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15	**Abstract**: For past many years, researchers are studying many parameters affecting the formation of cyclone. It is well known that the atmosphere does not only interact with ocean surface but upper layers of the ocean as well. Based on past observations, it is known that sea waters having higher temperature than 26 ^{o}C contribute in cyclone formation. So it is important to consider the heat content with respect to the 26 ^{o}C temperature. Such heat content, also known as Tropical Cyclone Heat Potential (TCHP), can be a better predictor than SST. In present report, the methodology and validation work of insitu data are described to generate TCHP based on Two Layer reduced Gravity Model for 1993 to May, 2019 (27 years) for Tropical Indian ocean using monthly climatologies of temperature and salinity profiles, daily Sea Surface Height Anomaly (SSHA) and daily Sea Surface Temperature (SST). **Key Words**: Tropical Cyclone Heat Potential (TCHP), Two Layer reduced Gravity Model, Sea Surface Temperature (SST), Sea Surface Height Anomaly (SSHA)			

Tropical Cyclone Heat Potential using Two Layer Reduced Gravity Model

Ghetiya Satyeshkumar, Shiva Shankar Manche, R K Nayak

Contents

Abstract

For past many years, researchers are studying many parameters affecting the formation of cyclone. It is well known that the atmosphere does not only interact with ocean surface but upper layers of the ocean as well. Based on past observations, it is known that sea waters having higher temperature than 26 °C contribute in cyclone formation. So it is important to consider the heat content with respect to the 26 °C temperature. Such heat content, also known as Tropical Cyclone Heat Potential (TCHP), can be a better predictor than SST. In present report, the methodology and validation work of insitu data are described to generate TCHP based on Two Layer reduced Gravity Model for 1993 to May, 2019 (27 years) for Tropical Indian ocean using monthly climatologies of temperature and salinity profiles, daily Sea Surface Height Anomaly (SSHA) and daily Sea Surface Temperature (SST).

1 Introduction

It is known that Sea Surface Temperature (SST) above 26 °C is necessary in order for tropical cyclogenesis to occur (Palmén 1948). Heat content of the ocean water is another parameter affecting the cyclone formation and sustainment. For cyclogenesis (the process of cyclone formation), many parameters need to be studied which includes sea level pressure, latent heat flux, wind shear, relative humidity and mid-troposphere temperature instability. But for ocean's perspective, heat content of ocean water supplies necessary energy to sustain cyclone's wind and energy. Heat content is a relative term and we can choose any temperature as a reference for heat content calculation, but 26 °C is majorly used because 26 °C is the sea surface temperature below which cyclones do not form (Byers 1959) and it is the mean air temperature at the surface for tropical atmosphere in cyclone season (Malkus 1962). Such heat content is called Tropical Cyclone Heat Potential (TCHP) (Leipper and Volgenau 1972). TCHP is integrated ocean heat content above 26 °C isotherm in the upper ocean. (Shay et al. 2000) and (Wada and Usui 2007) studied TCHP and its relation with changes in the intensity of tropical cyclones. TCHP can be calculated from the following formula (Leipper and Volgenau 1972):

$$TCHP = C_p \rho \int_0^{D26} (T - 26) dz \tag{1}$$

where C_p is specific heat capacity of water (4.186 kJ/kg·°C), ρ is the density of the water layer (neglecting small variation of density of water, we can put the density term outside the integration), T is the temperature of the water layer having thickness dz.

To calculate TCHP, we need temperature profile from the surface to the depth of 26 °C isotherm (here after the depth of 26 °C isotherm is referred to as D26 and the depth of 20 °C isotherm as D20). Due to practical limitations of in situ measurements, in situ vertical profiles are hardly available daily at our desired study area. If we can incorporate satellite data to calculate daily TCHP, we can get TCHP in good spatial and temporal resolution.

2 Data

2.1 Monthly average of temperature and salinity profiles

Monthly averages of temperature and salinity profiles having 0.5° x 0.5° spatial grid resolution of Simple Ocean Data Assimilation (SODA) from APDRC is used to generate monthly climatologies of D26, D20, upper layer density ρ_1 and lower layer density ρ_2 (Data provided by Asia-Pacific Data Research Center (APDRC), which is a part of the International Pacific Research Center at the University of Hawai'i at Mānoa, funded in part by the National Oceanic and Atmospheric Administration (NOAA). Retrieved in February, 2018). Upper layer is the layer starting from the surface to the depth of 20 °C, while Lower layer is the layer starting from 20 °C to the depth of 1000m. These climatologies are made using 26 years (1990-2015) of SODA monthly data of temperature and salinity profiles.

2.2 Daily SST and SSHA

'NOAA high-resolution blended analysis of daily Sea Surface Temperature (SST) and Ice' is used for Sea Surface Temperature (SST) data. This is Optimum Interpolation SST (OISST) with 0.25° x 0.25° spatial resolution and one day temporal resolution (NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site an.t https://www.esrl.noaa.gov/psd/data/gridded/. Retrieved in February, 2018). This OISST is from infrared sensor of AVHRR (**A**dvanced **V**ery **H**igh **R**esolution **R**adiometer) suitable for our work with mentioned temporal and spatial coverage.

Sea Surface Height Anomaly (SSHA) having 0.25° x 0.25° spatial grid and one day temporal resolution is used. This is multi altimeter satellite gridded sea surface heights computed with respect to a 20 year mean which is obtained and generated using E.U. Copernicus Marine Service Information (http://marine.copernicus.eu/services-portfolio/access-to-products/). The parameter SSHA is named as SLA (sea level anomaly) in CMEMS[1] dataset. Both SST and SSHA data are taken for the period 1993 to May, 2019 in the spatial range of 30°N-30°S and 40°E-120°E for Tropical Indian Ocean. For the recent years, where reanalysis data are not available for SST and SSHA, Near Real Time (nrt) data are taken for both SST and SSHA.

2.3 In situ temperature and salinity profiles from ARGO

For validation of satellite TCHP data , the in situ vertical profiles of temperature and salinity are required which are taken from Argo[2] float data from data selection utility of Coriolis database[3]. The Argo float data of the year 2011 for Tropical Indian Ocean (30°N-30°S and 40°E-120°E) is downloaded and used.

3 Methodology

3.1 Calculating daily TCHP

The method and validation work is similar to that described by Satyesh et al. 2019 (under review at the time this report is prepared). TCHP, can be written as (Leipper and Volgenau 1972):

$$TCHP = C_p \rho \sum_{z=0}^{D26} (T - 26) \Delta Z \tag{2}$$

To evaluate TCHP using satellite data with required spatial and temporal resolution, simplified equation (2) is used. Two Layer reduced Gravity Model (TLGM) is demonstrated to estimate upper layer thermal structure in terms of 20 °C and 26 °C isotherms in previous studies(Goni et al. 1996; Shay et al. 2000; Vissa et al. 2013). In Arabian sea and Bay of Bengal, the 20 °C isotherm is within the thermocline. So we can simplify ocean's vertical structure, under TLGM, as having two layers separated by 20 °C isotherm and hence we can use TLGM method.

[1] **C**opernicus **M**arine **E**nvironment **M**onitoring **S**ervice

[2] These data were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System. Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. http://doi.org/10.17882/42182

[3] http://www.ifremer.fr/co-dataSelection

Using TLGM, we estimated $D20$ (having one day temporal resolution) from equation 3. ρ_1 and ρ_2 are average densities of upper (surface to $D20$) and lower ($D20$ to 1000m) layers respectively. In equation 3, $\overline{D20}$, $\overline{\rho_1}$ and $\overline{\rho_2}$ are monthly climatologies (1990-2015) of $D20$, ρ_1 and ρ_2 based on SODA data (density is derived using Ferret's 'UNESCO state equation (density) for ocean water'). Monthly climatologies $\overline{D20}$, $\overline{\rho_1}$ and $\overline{\rho_2}$ are then linearly interpolated to make daily climatologies having same spatial resolution as SSHA. From TLGM, in few rare regions, D26 or D20 comes deeper than the ocean bottom if the ocean region is very shallow. Care has been taken for such cases to include the effect of shallow terrain using *etopo* [4] bathymetry. Monthly climatology of the ratio of $D26$ and $D20$ are calculated as in equation 4 and is called θ. θ is linearly interpolated to make its daily climatology having same spatial resolution as SSHA. Daily $D26$ is calculated from θ and $D20$ using equation 5. From this, TCHP is calculated using equation 6 (ρ_{26} is average density of water upto D26 from SODA monthly data which is then interpolated to make its daily climatology having spatial resolution same as SSHA). C_p is 4.186 kJ/kg·°C, SST is in °C, D26 is in meter and ρ_{26} is in kg/m^3. 10^{-4} is to convert TCHP in units of kJ/cm^2. Further the TCHP is assigned 0 value at locations where SST is cooler than 26 °C.

$$D20 = \overline{D20} + \frac{\overline{\rho_2}}{\overline{\rho_2} - \overline{\rho_1}} * SSHA \tag{3}$$

$$\theta = \overline{D26/D20} \tag{4}$$

$$D26 = \theta \times D20 \tag{5}$$

$$TCHP = C_p * \rho_{26} * (SST - 26°C) * D26 * 10^{-4} \tag{6}$$

3.2 Validation of generated TCHP

Validation of created TCHP data set is done to compare Two Layer reduced Gravity Model (TLGM) derived satellite TCHP and TCHP derived from in situ measured ARGO profiles. For this, Argo salinity and temperature profiles for one full year (2011) for Tropical Indian Ocean (30°N-30°S and 40°E-120°E) are used. Argo profiles' pressure levels are converted using

[4]National Geophysical Data Center, 2006. 2-minute Gridded Global Relief Data (ETOPO2) v2. National Geophysical Data Center, NOAA. doi:10.7289/V5J1012Q [January 2018].

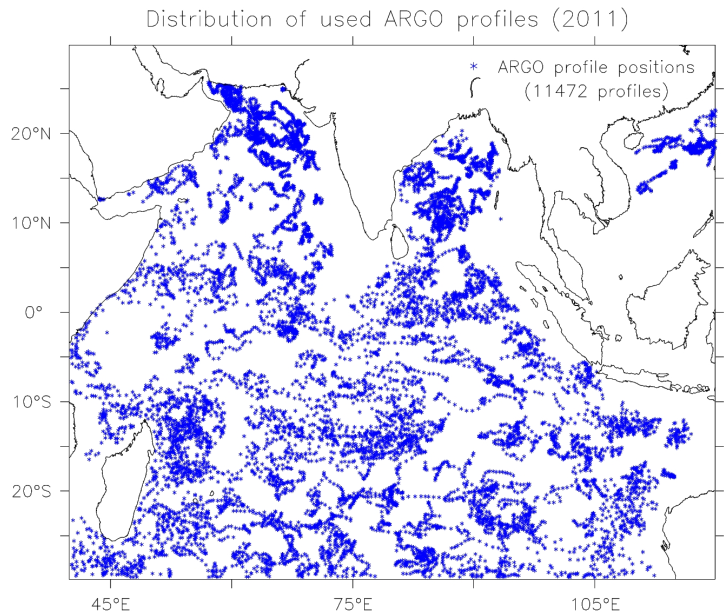

Figure 1: Distribution of utilized Argo profiles in Tropical Indian Ocean (2011). Total 11472 profiles are used.

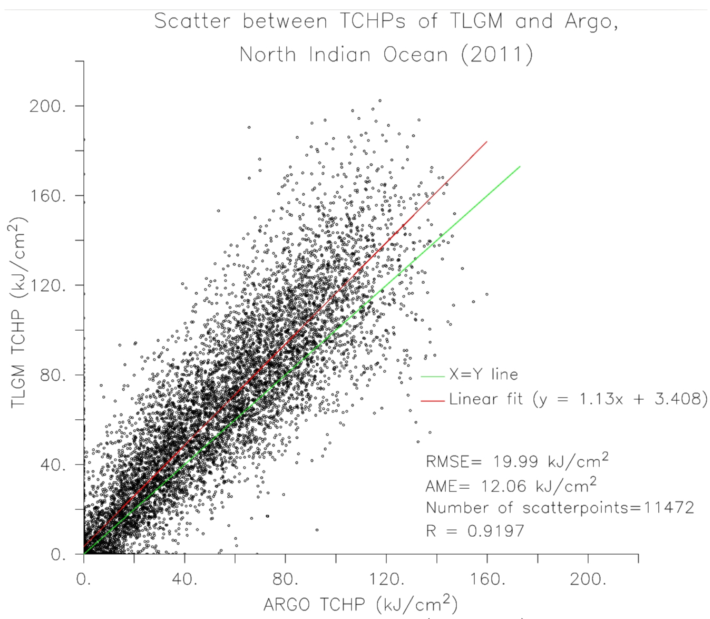

Figure 2: Scatter between satellite derived (TLGM) TCHP and Argo derived TCHP

Saunders' formula (Saunders et al. 1981) to depth levels. After addition of the product $C_p\rho(T-26)\Delta Z$, TCHP is derived at profile locations in Tropical Indian Ocean. If the top most depth level of Argo temperature profile is cooler than 26 °C, TCHP was assigned value 0. Out of total 16115 profiles obtained from 480 Argo floats, 11472 were useful and TCHP is derived for all of these locations. Spatial distribution of used Argo profiles, where TCHP is derived, is plotted in Figure 1. This insitu derived TCHP data set is used to analyse the satellite derived TLGM TCHP at co-located points. Figure 2 shows the scatter plot between Argo TCHP and TLGM TCHP. The correlation coefficient r is 0.920 ($p < 0.00001$) for sample size of 11472 indicating its high statistical significance. Using Fisher transformation for correlation coefficient r and given sample size, 99.99% confidence interval for r comes $0.914 \leq r \leq 0.925$. This interval gives the range of correlation coefficient r for full population points of Tropical Indian Ocean with 99.99% confidence level which supports the validity of satellite derived TLGM TCHP and its variation with corresponding in situ Argo TCHP. Other statistical parameters are listed in Figure 2. Here one point to be noted is that, the validation of TLGM TCHP is done for full NIO region wherever ARGO profiles were available for 2011 year. So this includes the validation of regions where cyclogenesis is not so frequent and hence this work validates the TLGM TCHP with insitu derived TCHP in an unbiased way. This TCHP data set is being hosted in NRSC's NICES portal in netcdf format (https://bhuvan-app3.nrsc.gov.in/data/download/index.php).

4 Monthly Climatology of TCHP from TLGM

In Figure 3 and 4, the typical climatologies of TCHP is shown using year 2011 data. The shown monthly climatologies are from TLGM scheme. In Figure 3, month of May shows very high TCHP in both Arabian sea and Bay of Bengal, but Bay of Bengal has more favorable conditions in terms of low vertical wind shear and other atmospheric parameters which makes southern Bay of Bengal frequent cyclogenesis region. October and November TCHP (Figure 4) shows again southern Bay of Bengal as having high TCHP regions. Typical TCHP values varies from 0 kJ/cm^2 (areas having temperature near 26 °C) to more than 200 kJ/cm^2 (near regions having warm ocean waters and high stratification)

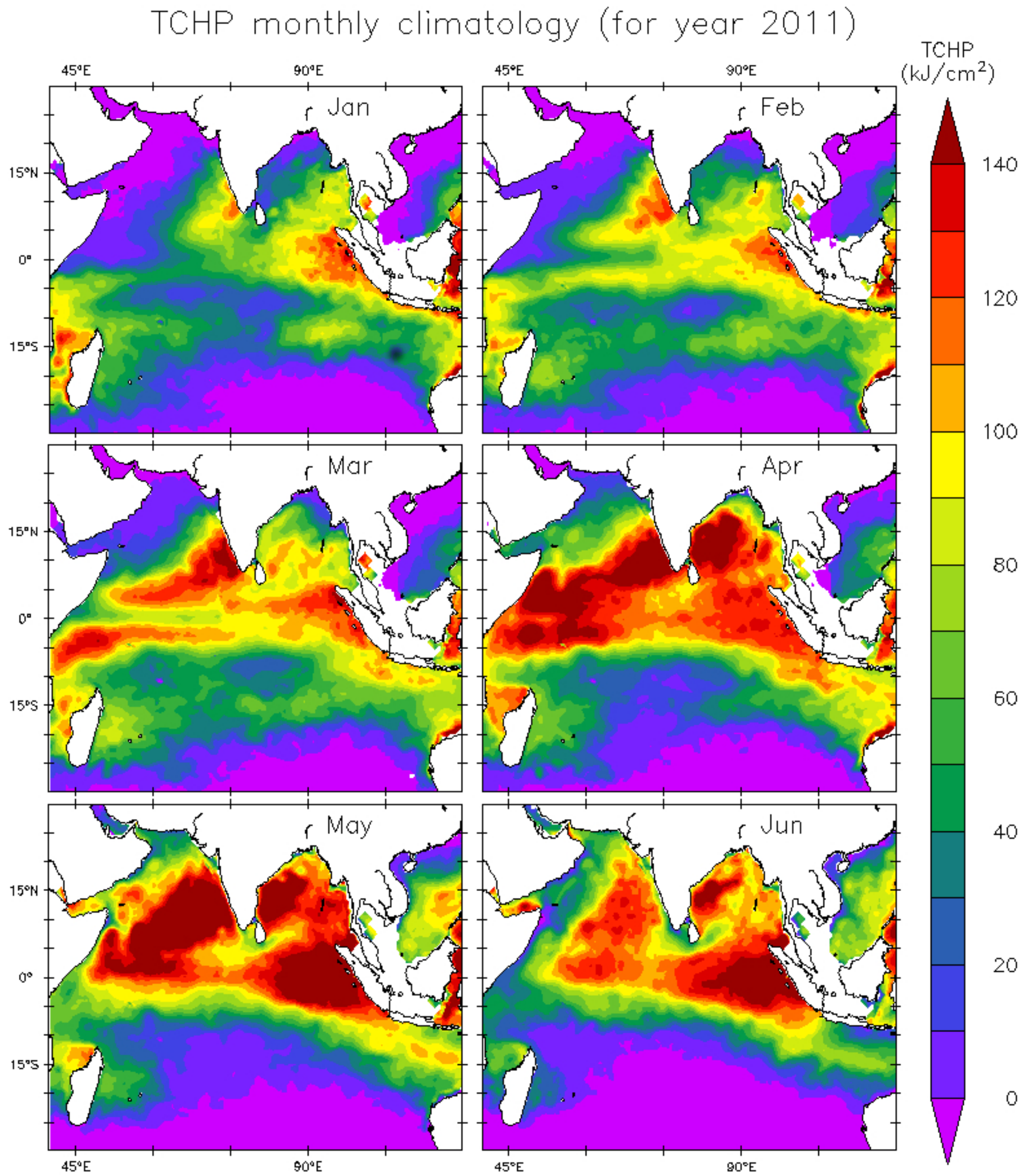

Figure 3: Typical Monthly Climatology of TCHP derived from satellite data using TLGM (January to June for the year 2011)

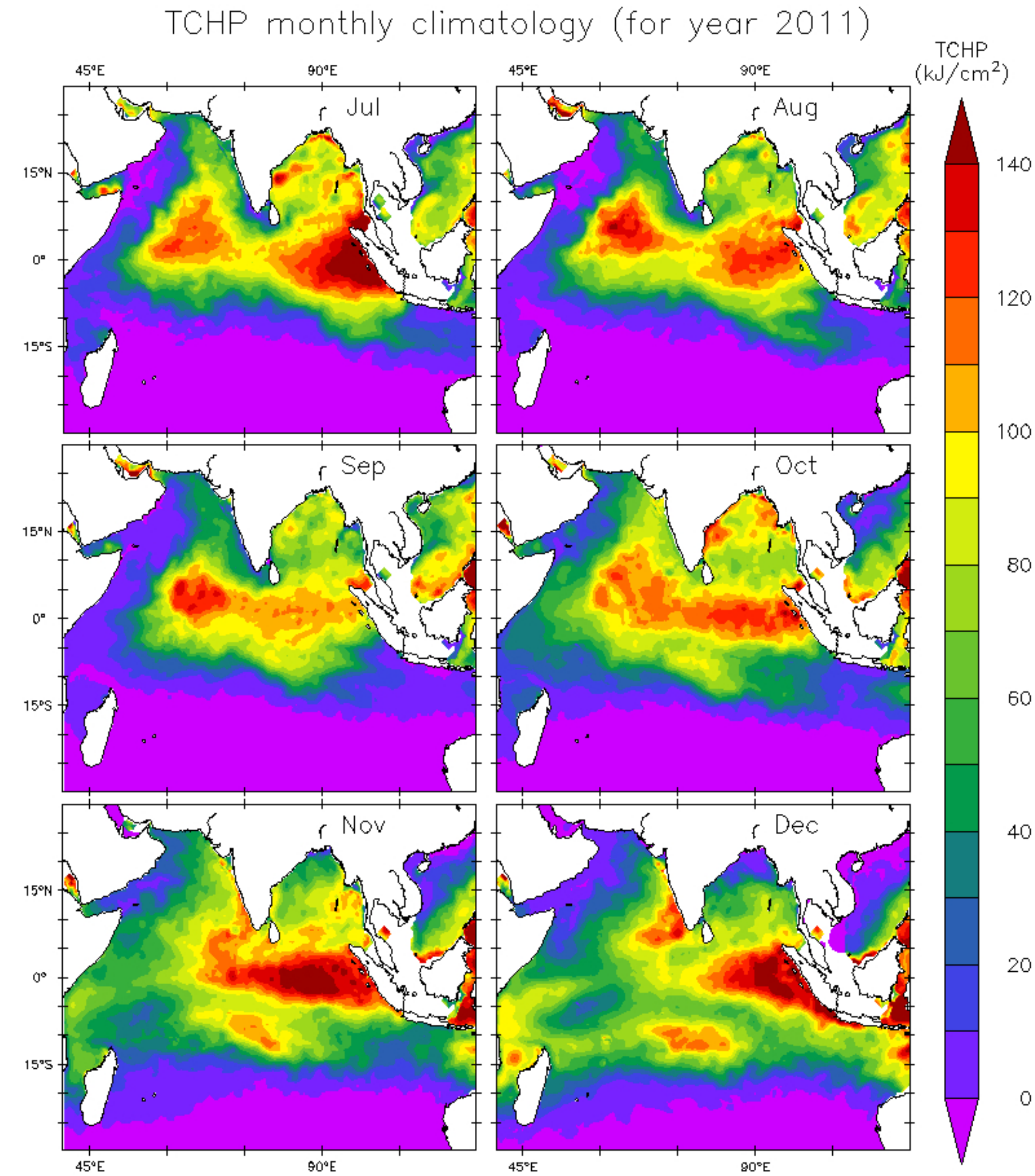

Figure 4: Typical Monthly Climatology of TCHP derived from satellite data using TLGM (July to December for the year 2011)

5 Conclusion

In this study, the TCHP from TLGM is generated and validated. TCHP calculation from TLGM method has advantage of being a physical method rather than a statistical regression method. The validation with in-situ TCHP from ARGO suggests that TCHP from TLGM could be used to carry out research on cyclone studies. Further, using near real time SSHA and SST, operational TCHP can be made and can be used for near real time cyclone research and heat content studies as well.

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