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Importance of Ocean Heat Content for Cyclone Studies

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Abstract

The physical process involved from formation to dissipation of any cyclone is very complex in nature. Thus, accurate and timely prediction of cyclone intensity and track still remain as challenging scientific problems. Though presently available cyclone prediction models have improved our understanding about many physical processes from cyclone formation to dissipation, some are still unresolved. The input parameters that used into the models as a source of energy for the cyclones need to be reconsidered. Model estimate the energy for cyclones as latent heat release through evaporation computed using only Sea Surface Temperature (SST). However, the energy in the ocean for cyclone is available in the upper layers of the oceans rather than in the skin layer represented by SST. Therefore we examined the importance of heat content of the upper ocean in estimating four important aspects of cyclones (i) pressure drop, (ii) track change, (iii) intensity and (iv) storm surge height. The results obtained during the series of analysis emphasized that the thermal structure of the upper ocean is more critical and sensitive predictor for cyclones compared to SST, which need to be incorporated in numerical models for better and accurate forecasting.

Keywords: Cyclones; Sea surface height anomaly; Ocean mean temperature; Ocean heat content

Introduction

Timely and accurate prediction of the cyclone life cycle from genesis to dissipation is a challenging scientific problem. Though solutions from numerical models have resolved many complex physical processes responsible for cyclone formation, development and dissipation, many issues are to be unfolded. Thus, in addition to improving the understanding of the physics of the problem, critical examination of input parameters that are used in the numerical models is also important. Along with a number of atmospheric parameters, Sea Surface Temperature (SST) is the only oceanographic parameter used in the models for cyclone prediction. However, cyclones interact with the upper layer of the ocean rather with the sea surface skin temperature represented by SST alone. A number of studies have shown a relationship between the thermal structure of the ocean and cyclone intensity (CI). For example, using a coupled ocean-atmospheric model, Mao et al. [1] conclude that the rate of intensification and final CI are sensitive to the initial spatial distribution of the mixed layer rather than to SST alone. Namias and Cayan [2] argue that patterns of lower atmospheric anomalies are more consistent with anomalies of the upper ocean thermal structure than with SST. Lin et al. [3] show ocean sub-surface warm features such as eddies are critical for the sudden intensification of cyclones.

Thus, an important but generally neglected parameter that enhances the understanding of the intensification of the cyclones is the upper ocean heat storage, known as Ocean Heat Content (OHC) or Tropical Cyclone Heat Potential (TCHP: Goni and Knaff) [4]. TCHP is generally reflected in the altimeter-derived oceanic eddies and sea surface height anomalies (SSHAs). Recently, Ali et al. [5] studied the statistical relationship between cyclone intensity (CI) and SST in the

tropical Indian Ocean (TIO; 30°S–30°N, 30°E–120°E) and concluded that satellite-derived SST is not a good indicator of CI. They suggested a more accurate parameterization of SST throughout the lifetime of a cyclone, for example OHC.

Hence, in this paper, we examined the importance of TCHP/OHC over SST in cyclone (i) pressure drop, (ii) track change, (iii) intensity and (iv) storm surge. The results show that in comparison with SST, TCHP/OHC derived from SSHA is more critical for cyclone studies.

The structure of the paper is organized as follows: Under discussion in SSH and OHC, we first showed how the subsurface thermal structure is reflected in sea surface height (SSH) but not in SST. Then we documented the relationship between SSHA, SST and CI. In the next sub-section we proved how the information on SSHA improves the cyclone track prediction. Then the importance of TCHP in simulating the pressure drop in a cyclone and the storm surge height is discussed. The next subsection demonstrates the sensitivity of OHC in CI estimations. The role played by TCHP in more intensifying cyclones in the Arabian Sea in the recent years is discussed in TCHP and number of intensifying cyclones. Finally the discussions are concluded in conclusion.

Discussions

SSH and OHC

OHC available for the atmospheric processes depends upon the thickness of the upper layer of the ocean. This thickness is reflected to a large extend on the SSHA obtained from satellite altimeters. The increase in SSH can be because of the two factors: (i) due to the convergence of water because of the wind stress curl and anticyclonic eddies and (ii) due to the thermal expansion of water because of the increase in the average temperature of the layer. Whenever SSH

increases, the isotherms go down Figure 1 and when the SSH decreases the isotherms come up. As a result, if we consider a layer of ocean to a fixed depth, the average temperature of the layer and hence the OHC is more where SSH is more and vice versa. Having a priori information on the thermal structure, OHC or TCHP can be statistically obtained having information on SST and SSHA. The detailed procedure of estimating TCHP is given by Goni et al. [6] and Shay et al. [7]. Thus, SSH is an indirect indicator of OHC. On the contrary, SST many times does not represent this heat energy. For example, SST is almost same all along the ship track Figure 2 whereas a significant variation is present in the subsurface thermal structure due to the presence of anticyclonic and cyclonic eddies. These variations in the subsurface thermal structure are very clearly reflected in SSHA. Thus, we can conclude that changes in SSHA represent better the variations in the subsurface thermal structure and hence the OHC than in SST. Having a priori information on the thermal structure of the ocean, at least climatologically, we can estimate OHC from SSHA, which in turn can be used as an input to the cyclone models.
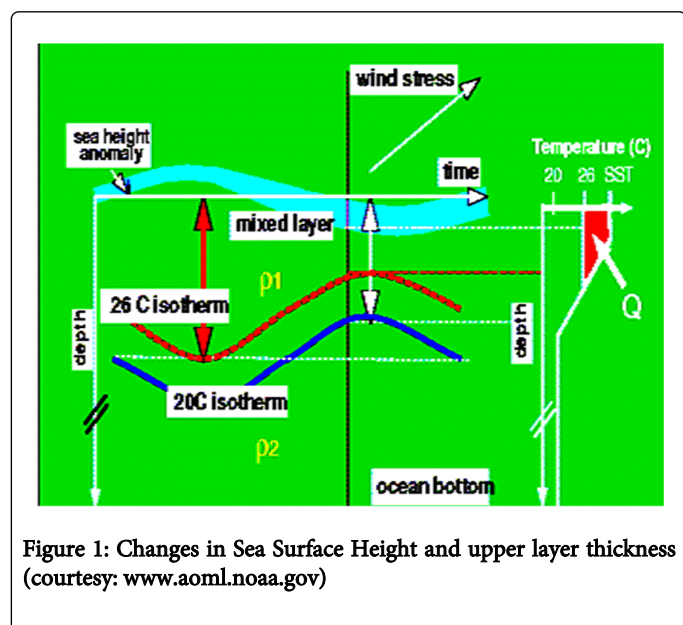

Figure 1: Changes in Sea Surface Height and upper layer thickness (courtesy: www.aoml.noaa.gov)

Satellite altimeters can provide SSHA to a required accuracy. Ali et al. [9] estimated sub- surface temperature profiles from dynamic height (considering as a proxy to SSHA) and other surface parameters. Recently Pun et al. [10] used altimeter derived SSHA to estimate the subsurface thermal structure for cyclone studies. These temperature profiles can also be used to estimate OHC. Mainelli et al. [11] have shown the importance of OHC in the operational forecasting of category-5 hurricanes in the Atlantic. Mei et al. [13] reported that SSHA obtained from satellites is a unique way of tracking the changes in OHC on seasonal and longer time scales.

SSHA, SST and CI

Initially, without computing TCHP, Ali et al. [12] studied the impact of SSHA on CI on two Bay of Bengal cyclones (10-19 May 2003 and 15-22 December 2005). For this purpose, a 3-day composite SST from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and 10-day composite of near real time SSHA from Jason and European Remote Sensing Satellite-2 were used.
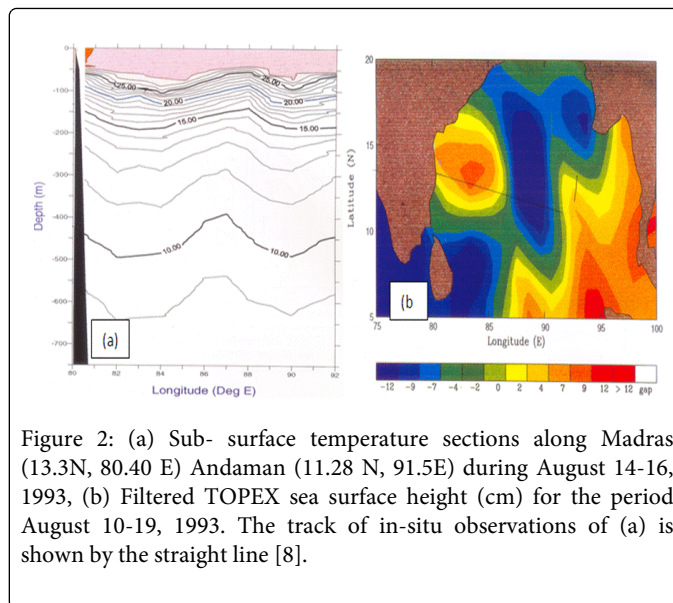

Figure 2: (a) Sub- surface temperature sections along Madras (13.3N, 80.40 E) Andaman (11.28 N, 91.5E) during August 14-16, 1993, (b) Filtered TOPEX sea surface height (cm) for the period August 10-19, 1993. The track of in-situ observations of (a) is shown by the straight line [8].

The cyclone intensified at the place of warm core eddy with more OHC and its intensity reduces with a decrease in the SSHA Figure 3a, b and e. CI has shown almost one to one correspondence with SSHA Figure 3c. On the contrary, such a relation is not observed between SST and CI; in fact CI is more when SST is less and it is less when SST is more Figure 3d. Generally, cyclones/depressions do not dissipate in the ocean. 15-22 December 2005 depression is one depression, which dissipated in the ocean without crossing the land. Cyclone eddy with low OHC could be one of the reasons for this dissipation in the ocean itself. Several other studies also reported that CIs are positively (negatively) correlated with positive (negative) SSHAs [3,13,14].
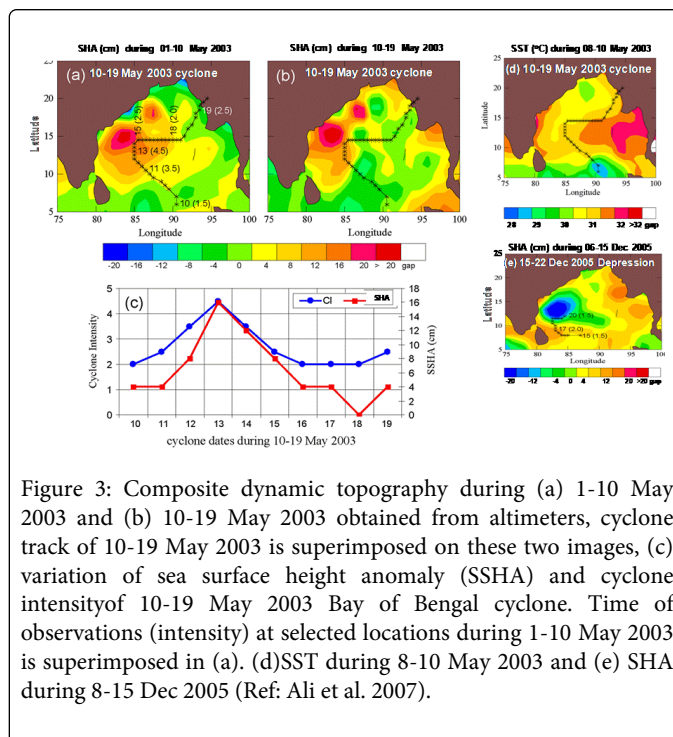

Figure 3: Composite dynamic topography during (a) 1-10 May 2003 and (b) 10-19 May 2003 obtained from altimeters, cyclone track of 10-19 May 2003 is superimposed on these two images, (c) variation of sea surface height anomaly (SSHA) and cyclone intensity of 10-19 May 2003 Bay of Bengal cyclone. Time of observations (intensity) at selected locations during 1-10 May 2003 is superimposed in (a). (d)SST during 8-10 May 2003 and (e) SHA during 8-15 Dec 2005 (Ref: Ali et al. 2007).

Ali et al. [15,16] further analyzed TRMM Microwave Imager (TMI) daily SST and CI, defined as the maximum sustained winds from Joint Typhoon Warning Center (JTWC) best track data. They reported that out of 75 cyclones occurred in the tropical Indian Ocean during 1998-2011; more than 50% of the cyclones have no significant correlation between CI and SST. The number of cyclones with significant negative (positive) correlation are 31(3), 13(10) and 17(14) with SST leading CI by one, two and three days respectively Figure 3 of Ali et al. [15,16]. In these cases SST of previous days is correlated with CI. Therefore, cooling of SST due to strong cyclonic winds of the same day is ruled out. Since the number of cyclone with a negative correlation between CI and SST are more than those having positive correlations, Ali et al. [17] suggested to have a relook at the use of satellite derived SST as a measure of CI.

From these studies, it is clear that SSHA, representing the OHC of the upper layer would be a better parameter than SST representing the heat of a very thin surface layer.

SSHA and cyclone track

The cyclone during 6-11 May 2002 is one of the very few cyclones that originated in the central Arabian Sea during May and moved westward. Incidentally, there was a strong anticyclonic eddy in the western Arabian Sea, which has more heat content compared to the surroundings. Ali et al. [9] examined the effect of this eddy on the unusual westward movement of this cyclone. They linearly converted the SSHA to SST and used these SST values in the Mesoscale Model (MM5). They found an improvement in the track prediction indicating the importance of SSHA, representing OHC on cyclone track prediction. The actual cyclone track taken from JTWC, the track obtained by using the National Center for Environmental Prediction (NCEP) SST and the track obtained by using the SST converted from SSHA are shown in Figure 4. The track obtained by using SSHA converted SST is very close to the actual track. The track error also reduces as the lead time increases (Figure not shown).
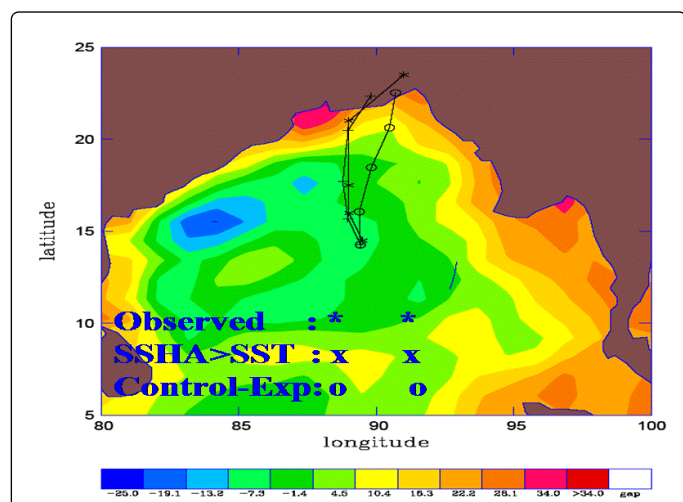

Figure 4: comparison of the observed SIDR cyclone track with the one obtained using NCEP SST and using SST converted from SSHA.

Thus, the track prediction improves if the information available from SSHA is used.

TCHP and cyclone pressure drop and storm surge

As pressure drop is another indicator of the CI, Goni et al. [4] analyzed the results using Geophysical fluid Dynamics Laboratory (GFDL) coupled hurricane ocean model sensitivity experiments for selected hurricanes with and without assimilating TCHP data to evaluate the impact of measoscale oceanic features on both SST cooling under the storm and subsequent change in the storm intensity. For the hurricane Katrina (2005) the assimilation improved the actual storm's intensity forecast with respect to that obtained without assimilating the altimetry derived TCHP. Besides intensity, they found the pressure drop obtained by assimilating TCHP to be closer to the actual pressure drop.

Lin et al. [5] observed that hurricane Rita when encountered with a high TCHP region lead to large storm surge and inundation. They showed that this hurricane passed over two prominent warm ocean eddies (characterized by positive SSHA of 10–40 cm) in the Gulf of Mexico, just prior to its landfall. The analysis revealed ~30% increase in surge and inundation along the coast as compared to a tropical cyclone that does not encounter a high TCHP. They simulated the differences in the upper-ocean thermal structure of the two scenarios. The eddy encountering scenario (red profile in their Figure 5) is characterized by a much deeper subsurface warm layer, with depth of 26C isotherm (D26) reaching 100 m. In contrast, the 'without eddy encounter' normal climatological subsurface warm layer is much shallower with a D26 of 50m. Similar feature is observed during cyclone SIDR in Bay of Bengal before its landfall. During its travel across the Bay of Bengal it passed over an area with high TCHP values of 80 kJ cm^{-2} Figure 5 just before landfall in a region where storm surge was exacerbated by a shallow continental shelf.

Thus, including TCHP into the models resulted in better representation of cyclone pressure and storm surge height.
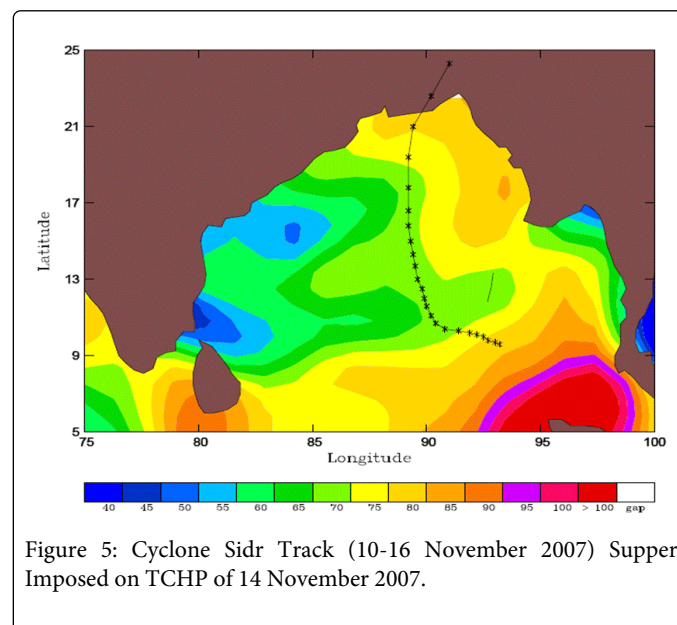

Figure 5: Cyclone Sidr Track (10-16 November 2007) Supper Imposed on TCHP of 14 November 2007.

Sensitivity of CI to TCHP

Shay and Brewster [18] demonstrated the application of OHC variability in hurricane intensity forecasting in the Eastern Pacific Ocean. Recently, Sharma et al. [19] addressed a challenging problem of

cyclone intensity prediction by developing a new scheme called Soft-computing Cyclone Intensity Prediction Scheme (SCIPS) using Artificial Neural Network (ANN) technique and OHC as an additional predictor over North Western Pacific Ocean. The SCIPS predictions improved the intensity forecasts made by more widely used Multiple Linear Regression (MLR). The performance of SCIPS compared with MLR increases as a function of both intensification and lead forecast hour. Out of 13 predictors used to develop the model, including those estimated from SST, OHC has the fourth rank.

TCHP and number of intensifying cyclones

Cyclones over the Arabian Sea are more intensifying in the recent years. Besides the increasing aerosols over this region [20], Rajeevan et al. [21] found an increasing trend in the area averaged TCHP over North Arabian Sea ($15°$–$25°$N, $60°$–$75°$E). The 11-year running mean shows epochal variations, with higher TCHP during the first (1955–1973) and third (1993–2011) epochs compared to the second (1974–1992) epoch. Out of 19 years in the middle epoch of 1974–1992, in 13 years, the area with TCHP exceeding 50 kJ cm^{-2} was below the long-term average. Compared to the middle epoch, the recent epoch witnessed an increase of about 6% in the area with TCHP exceeding 50 kJ cm^{-2} and 26% in TCHP exceeding 90 kJ cm^{-2}. They observed the observed epochal variations of intense TCs over the Arabian Sea to be consistent with the epochal variations of TCHP. On the other hand, such an increasing trend is not observed in SST. Thus, TCHP may be more responsible in increasing the number of intensifying cyclones rather than SST. Using satellite altimetry and gravity observations, Pun et al. [22] found that the subsurface ocean conditions in the western North Pacific have become more favorable for the intensification of typhoons and super typhoons. Normile [23] reported that warmer subsurface waters along super typhoon Haiyan's track and rising of sea level due to the pushing of warmer water to the western North Pacific by the easterly trade winds are responsible for the fury of the super typhoon.

Conclusion

These analyses indicate that OHC act as a more important predictor than SST to estimate the life cycle of a cyclone through pressure drop, track change, intensity and to predict storm surge height. This parameter also explains the increasing number of intensifying cyclones. Since the atmosphere interacts with the ocean through SST, a better parameterization of SST that takes into account the OHC is required to be developed. One such option is to get the ocean mean temperature of the upper layer that interacts with the atmosphere. Since this parameter has the same units as that of SST, assimilating it in the cyclone models is simple.

Acknowledgement

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