Changes in tropical cyclone activity offset the ocean surface warming in northwest Pacific: 1981–2014

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Abstract

Tropical cyclones (TCs) leave a cold wake in the sea surface temperature (SST). In the northwest Pacific, TC activity and SST have both increased since the 1980s, but the extent to which ocean surface warming is affected by the changing TC activity is unknown. Analysis of the 1981–2014 period indicates that the intensified effect of TC cold wakes has offset the SST warming trend by 37% during the typhoon season, implying that the observed SST warming might be underestimated. This factor could affect long-term climate simulations that are forced with prescribed SST.

Keywords: northwest pacific; tropical cyclones; cold wakes; warming offset

1. Introduction

Tropical cyclones (TCs) are known to leave behind a cold wake in the sea surface temperature (SST) that extends for hundreds of kilometers (Hart et al., 2007; Dare and McBride, 2011). As an example, Figure 1(a) shows a TC cold wake in which a noticeable cold-water trail of Typhoon Ma-On (Category 4) is observed in the SST with a local maximum cooling of 5.5 °C. The northwest Pacific warm pool is a hotspot for TCs (Figure 1(b); the climatological TC frequency) and it also features the strongest TC-induced cooling than other ocean basins (Sriver and Huber, 2007; Gentermann and Scott, 2014). There, recent warming in the upper ocean has led to increases in average TC intensity (Mei et al., 2015) and frequency of strong typhoons (Wu and Zhao, 2012). The long-term change in TC cold wakes has an important, but perhaps overlooked implication on SST trends – that is, to what extent does the TC-induced cooling and associated change affect the warming trend in SST? The answer to this question cannot be found in the literature and is examined herein.

TC cold wakes are primarily a result of wind-induced upwelling and vertical mixing of cooler subsurface water beneath the TC (Price, 1981; Lin et al., 2009; Mei and Pasquero, 2013). Generally, it takes 1–2 weeks for the TC-induced cooling to rebound and 4–6 weeks to fully regain its climatological values (Hart et al., 2007; Dare and McBride, 2011), depending on the ocean state such as a shallow mixed layer depth (Jacob and Shay, 2003; Vincent et al., 2012) and the translational speed of the TC (Emanuel, 2003). TCs cool the ocean surface through pumping heat into the subsurface (Sriver and Huber, 2007), and the excess heat is either redistributed poleward (Emanuel, 2001) or reabsorbed by the mixed layer and lost to the atmosphere (Jansen et al., 2010).

Projecting future changes in the TC heat pump effect is difficult due to challenges in simulating the TC–ocean interaction by most climate models (Yablonsky et al., 2015).

The pattern of the 1980–2014 trend in the Pacific Ocean SST appears to be asymmetric, consisting of a broad warming area in the west and slight cooling in the east (Guan and Nigam, 2008; Schubert et al., 2009), as is shown in Figure 1(c) for the typhoon season. Regionally, the effect of TC cold wakes can rival the scale of a pre-existing warm SST anomaly. For instance, TC cold wakes in the Caribbean Sea can mitigate coral bleaching by slowing down the build-up of thermal stress associated with seasonal SST warming (Carrigan and Puotinen, 2014). Therefore, as the ocean becomes warmer, the subsequent increases in TC activity and/or intensity could enhance cooling over the ocean surface. If this is the case, then it would produce a negative feedback that offsets the warming trend of SST. The goal of this study is to examine this potential offset and quantify the effect.

2. Data and method

2.1. Data sources

The NOAA 1/4° daily optimum interpolation sea surface temperature (OISST) allows the examination for the long-term change in TC cold wakes starting from 1981. OISST was constructed by combining observations from different platforms including satellites, ships, and buoys with full-year data (Reynolds et al., 2007). To depict TC positions, 6-h interval best track records of TCs were obtained from the Joint Typhoon Warning Center (JTWC). Among other TC track data sets, Wu and Zhao (2012) found that the JTWC data set
Figure 1. (a) SST on 20 July 2011 for Typhoon Ma On (typhoon symbol) and its track (blue dots); the black box and the center black dot indicates the typhoon’s 17 July location surrounded by the 4° × 4° domain used for TC tracking (see text). (b) Seasonal mean SST (shadings) overlaid with the long-term areal frequency of TC best tracks per 2° × 2° grid (contours). (c) Linear trend pattern of SST from 1981 to 2014 during JJASO (total change) overlaid with the three domains used for Figure 3.

produced the TC intensity trends that are in good agreement with those derived dynamically from changes in SST, vertical wind shear, and prevailing tracks. For subsurface ocean temperatures, we utilized the NCEP Global Ocean Data Assimilation System (GODAS) produced by the Geophysical Fluid Dynamics Laboratory’s Modular Ocean Model with a horizontal resolution of 1° × 1° enhanced to 1/3° in the north–south direction within 10° of the equator, and 40 vertical levels down to 4000 m (Behringer and Xue, 2004).

2.2. TC cold wake tracking

In order to capture the general size of a TC based upon the grid spacing of OISST data, we tested various settings of longitude × latitude of 2°, 3°, … 6° based upon category 1 TCs, leading to the selection of a 4° longitude × 4° latitude area. As shown in Figure 1(a), the 4° area effectively covered the cold wake of TC Ma_On; the difference in TC cold wake effect derived between the 3° and 5° areas was negligible. We then centered this 4° area at the daily location of each TC (average location of 00-18Z) and averaged the SST within this area to represent TC cold wakes. Using this method, the data points of TC passages covered 87% of the northwest Pacific Ocean (100°–170°E, 5°–35°N).

The effect of TC cold wakes was computed by averaging SST in each 4° × 4° area for 7 days after the day of TC passage (post-TC days). This method followed the e-folding time of SST recovery of about 10 days estimated by Dare and McBride (2011). To calculate ‘TC-free’ SST, an average of 7 days from one day before the TC [excluding the day before the TC
passage (Huang et al., 2009) was computed at each corresponding TC location (pre-TC days). However, using 7 days after the TC passage could exaggerate the cooling in the long-term effect of TC cold wakes. Thus, we also computed 30-day average of SST after the TC passage, and 30 days before that for estimating TC-free SST. The analysis was performed for three seasons: June-August (JJA), September-October (SO), and June-October (JJASO), based upon the typhoon season of this region (Chen et al., 2006). Furthermore, since SST in the northwest Pacific peaks around August or September, the calculation of SST cooling (composite) was conducted after removing the seasonal cycle in SST using a second-order polynomial fit on the monthly climatological values.

Note that this composite approach potentially included the ‘cyclone-cyclone’ interaction as reported by Balaguru et al. (2014), in which a TC could reduce intensity of the subsequent TC(s) moving across its cold wake. The same composite methodology was applied to the subsurface temperature data. However, GODAS only provides 5-day mean data and hence we used two pentads (10 days) for post-TC days (including the day of TC) and four pentads (20 days) for pre-TC days to construct the composite.

3. Results

3.1. TC-induced cooling

The basin-integrated pre-TC composite SST (i.e. TC-free) is shown in Figure 2(a) for the JJA, SO, and JJASO seasons. Increasing trends were observed in all three seasons, consistent with the trend pattern in Figure 1(c). The JJA season exhibits the largest SST increase of 0.57 °C from 1981 to 2014, larger than JJASO of 0.38 °C and SO of 0.22 °C. It is important to note that the SST presented here only followed the TC tracks and, therefore, were not equivalent to any region-averaged SST values. To examine the effect of TC cold wakes on SST trends, we show in Figure 2(b) the post-TC SST anomalies, computed as the departure from the pre-TC composite to represent the TC cold wake effect. The mean difference in SST is −0.37 °C during JJASO, comparable with the TC-induced cooling found in Dare and McBride (2011) that was estimated within the e-folding time. Sensitivity testing applied to the range of 5–15 days after cyclone passage resulted in a cooling range between −0.48 and −0.32 °C.

Over the 1981–2014 period, the net change in the TC-induced cooling (estimated from the regression coefficient multiplied by 34 years) amounts to −0.23 °C in JJASO, −0.08 °C in JJA, and −0.34 °C in SO. Furthermore, there was a discernable acceleration in the cooling effect after 1995 across all seasons, and by computing a second-order polynomial trend (not shown) it was found that the post-1995 cooling is twice as much as the 1981–2014 one, suggesting concurrent enhancements in both SST warming and TC-induced cooling.

| Table 1. SST change estimates from the entire TC tracks. |
|----------------------------------|-----|-----|-----|
| Season                          | JJA | SO  | JJASO|
| Seasonal mean warming (°C) – 7 days | 0.57 | 0.22 | 0.38 |
| Pre-TC (TC-free) (°C) – 7 days   | −0.08 | −0.34 | −0.23 |
| TC cold wake effect (%) – 7 days | 12%  | 60%  | 37%  |
| Seasonal mean warming (°C) – 30 days| 0.56 | 0.25 | 0.39 |
| Pre-TC (TC-free) (°C) – 30 days  | −0.02 | −0.38 | −0.22 |
| TC cold wake effect (%) – 30 days| 4%   | 61%  | 37%  |

To quantify the effect of long-term change in TC cold wakes, we divided the total change in post-TC SST by total SST (pre-TC + post-TC). For the JJA, SO and JJASO seasons, TC-induced cooling reduced SST trends by 12, 60, and 37%, respectively (Table 1) and these percentages represent the degree of SST reduction from the seasonal-mean warming trends since 1981. One apparent factor linking the rather large reduction in the SO trend is its weaker change in the pre-TC SST (Figure 2(a)). It is plausible that the increased effect of TC cold wakes nearly canceled out the SST warming during SO when TCs are generally stronger and/or last longer (Chen et al., 2006). In terms of interannual variability, years 2013 and 2014 feature three super typhoons in each SO season and their combined cooling effect is visible in Figure 2(b). To test the sensitivity of 2013 and 2014 on the SST trend, we removed these 2 years and the JJASO cooling rate was reduced by 28%, still significant at $p < 0.05$. In Figure 2(c) and (d), we show the similar result derived from 30-day averages of pre-TC SST and post-TC SST anomalies, with the relevant change in SST and percentage of cooling contribution shown in Table 1. This 30-day analysis served as a sensitivity test for the duration of which TC-reduced SST rebounds. In this case, the magnitude of the long-term change in TC cold wakes is similar to that of the 7-day composites, despite a flat trend in JJA’s post-TC SST anomalies.

Next, we examined the TC occurrence in terms of accumulated days versus the TC intensity in terms of the Saffir-Simpson hurricane wind scale. The result for the JJASO season is shown in Figure 2(e) and it indicated an overall increase in the TC occurrence (including duration) from 1981 to 2014, amounting to 54 days in all TCs, 72 days in Category 1–5, and 40 days in Category 3–5 over the 34 years, suggesting that the lengthening of cyclone days resulted mainly from stronger TCs. This result echoes previous observation (Emanuel, 2007; Yu et al., 2010; Pun et al., 2013; Mei et al., 2015) that both the TC intensity and duration in the northwest Pacific have increased, especially Category 3–5 TCs (Holland and Bruyère, 2014). Also noteworthy is the marked decadal fluctuation in TC days that is consistent with the documented interdecadal variability of TC activity in this region (Matsuura et al., 2003; Chen et al., 2006). By computing the Pearson correlation ($r$) between the JJASO TC days (as in Figure 2(e)) and TC-induced cooling (as in Figure 2(b)), we obtained $r$ of −0.31, −0.44 and −0.4 for the total, Category 1–5 and Category 3–5 TCs, respectively. The highest $r$ in
Figure 2. (a) TC-free SST composite during the seasons of JJA (blue), SO (green) and JJASO (red) overlaid with their linear trends in the corresponding color. (b) Post-TC SST anomaly for each season and linear trends estimated from the 7-day composites. (c) and (d) TC-free SST composite during JJA (blue), SO (green) and JJASO (red) overlaid with their linear trends in the corresponding color and Post-TC SST anomaly for each season and linear trends, estimated from the 30-day composites, respectively. (e) Accumulated TC days during JJASO at three intensity scales: total (blue), category 1–5 (pink), and category 3–5 (green), overlaid with linear trends.

Category 1–5 is significant at $p < 0.01$, suggesting that the extent to which TC cold wakes reduce SST in the long term is relevant to both duration and intensity of TCs. This interannual connection lends support to the effect of increased TC-induced cooling on offsetting the local warming trends of SST.

Next, we focused on three regions as indicated in Figure 1(c) as they encompass two areas of relatively weak warming over Northwest Pacific. We then computed the SST trends of each region for the JJASO season. Each region’s TC-free SSTs and the associated trend are shown in Figure 3(a); likewise, SST anomalies...
representing TC cold wakes are shown in Figure 3(b). Region 1 (South China Sea) experienced a ‘TC-free’ warming of 0.61 °C; Region 2 (midlatitude belt) showed a warming of 0.23 °C; and Region 3 (equatorial western Pacific) revealed a warming of 0.35 °C (Table 2). Meanwhile, TC cold wakes resulted in a long-term cooling of −0.07, −0.20, and −0.23 °C in regions 1, 2 and 3, respectively. Combined, TC cold wakes may have offset the post-1981 SST warming by 10% in region 1, 46% in region 2 and 40% in region 3. The mean reduction averaged from these regions is slightly smaller than the basin-scale SST reduction. This is expected since the equatorial western Pacific (Region 3) is characterized with a thick isotherm of 26 °C (D26) and a high tropical cyclone heat potential (TCHP), which are associated with the growth of intense TCs (D’Asaro et al., 2011; Lin et al., 2013). The fact that there was a more than 30% increase in both the D26 and TCHP in region 3 over the past 34 years (not shown) can explain why the equatorial Pacific had the maximum increasing TC-induced cooling among the three regions.

3.2. Implication from subsurface temperature

Next, the change in the basin-scale ocean heat content was analyzed with a focus on the ocean layer down to 200 m, a documented depth limit for the effect of TC cold wakes (Sriver and Huber, 2007). Using GODAS data, we computed subsurface temperatures anomalies (ΔT) between the TC cold wakes and TC-free composites. The results are shown in Figure 4 as vertical cross section of ΔT overlaid with linear trends computed for each depth (contoured). Over the northwest Pacific basin (Figure 4(a)), TCs caused a pronounced vertical redistribution of heat accompanied by noticeable cooling at the upper 25 m and warming within the depth of 30–70 m. The surface cooling has intensified and extended deeper from around 25 m prior to year 2000 to near 50 m after year 2010, indicating an enhanced vertical mixing associated with increased TC-induced cooling. Between the depth of 25 and 100 m, the warming appears to have either weakened (as in Region 2) or deepened (as in Region 3). The change in the TC-induced mixing/cooling is relatively weak in the South China Sea (Figure 4(b)), despite an enhanced warming that took place below 50 m.

Table 2. SST change estimates for the three regions designated in Figure 1(a).

| Region   | TC-free (°C) | TC cold wake (°C) | Total (°C) | Contribution (%) |
|----------|--------------|------------------|------------|-----------------|
| Region 1 | 0.61         | −0.07            | 0.68       | 10              |
| Region 2 | 0.23         | −0.20            | 0.44       | 46              |
| Region 3 | 0.35         | −0.23            | 0.58       | 40              |
| Region 1 | 0.56         | −0.01            | 0.57       | 2               |
| Region 2 | 0.25         | −0.20            | 0.45       | 45              |
| Region 3 | 0.39         | −0.25            | 0.63       | 39              |
Overall, Figure 4 confirms previous research that TCs produce a heat pump effect in transporting ocean heat downward (Sriver and Huber, 2007), causing heat to be redistributed within the ocean column and remain within the storm region. Over time, there is a discernable change in this ‘stored’ heat in different regions. It is possible that, according to Emanuel (2001) and subsequent studies, the increase in the stored heat below 50 m in the subtropics (Region 2) is increasingly transported northward leading to the apparent heat reduction (accompanying the increased cooling above 25 m). However, a recent study (Huang et al., 2015) projects that ocean surface warming will reduce the intensity of TC cold wake due to increased stratification that inhibits mixing and prevents deepening of mixed layers. How these two effects counter or balance each other in the future climate poses an intriguing question calling for further research.

4. Summary and discussion

Using the OISST daily data and JTWC TC best tracks, the effect of the long-term changes in TC cold wakes on the ocean surface warming was analyzed for the northwest Pacific over the period of 1981–2014. The results indicated an intensification in TC-induced cooling amounting to $-0.23 \, ^\circ\text{C}$ during the JJASO season and this corresponds to the observed increase in stronger TCs. The enhanced cooling arguably offset the seasonal-mean ocean surface warming trend by as much as 37%. The maximum cooling effect of TC cold wakes took place in the SO season when TCs are generally stronger and last longer. In the South China Sea (region 1), where TCs are frequent but not as strong as those in the Philippine Sea (region 3), the long-term change in TC cold wakes on the SST trends was moderate.
The implication of this study is twofold: (a) increased upper ocean warming in the northwest Pacific leads to the general intensification of TCs, as was previously found. Subsequently, (b) more intense TCs can induce stronger cold wakes and, over time, this can offset the warming trend derived from seasonal-mean SST. Together, the long-term effect of intensified TC cold wakes resulted in a 37% reduction of the ocean surface warming (during JJASO) – i.e. an offset that could have been ‘added’ to the observed warming trend of SST. Another implication is that long-term model simulations forced by time-mean SST as the boundary condition (so-called AMIP style) would not have accounted for the effect of TC-induced cooling, thereby underestimating tropical SST forcing. This bias can then affect the SST variation at both the interannual and interdecadal timescales and associated meridional heat transport. Future research should focus on the interactions between TCs, ocean mixing, and ocean heat uptake and the gained knowledge will improve the projection of SST trends and associated TC activity.

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References

Balaguru K, Taraphdar S, Leung LR, Foltz GR, Knaff JA. 2014. Cyclone-cyclone interactions through the ocean pathway. Geophys. Res. Lett. 41(19): 6855–6862.

Behringer D, Xue Y. 2004. Evaluation of the global ocean data assimilation system at NCEP: the Pacific Ocean. In Proceedings of Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, AMS 84th Annual Meeting, Washington State Convention and Trade Center, Seattle, WA, 11–15 January 2004.

Carrigan AD, Puotinen M. 2014. Tropical cyclone cooling combats region-wide coral bleaching. Glob. Change Biol. 20(5): 1604–1613.

Chen T-C, Wang S-Y, Yen M-C. 2006. Interannual variation of the tropical cyclone activity over the western North Pacific. J. Clim. 19(21): 5709–5720.

Dare RA, McBride JL. 2011. Sea surface temperature response to tropical cyclones. Mon. Weather Rev. 139(12): 3798–3808.

D’Asaro EA, Black PG, Centurioni LR, Harr P, Jayne SR, Lin I-I, Dare RA, McBride JL. 2011. Sea surface temperature response to tropical cyclones. J. Geophys. Res. 116: C10001.

Yu J, Wang Y, Hamilton K. 2010. Response of tropical cyclone potential intensity to a global warming scenario in the IPCC AR4 CGCMs. J. Clim. 23(6): 1354–1373.

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