree resolution and 75 vertical levels starting from 0.5 m. Momin *et al*., (2020b) used NEMOVar to study impact of Altika derived sea level anomaly data and shows that the sea surface height is improved after assimilation of altimeter data.

3. Methodology

In this study, the NEMO based global daily ocean analysis from 2016-2020 are used to study the upper ocean parameters during passage of pre-monsoon TCs. Table 1 shows the list of cyclones with details of their name, date and category of TCs for Arabian Sea (AS) and Bay of Bengal (BoB) regions. Total four TCs (two in AS and two in BoB) with category above cyclonic storms are considered during the study periods. During the passage of TCs, the three important upper ocean parameters such as Sea Surface Temperature (SST), Sea Surface Height (SSH) and TCHP are studied in term of climatology, mean and its anomaly. Here, the global NEMO analysis of temperature and salinity is used to compute TCHP by adding heat content in a vertical column from sea surface to 26 °C isotherm depth. The Upper Ocean parameters are average over the TCs period defined in Table 1 while the climatology is computed for respected TCs month from 2016-2020. The surface wind stress used as air-sea momentum flux is defined as

$$\tau = (\tau_x, \tau_y) = \rho_a C_d W(u,v) \qquad (1)$$

Where, τ_x and τ_y are east-west and north-south components of wind stress respectively. $W(u,v)$ is magnitude of surface wind (at 10 m) with its east-west and north-south components (u, v) from NCMRWF Unified Model (NCUM). ρ_a is the density of surface air, C_d is the drag coefficient. Estimating the surface wind stress is most crucial especially during the tropical cyclone due to wind dependent drag coefficient. In this study, the wind stress is computed using the Coordinated Ocean Reference



Figs. 3(a-c). Sea Surface height (SSH, m) in AS (upper panel) and BoB (lower panel) during the TCs (a) Climatology (b) Observed and (c) Anomaly in AS and BoB regions

Experiments (CORE) bulk formulae developed by Large and Yeager (2004). SSH is defined as the vertically integrated sea surface changes in the entire water column. It is related to the density variation through the changes in temperature and salinity. Further, it provides the information of subsurface ocean and air-sea interaction parameters such as thermocline depth and TCHP, and thus is another important for the coupled atmosphere ocean phenomena.

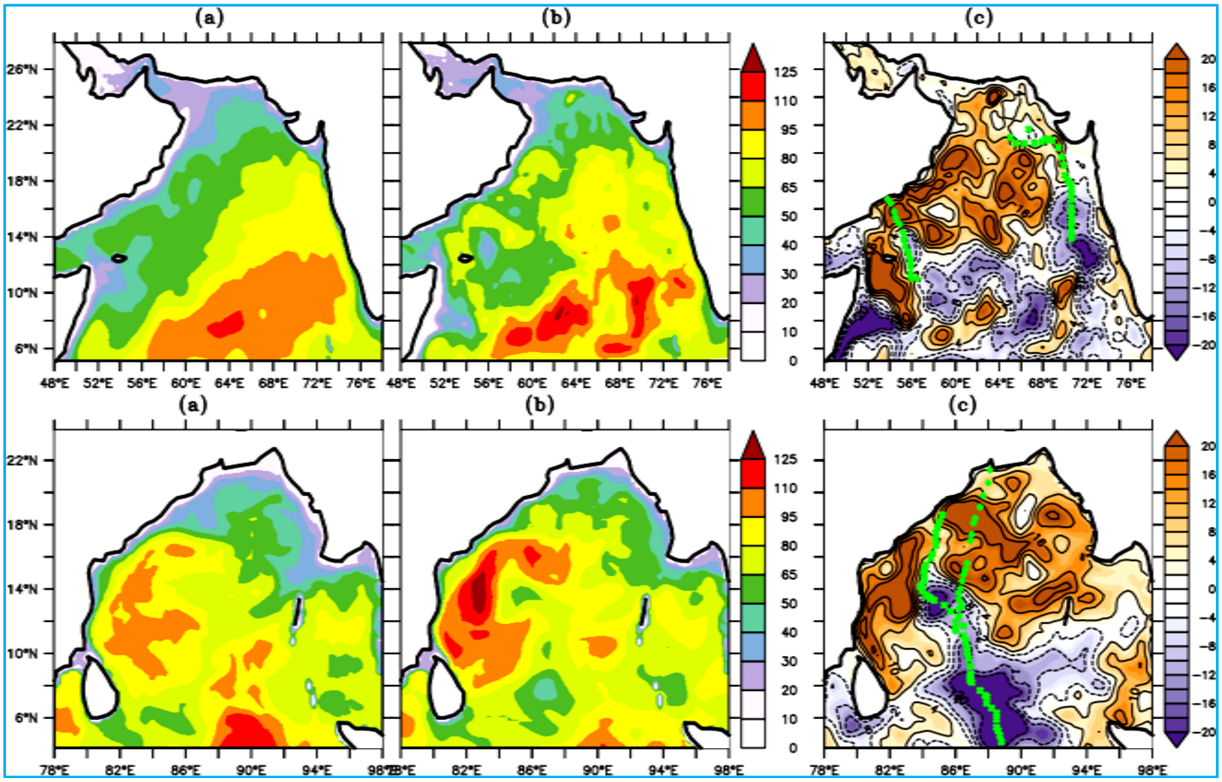
4. Upper ocean parameters during TCs

4.1. *Sea surface temperature*

For TCs, the primary heat source is the upward latent heat fluxes that are directly related to SST. Figs. 2(a-c) shows the climatology, mean and anomaly of SST during composite TCs in AS (upper panel) and BoB (lower panel) regions. The composite mean wind stress anomaly is also overlaid over the SST anomaly during TCs in the AS and BoB regions. The composite mean wind stress anomaly also indicates the cyclonic circulation in west central AS and near the Gujarat coast for AS regions, and in west central BoB region. The composite SST anomaly shows the SST drop (0.2-0.8° C) during TCs. Further, this cyclone-induced SST drop directly related to a negative feedback of energy supply through negative total heat flux and, subsequently to limit the strength of a cyclone. Similarly, the drops in SST anomalies of more than 1 °C have been observed over the different oceanic regions such as Atlantic Ocean; Indian Ocean, and South China Sea at daily scale (Leipper 1972; Shay *et al*., 2008; Lin *et al*. 2003; Veeranjaneyulu Ch and A. A. Deo 2019). Further, the SST drops is much more over the regions where the surface wind stress anomaly is strong.

4.2. *Sea surface heightand tropical cyclone heat potential*

Figs. 3(a-c) shows the climatology, mean SSH and its anomaly during composite TCs in AS (upper panel) and BoB (lower panel) regions. In both regions, various small scale warm and cold eddies are observed during TCs. Here warm and cold core eddy are associated with positive and negative SSH anomaly respectively. All TCs except Amphan TC passes through the negative SSH anomaly. The warm core eddy is also observed during the Amphan TC in BoB region. This may be one of reason for rapid intensification of Amphan TC. Shay *et al*., 2008 shows the sudden unexpected intensification of Hurricane



Figs. 4(a-c). Tropical Cyclone Heat Potential (KJ cm^{-2}) in AS (upper panel) and BoB (lower panel) during the TCs (a) Climatology (b) Observed and (c) Anomaly in AS and BoB regions

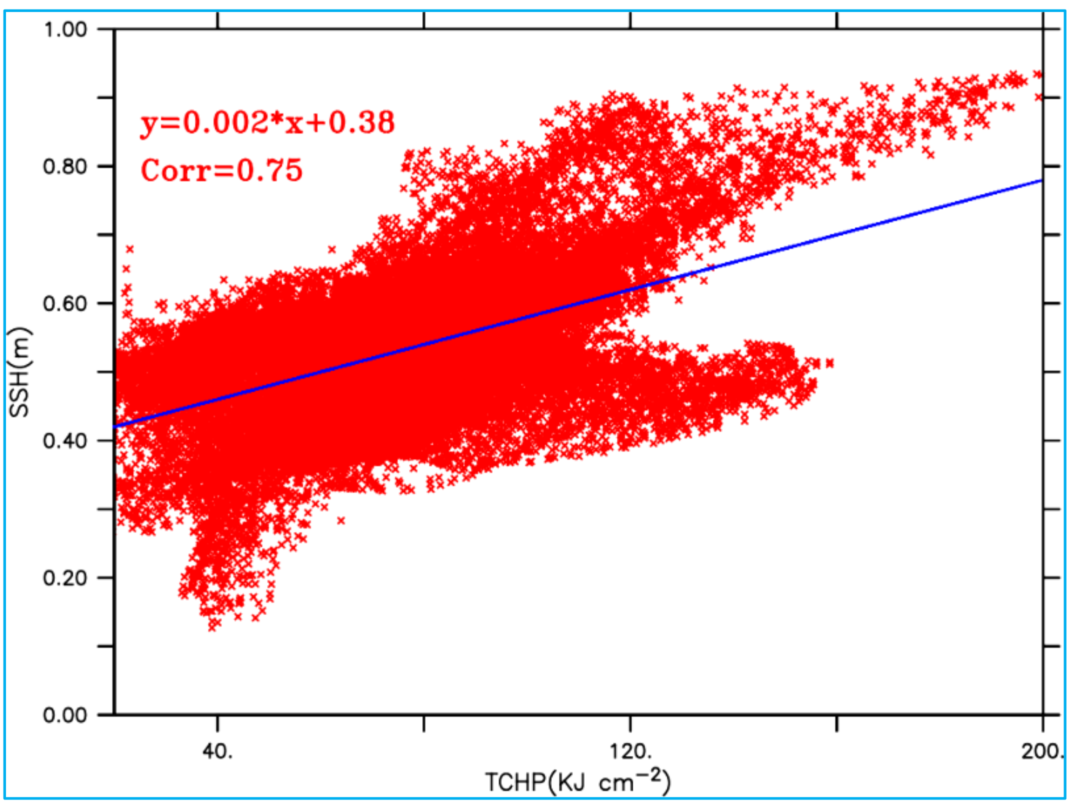


Fig. 5. Scatter plot of SSH (m) *vs* TCHP (KJ cm^{-2}) during the FANI TC (27-3 May, 2019)

Opal in the Gulf of Mexico after passing over a warm core eddy with drop of pressure from 965 to 916 hPa in14-hour period. Further, an increase/decrease in SSH represents a corresponding increase/decrease of the warm water (or heat content) of the ocean. TCHP anomaly is positive/negative over the region where SSH anomaly is positive/negative [Fig. 4(c)]. From [Fig. 4(c)] it is manifest that the magnitude of TCHP anomaly is higher in BoB than AS region during TC. Further, the scatter plot of SSH and TCHP in BoB region (80-95° E; 4-20° N) during FANI cyclone (27-03 May 2019) clearly shows the strong relation with correlation of 0.75 (Fig. 5). There are more than 30,000 points collocated SSH and TCHP points in this analysis. Ali *et al*., 2007 also described the close relationship between the TCs intensity with SSH anomaly in the BoB region.

5. Summary

In the present study, we used the Nucleus European Modelling of Ocean (NEMO) based global ocean analysis and forecast system to compute the Tropical Cyclone Heat Potential (TCHP) at daily time period. The TCHP data are produced in real time up to day 10 using ocean only model forecast and up to 15 days using the global coupled model forecast. This data will be useful for monitoring the global Upper Ocean as well as for research purpose especially during the Tropical Cyclones (TCs). We further analyzed the long term TCHP data (2016-2020) from NEMO analysis system during four TC cases with category above cyclonic storms. In four pre-monsoon TCs, out of which two from Arabian Sea (AS) and two from Bay of Bengal (BoB) are considered here. During the passage of TCs, the three important upper ocean parameters such as Sea Surface Temperature (SST), Sea Surface Height (SSH) and TCHP are studied in term of climatology, mean and its anomaly. The composite SST anomaly shows the SST drop (0.2-0.8° C) during TCs. This cyclone-induced SST drop directly related to a negative feedback of energy supply through negative total heat flux and, subsequently to limit the strength of a cyclone. In both AS and BoB regions, various small scale warm and cold eddies are observed during TCs. TCHP anomaly is positive/negative over the region where SSH anomaly is positive/negative. The magnitude of TCHP anomaly is higher in BoB than AS region during TC. Finally, NCMRWF is actively analyzing various oceanic parameters during TC operationally and for research purpose from ocean forecast system and coupled forecast system.

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References

Ali, M. M., Jagadeesh, P. S. V. and Jain, Sarika, 2007, “Effects of eddies on Bay of Bengal cyclone intensity”, *Eos*., **88**, 8.

Ali, M. M., D. Swain, T. Kashyap, J. P. McCreary and Nagamani, P. V., 2013, “Relationship between cyclone intensities and sea surface temperature in the tropical Indian Ocean”, *IEEE Geosci. Remote Sens. Lett*., **10**, 841-844. doi : 10.1109/LGRS. 2012.2226138.

Balmaseda, M. A., Mogensen, K. and Weaver, A. T. 2012, “Evaluation of the ECMWF ocean reanalysis system ORAS4”, *Q. J. Roy. Meteor. Soc*., **139**, 1132-1161. doi : 10.1002/qj.2063.

Dube, A., Ashrit, Raghavendra, Kumar, Sushant and Mamgain, Ashu, 2020, “Improvements in tropical cyclone forecasting through ensemble prediction system at NCMRWF in India”, *Tropical Cyclone Research and Review*, **9**, 106-116.

Emanuel, K., 2003, “Tropical Cyclones”, *Annu. Rev. Earth Planet. Sci*., **31**, 75-104.

Gray, W., 1968, “Global view of the origin of tropical disturbances and storms”, *Mon. Wea. Rev*., **96**, 669-700.

Goni, G., Demaria, Mark, Knaff, John, Sampson, Charles, Ginis, Isaac, Bringas, Francis, Mavume, Alberto, Lauer, Chris, Lin, I. I., Ali, M. M., Sandery, Paul, Buarque, Silvana Ramos, Kang, Kiryong, Mehra, Avichal, Chassignet, Eric and Halliwell, George, 2009, “Applications of Satellite-Derived Ocean Measurements to Tropical Cyclone Intensity Forecasting”, *Oceanography*, **22**, 3, 190-197.

Gupta, A., Mitra, A. K. and Rajagopal, E. N., 2019a, “Implementation of Unified Model based Global Coupled Modelling System at NCMRWF”, NMRF/TR/01/2019, p52.

Gupta, A., Mitra, A. K. and Rajagopal, E. N., 2019b, “Implementation of Sub-Seasonal to Seasonal Forecast System with NCMRWF Global Coupled Model”, NMRF/TR/04/2019, p63.

Large, W. G. and Yeager, S., 2004, “Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies”, NCAR Technical Note, NCAR/TN-460+STR, CGD Division of the National Center for Atmospheric Research.

Leipper, D. and Volgenau, D., 1972, “Hurricane heat potential in the Gulf of Mexico”, *Journal of Physical Oceanography*, **2**, 218-224.

Lin, I. I., Chen, C. C., 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. Lett*., **36**, L03817. doi : 10.1029/ 2008GL035815.

Madec G. 2008, “NEMO ocean engine”, Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No **27** ISSN No 1288–1619.

Mohapatra, M. and Sharma, M., 2019, “Cyclone Warning Services in India during Recent Years : A Review”, *Mausam*, 70, 4, 635-666.

Mogensen, K. S**.**, M. A. Balmaseda, and A. Weaver, 2012, “The nemovar ocean data assimilation system as implemented in the ECMWF ocean analysis for system 4”, Technical Report **668**, ECMWF.

Momin, I. M., Mitra, A. K., Mahapatra, D. K., Gera, A. and Rajagopal, E. N., 2014, "Impact of model resolutions on Indian ocean simulations from Global NEMO Ocean Model", *Indian Journal of Geo-Marine Science*, **43**, 9, 1667-1674.

Momin, I. M., Mitra, A. K. and Rajagopal, E. N., 2020a, "Implementation of NEMO based Global 3DVar Ocean Data Assimilation System at NCMRWF : Technical Aspects", NMRF/TR/ 02/2020, p26.

Momin, I. M., Mitra, A. K., Waters, J., Martin, M. J. and Rajagopal, E., 2020b, "Impact of Altika Sea Level Anomaly data on variational assimilation system", *Journal of Coastal Research*, **89(sp1)**, 46-51.

Palmén, E. H., 1956, "Formation and development of tropical cyclones", Proc. Tropical Cyclone Symp., Brisbane, QLD, Australia, Bureau of Meteorology, 213-231.

Rai, D., Pattnaik, S., Rajesh, P. V. and Hazra, V., 2018, "Impact of high resolution sea surface temperature on tropical cyclone characteristics over the Bay of Bengal using model simulations", *Meteorol. Appl*., **26**, 130-139.

Sharma, N. and Ali, M. M., 2014, "Importance of Ocean Heat Content for Cyclone Studies, Oceanography", **2**, 2. http://dx.doi.org/10.4172/2332-2632.1000124.

Shay, L. K. and Uhlhorn, E. W., 2008, "Loop Current Response to Hurricanes Isidore and Lili", *Monthly Weather Review*, **136**, 9, 3248-3274. doi : 10.1175/2007MWR2169.1.

Veeranjaneyulu, Ch and A. A. Deo, 2019, "Study of upper ocean parameters during passage of tropical cyclones over Indian seas", *Int. J. Remote Sens*., **40**, 4683-4723.

Waters, J., J. Lea, Daniel, Martin, M. J., Mirouze, Isabelle, Weaver, Anthony and While, James, 2014, "Implementing a variational data assimilation system in an operational 1/4 degree global ocean model", *Q. J. Roy. Meteor. Soc*., **141**, 333-349. doi : 10.1002/qj.2388.

Wendland, W. M., 1977, "Tropical storm frequencies related to sea surface temperatures", *J. Appl. Meteor*., **16**, 477-481.