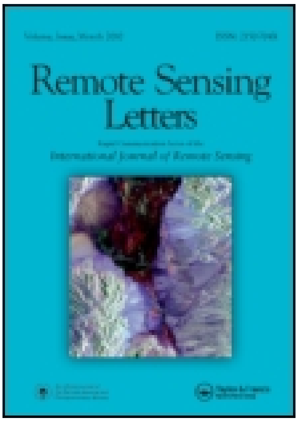

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Validation of satellite-derived tropical cyclone heat potential with *in situ* observations in the North Indian Ocean

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Tropical cyclone heat potential (TCHP) is an important ocean parameter influencing cyclones and hurricanes. The best approach for computing TCHP is to use *in situ* measurements. However, since *in situ* data have both spatial and temporal limitations, there is a need for satellite-based estimations. One potential solution is to use sea surface height anomalies (SSHAs) from altimeter observations. However, any estimation derived from satellite measurements requires extensive regional validation. In this letter, we compare satellite-derived TCHP values with those estimated using *in situ* measurements of the North Indian Ocean collected during 1993–2009. All the available measurements collected from the conductivity temperature and depth (CTD) profiler, expendable CTD profiler (XCTD), bathythermograph (BT), expendable BT (XBT) and Argo floats were used to estimate *in situ* derived TCHP values. TCHP estimations from satellite observations and *in situ* measurements are well correlated, with coefficient of determination R^2 of 0.65 (0.76) and a scatter index (SI) of 0.33 (0.25) on a daily (monthly) basis for the North Indian Ocean.

1. Introduction

The ocean parameter influencing tropical cyclone intensity (CI) and its intensification is the upper ocean heat energy. The relationship between sea surface temperature (SST) and CI has been long studied in statistical intensity prediction schemes such as the National Hurricane Center Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1994, DeMaria *et al*. 2005) and the Statistical Typhoon

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Intensity Prediction Scheme (STIPS; Knaff *et al*. 2005). STIPS is run at the Naval Research Laboratory in Monterey, CA, and is provided to the Joint Typhoon Warning Center (JTWC) to make tropical CI forecasts in the western North Pacific, South Pacific and Indian Oceans. Since the upper ocean heat content (OHC) better represents the energy available for cyclones than SST alone, the inclusion of OHC in the SHIPS and STIPS models improves the capability of forecasting cyclones and their intensity compared with using SST alone (Goni 2008, Goni *et al*. 2009). However, the energy available for cyclones is generally defined as the tropical cyclone heat potential (TCHP; Gray 1979) and is calculated by summing the heat content in a column where the SST is above 26°C (Leipper and Volgenau 1972). The best approach for computing TCHP is to use *in situ* measurements. However, since the *in situ* data have spatial and temporal limitations, there is a need for satellite-based estimations. The methodology for estimating TCHP using the European Remote Sensing Satellite-2 (ERS-2) and TOPEX/Poseidon satellite altimetry observations has already been developed by Goni *et al*. (1996) and Shay *et al*. (2000).

However, the satellite-derived TCHP values need regional validation with *in situ* estimations for quantification of their reliability and consistency. Once the validation has been carried out, the satellite-derived TCHP values with their improved temporal and spatial properties can be conveniently used. For this reason, in this letter, an attempt is made to validate the satellite-derived TCHP values with *in situ* observations in the North Indian Ocean. The temperature profiles collected during different ship campaigns using conductivity temperature and depth (CTD) profiler, bathythermograph (BT), expendable BT (XBT), expendable CTD (XCTD) profiler and Argo observations are used to derive *in situ* TCHP.

2. Study area and data

For this study, the North Indian Ocean covering 0–30° N, 40–100° E was selected. The spatial distribution of *in situ* data collected from the Argo floats and the conventional methods during 1993–2009 is shown in figure 1.

3. Methods

3.1 *TCHP from* in situ *observations*

In situ data collected during various ship campaigns from 1993 to 2009 in the Arabian Sea and the Bay of Bengal were used to compute TCHP following Leipper and Volgenau (1972):

$$\mathrm{TCHP} = \rho C_\mathrm{p} \int_0^{D_{26}} (T - 26)\mathrm{d}z, \tag{1}$$

where ρ is the average density of the sea water, C_p the specific heat capacity of sea water at constant pressure p, T the temperature (°C) of each layer of dz thickness and D_{26} the depth of the 26°C isotherm. When the SST is below 26°C, TCHP for the layer is assumed to be zero. The depth of the 26°C isotherm is interpolated if a measurement at this depth is not available. All the profiles that do not have observations up to 5 m depth from the surface are discarded, as TCHP is the integrated value from D_{26} to the surface. If a particular profile does not have measurement at the surface (0 m), the closest observation to the surface is repeated for 0 m.

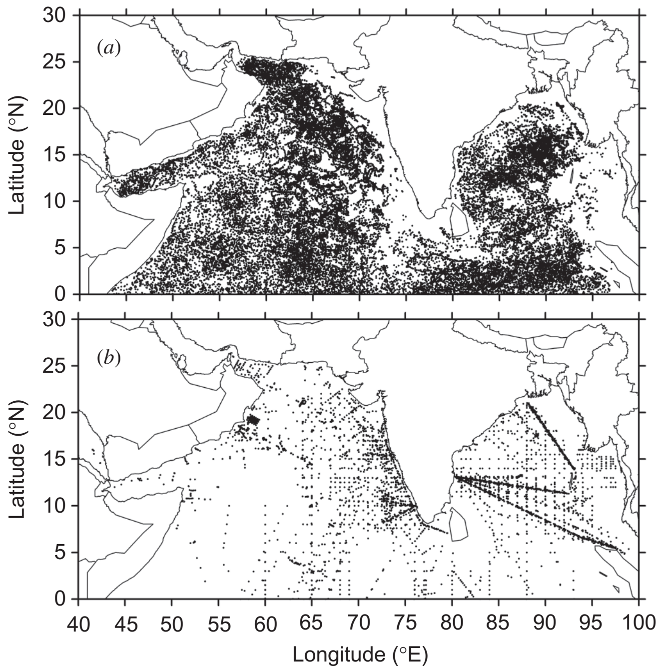

Figure 1. Geographical distribution of the *in situ* measurements from (*a*) Argo floats and (*b*) CTD, XCTD, BT and XBT profiles in the North Indian Ocean during 1993–2009.

3.2 *TCHP from satellite observations*

Sea surface height anomaly (SSHA) can be used as a proxy for the upper layer thickness from which OHC can be estimated if *a priori* information on the temperature profiles is available (Goni *et al*. 1996, Shay *et al*. 2000). If the ocean is approximated by a two-layer system, the upper-layer thickness (h_1) at latitude (x), longitude (y) and time (t) can be estimated from the altimeter-derived SSHA (η') field, provided that the mean upper-layer thickness ($\overline{h_1}$) at latitude x and longitude y and reduced gravity (g') fields are known to a first order from climatological measurements based upon the expression

$$h_1(x, y, t) = \overline{h_1}(x, y) + \frac{g}{g'(x, y)}\eta'(x, y, t), \tag{2}$$

where $g' = \varepsilon g$, g is the acceleration due to gravity and

$$\varepsilon(x, y) = \frac{\rho_2(x, y) - \rho_1(x, y)}{\rho_2(x, y)}, \tag{3}$$

where $\rho_1(x,y)$ and $\rho_2(x,y)$ represent the upper and lower layer densities, respectively. Once the depth of 26°C, here h_1, is estimated, and SST is obtained from satellite observations, the TCHP is the excess heat contained above the 26°C isotherm.

These satellite observations are available on a weekly basis during 1993–2007 (delayed-time data) and on a daily basis during 2008–2009 (real-time data) for the study area.

4. Validation of TCHP

The *in situ* and satellite-derived TCHP values were collocated following the technique of Cressman (1959) with weighting function (WF) given by

$$\mathrm{WF} = \frac{\left(S^2 - D^2\right)}{\left(S^2 + D^2\right)}, \tag{4}$$

where S is the search radius (2° in this case) and D is the distance between the *in situ* and satellite observations. Although 39,441 Argo and 3719 *in situ* observations were available, only 1294 daily observations met the quality checks and collocation criteria. These collocated points reduced to 128 when averaged on a monthly basis.

The scatter between the TCHP values estimated from the *in situ* measurements and satellite observations (figure 2) has a relatively consistent relationship between the two estimations for the North Indian Ocean. The satellite estimation compares well with the *in situ* estimations with a bias of 11.27 kJ cm^{-2}, coefficient of determination (R^2) of 0.65 and a root mean square error (RMSE) of 20.95 kJ cm^{-2}. The scatter index (SI), defined as the ratio between RMSE and the data mean, is a measure of the satellite estimation accuracy and was found to have a value of 0.33.

D_{26} has a diurnal variation due to internal tidal oscillations and other controlling factors. The difference between the *in situ* and satellite observations could be due to the mismatch between the satellite and *in situ* observation times. To minimize these high-frequency differences, we compared the two observations on a monthly basis for the North Indian Ocean. The *in situ* and satellite-derived TCHP monthly data (figure 3)

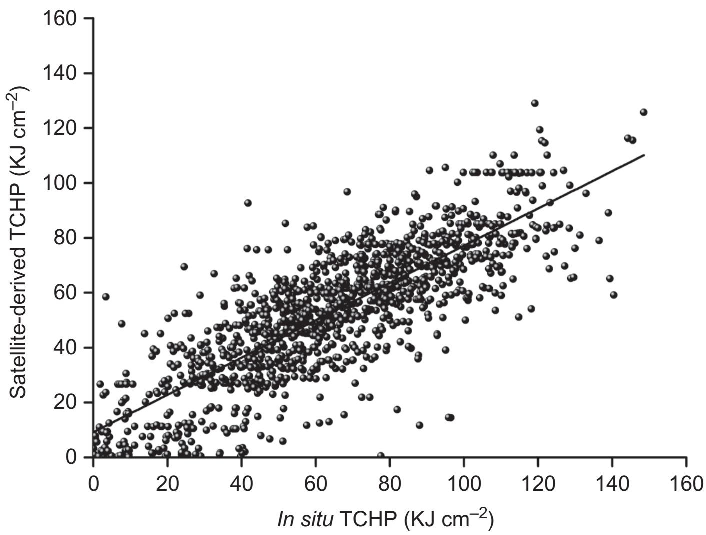

Figure 2. Comparison of estimated and satellite-derived daily TCHP values for the North Indian Ocean during 1993–2009.

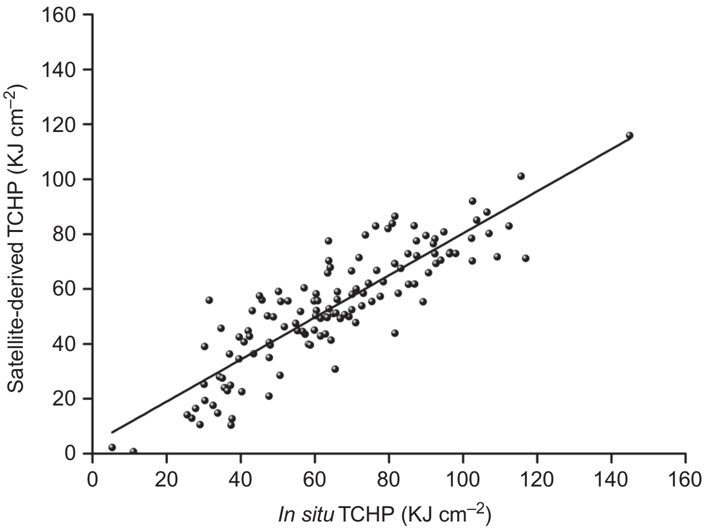

Figure 3. Comparison of estimated and satellite-derived monthly TCHP values over the North Indian Ocean during 1993–2009.

have a favourable correlation with an R^2 of 0.76. The RMSE reduced from 20.95 to 16.57 kJ cm^{-2} with an improved SI of 0.25. Since the diurnal errors average out over longer periods, the monthly satellite-derived estimations compare better than daily estimations made with *in situ* measurements.

5. Conclusions

The satellite-derived TCHP compares favourably with the *in situ* estimations. The difference between these two estimations on a daily basis is due to the difference between measurement times. These differences are smaller when the two estimations are compared on a monthly basis. From this statistical analysis, we can conclude that the satellite-derived TCHP values can be conveniently used over larger spatial and temporal scales over the North Indian Ocean.

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