Recent increase in high tropical cyclone heat potential area in the Western North Pacific Ocean

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[1] The Main Development Region (MDR) for tropical cyclones (TCs) in the western North Pacific Ocean is the most active TC region in the world. Based on synergetic analyses of satellite altimetry and gravity observations, we found that the subsurface ocean conditions in the western North Pacific MDR has become even more favorable for the intensification of typhoons and supertyphoons. Compared to the early 1990s, a 10% increase in both the depth of the 26°C isotherm (D26) and Tropical Cyclone Heat Potential (TCHP) has occurred in the MDR. In addition, the areas of high TCHP ($\geq$ 110 kJ cm^{-2}) and large D26 ($\geq$ 110 m) have 13% and 17% increases, respectively. Because these high TCHP and large D26 regions are often associated with intensification of the most intense TCs (i.e. supertyphoons), this recent warming requires close attention and monitoring.
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1. Introduction

[2] The western North Pacific Ocean is the most active tropical cyclone basin of the world (Figure 1a) [*Emanuel*, 2005; *Peduzzi et al.*, 2012; *Lin et al.*, 2013]. This cyclone basin is in the immediate vicinity of the densely populated East Asia (Figure 1a). Each year, 20–30 tropical cyclones (namely, typhoons) may threaten the one billion people and impact the enormous economic activities in East Asia [*Lin et al.*, 2011; *Moon and Kwon*, 2012; *Peduzzi et al.*, 2012]. Most of these typhoons form and develop in the Main Development Region (MDR) of the western North Pacific Ocean, which is defined here as 10°N–26°N, 122°E–170°E (Figure 1a). Monitoring the variability of the MDR is thus critically important, because changes in the MDR environment may lead to changes in typhoon activity [*Holliday and Thompson*, 1979; *Emanuel*, 1999; *Frank and Ritchie*, 2001; *Wang and Chan*, 2002; *DeMaria et al.*, 2005; *Goni et al.*, 2009; *Lin et al.*, 2005, 2008; *Wada*, 2009].

[3] TCs interact with both surface and upper subsurface ocean [*Tseng et al.*, 2010; *D'Asaro et al.*, 2011; *Pun et al.*, 2011; *Lin*, 2012; *Mrvaljevic et al.*, 2013]. The ocean surface and subsurface thermal conditions have an important influence on tropical cyclone intensity [*Emanuel*, 1999; *Shay et al.*, 2000; *Lin et al.*, 2005, 2008; 2009; *Goni et al.*, 2009; *Wada*, 2009; *Moon and Kwon*, 2012]. The higher the sea surface temperature (SST), the thicker the subsurface warm layer (typically represented by D26), and consequently, the larger the upper ocean heat content (often referred to as Tropical Cyclone Heat Potential, TCHP, defined as the depth-integrated ocean heat content from SST down to D26), the more favorable the ocean conditions for tropical cyclone intensification [*Shay et al.*, 2000; *Lin et al.*, 2008; *Goni et al.*, 2009]. The ability to analyze the subsurface thermal conditions has been advanced by satellite altimetry measurements since the early 1990s and by in situ measurements (e.g., Argo floats) [*Shay et al.*, 2000; *Pun et al.*, 2007, 2013; *Lin et al.*, 2008, 2009; *Goni et al.*, 2009; *Lyman et al.*, 2010; *Levitus et al.*, 2012]. The nearly two decades (1993–2011) of altimetry observations allow a longer-term diagnosis [*Cazenave and Remy*, 2011; *Qiu and Chen*, 2012]. The objective of this study is to examine the long-term variability of the ocean conditions in the western North Pacific MDR during the July–October typhoon season using altimetry observations and other supporting data sets.

2. Data and Method

[4] The U.S. National Oceanic and Atmospheric Administration Optimum Interpolation SST database [*Reynolds et al.*, 2002] is used to characterize the ocean surface condition. Sea Surface Height Anomaly (SSHA) data from the French Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) database are used to characterize the ocean subsurface conditions [*Ducet et al.*, 2000]. Significant positive (+) SSHA (typically $>$ 8 cm) regions are considered to be favorable for tropical cyclone (TC) intensification because the subsurface is warmer (or subsurface warm layer is thicker) than climatology [*Shay et al.*, 2000; *Pun et al.*, 2007, 2013; *Lin et al.*, 2005, 2008; *Goni et al.*, 2009]. Conversely, negative ($-$) SSHA (typically < -8 cm) areas, where subsurface is colder (or subsurface warm layer is thinner) than climatology, are considered to be less favorable. Neutral conditions (SSHA typically between -8 cm and +8 cm) represent subsurface conditions similar to climatological [*Shay et al.*, 2000; *Lin et al.*, 2008; *Goni et al.*, 2009].

[5] Delay time reference series AVISO SSHA product is used for this study. The product is constructed for long-term climate studies through the use of altimetry observations that are homogenous in time. It takes into account the variability in the sampling throughout the data set (1993–2011) by normalizing to two ordinary-configured altimetry missions [*SSALTO/DUACS User Handbook*, 2012].

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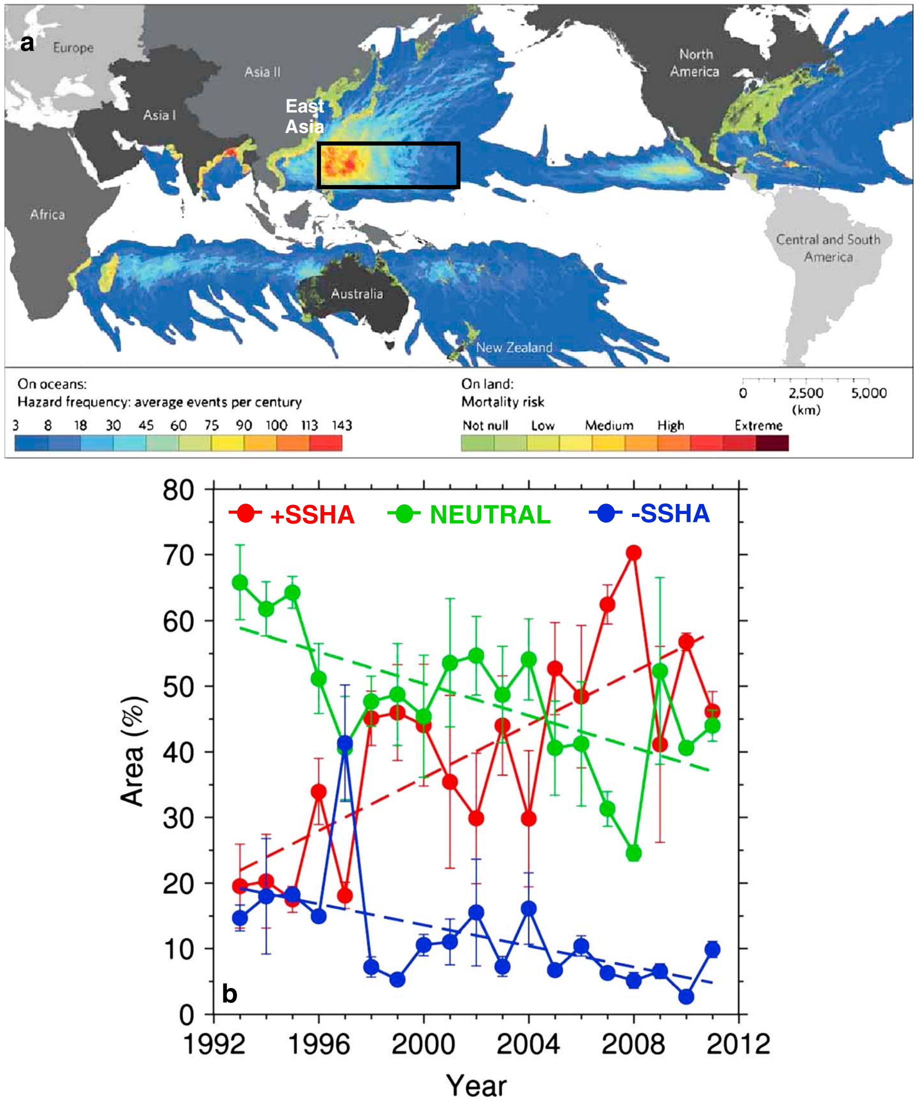

Figure 1. (a) Locations of the western North Pacific MDR (black box) and East Asia shown on a global tropical-cyclone hazard frequency map [after *Peduzzi et al.*, 2012]. (b) Annual averages of the percent ($\pm$ one standard deviation) area in the MDR with $+$ SSHA $>$ 8 cm (red), -SSHA < -8 cm (blue), and neutral conditions between +8 cm and -8 cm (green). All curves pass 98% statistical significance test.

[6] Based on these SSHA and SST observations, the relevant ocean subsurface parameters of D26 and TCHP (depth-integrated ocean heat content from surface down to D26) can be calculated through a two-layer reduced gravity ocean model [*Shay et al.*, 2000; *Goni et al.*, 2009]. This approach has been validated for the western North Pacific Ocean using several thousand in situ Argo float observations [*Pun et al.*, 2007]. As the altimetry SSHA measurement includes the contributions from both the thermal and mass components [*Cazenave and Remy*, 2011], Gravity Recovery and Climate Experiment (GRACE) satellite data are used to quantify the mass contribution [*Chambers*, 2006]. The Release-04 of the GRACE data, which was produced by the Center for Space Research at the University of Texas at Austin [*Chambers*, 2006], was used because the postglacial rebound signal has been removed [*Paulson et al.*, 2007]. After removal of the mass contribution in SSHA, the remaining SSHA (i.e., the thermal SSHA component) is then used to calculate D26 and TCHP.

[7] Averages of SST, SSHA, D26, TCHP, areal coverage under different SSHA features, areal percentages of high TCHP ($\geq$ 110 kJ cm^{-2}), and high D26 ($\geq$ 110 m) regions are calculated over the MDR domain during the typhoon season (July–October) between 1993 and 2011. Finally, standard deviations and statistical significance are tested for all results.

3. Results

[8] The percentage areas in the MDR with +SSHA, $-$SSHA, and neutral conditions have large interannual variability, but the area with +SSHA has notably increased during the past two decades (Figure 1b). For example, only about 20% area in the MDR had +SSHA in the early 1990s, but the area increased to about 50%–60% in the late 2000s. Correspondently, clear declines are noted in the areas with $-$SSHA and with neutral conditions.

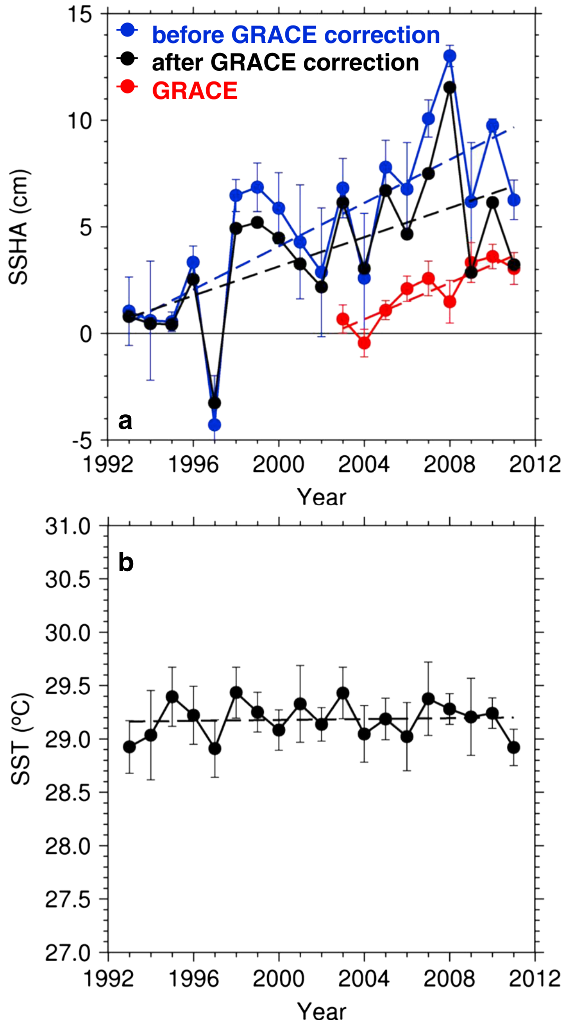

Figure 2. (a) Area-averaged SSHA over the MDR from 1993 to 2011 with SSHA before (blue curve) and after (black curve) after the mass correction from the GRACE observations (red curve). All curves pass 98% statistical significance tests. (b) Corresponding area-averaged SST in the MDR from 1993 to 2011.

[9] Viewed in another way, the area-averaged SSHA over the MDR increased by 10 cm during the past 19 years (Figure 2a, blue curve). Even after removal of the mass contribution using the GRACE observations (red curve), this increase is still evident (black curve). By contrast, changes in SST are much smaller (Figure 2b). Using the GRACE-corrected SSHA, both the area-averaged D26 and TCHP over the MDR have clear increases in the past two decades (Figure 3). For example, the averaged D26 was about 84 m during 1993–1995, but by 2010, it had increased to about 92 m, a nearly 10% increase. Similarly, the area-averaged TCHP over the MDR increased from about 88 kJ cm^{-2} in the early 1990s to about 96 kJ cm^{-2} in the late 2000s.

[10] The high TCHP and large D26 in the western North Pacific MDR have a strong implication. More than 50% of category-5, i.e., the most intense tropical cyclones over the globe occur in this region. In addition to a SST of about 29°C, sufficiently high TCHP (100–110 kJ cm^{-2}) and large D26 (100–110 m) are required to have tropical cyclones to reach such high intensity [*Goni et al*., 2009; *Lin et al*., 2008, 2009, 2013]. Whereas about 28% of the MDR area had such high TCHP values in the early 1990s, this areal coverage had increased to about 41% in recent years (Figure 4b). This TCHP increase is in part due to a significant areal increase in D26$\geq$110 m from 20% to 37% over the past two decades.

4. Discussion and Conclusion

[11] Although the SSTs in the western North Pacific MDR have varied little over the last two decades, the subsurface conditions have become more favorable for typhoon and supertyphoon (e.g., category 5 typhoons) intensification. Global altimetry analyses by *Cazenave and Remy* [2011] and *Qiu and Chen* [2012] have shown that this increase in SSHA over the subtropical western North Pacific is the highest in the global oceans (Figure 4a). *Qiu and Chen* [2012] suggest that this increase is possibly caused by multiple factors including piling up of the warm, surface water due to wind strengthening and possibly global warming. How long this trend will be continued is an important issue of investigation [*Cazenave and Remy*, 2011].

[12] The result of the study has multiple important implications for typhoon intensity. First, this increase in TCHP, D26, and high TCHP (large D26) areal coverage is an “add-on” to the already favorable ocean conditions for tropical cyclone intensification [*Goni et al*., 2009; *Lin et al*., 2008, 2009]. It is unknown to what extent this additional warming will contribute to more intense typhoons when the prior conditions were already favorable. Also, the ocean is only one of many factors controlling typhoon intensity. While the ocean conditions have become more favorable, have the atmospheric conditions become more or less favorable? The interplay between atmospheric conditions and ocean conditions for typhoon intensity will be addressed in future research.

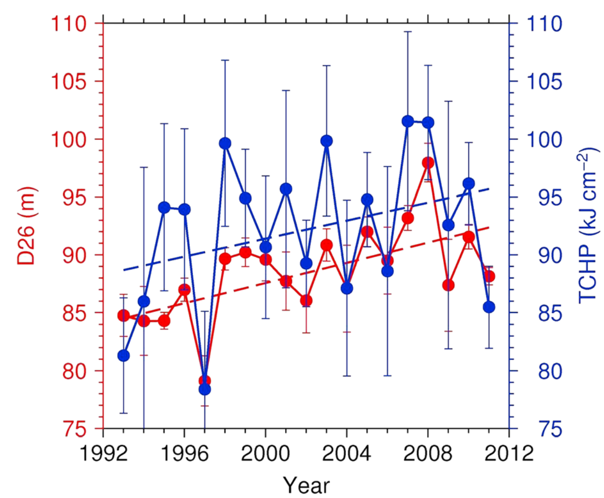

Figure 3. MDR area-averaged D26 (red, left axis) and TCHP (blue, right axis) calculated using the mass-corrected SSHA during the typhoon season (July–October) from 1993 to 2011. The error bars are $\pm$ one standard deviations. The D26 (TCHP) curve passes a 99% (80%) statistical significance test.

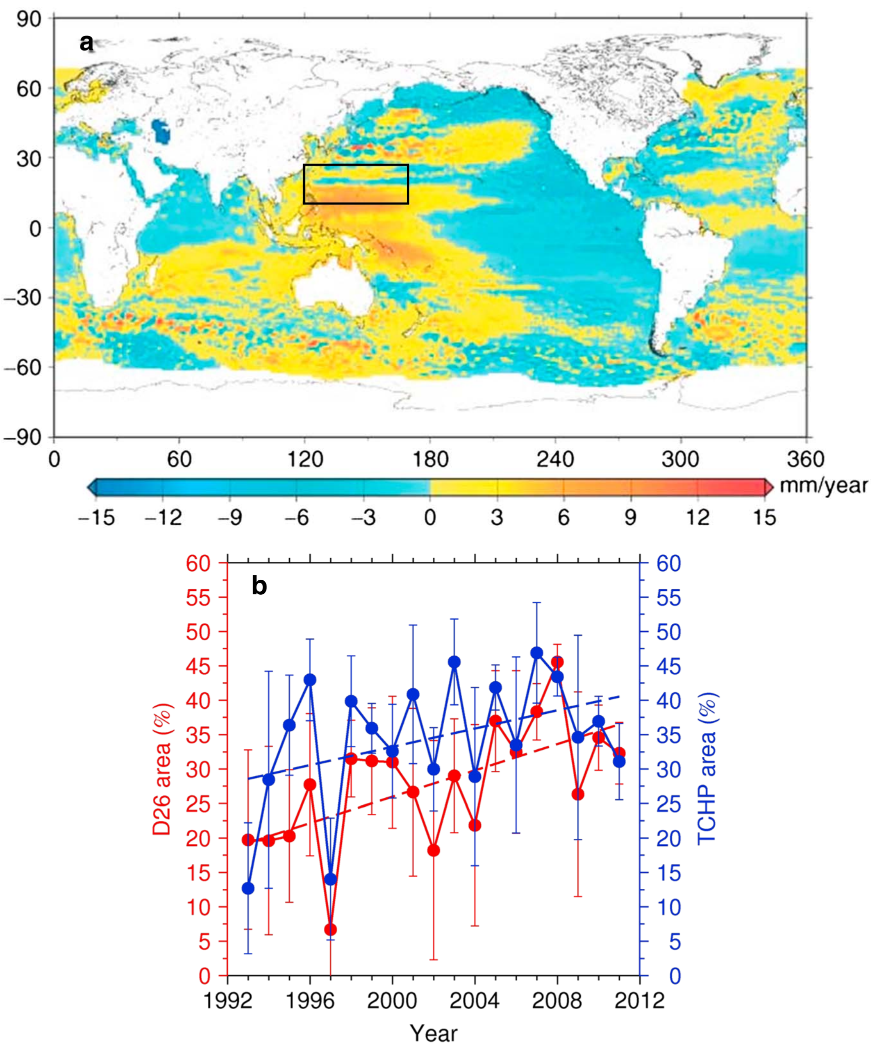

Figure 4. (a) Spatial distribution of altimetry-derived SSHA trend between 1993 and 2009 (after removal of global mean sea level rise) over global oceans [after *Cazenave and Remy*, 2011]. (black box) The western North Pacific MDR is the area with the largest increase in SSHA. (b) Areal percentage with the (blue, right axis) TCHP ≥ 110 kJ cm^{-2} and (red, left axis) D26 ≥ 110 m in the MDR during the typhoon season between 1993 and 2011. The D26 (TCHP) curve passes a 99% (90%) statistical test.

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