RESEARCH ARTICLE

Role of barrier layer in the developing phase of "Category 6" super typhoon Haiyan

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Abstract: With the remarkable intensity of 170 knots, Typhoon Haiyan started as a tropical depression on November 3 and developed to the peak as super tropical cyclone (TC) on November 7 in 2013. This intensity makes Haiyan one of the strongest TCs record ever observed and 35 knots higher than the maximum of the existing highest category. Haiyan originated from the eastern part of the Northwest Pacific Warm Pool and moved westward over warm water with a thick barrier layer (BL). The BL reduced the vertical mixing and entrainment caused by Haiyan and prevented the cold thermocline water into the mixed layer (ML). As a result, sea temperature cooling associated with wind stirring was suppressed. Relative high sea surface temperature (SST) kept fueling Haiyan via latent heat flux release, which favored the rapid development of a "Category 6" super typhoon.

Keywords: Barrier Layer, Super TC, Haiyan, SST Cooling

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1. Introduction

Super typhoon Haiyan is the strongest TC in 2013. It originated as tropical depression in the eastern part of the Northwest Pacific Warm Pool on November 3 and proceeded quickly westward at a very low latitude (south to 10°N). On November 7, Haiyan reached its peak intensity of 170 knots, which is the highest sustained winds speed record ever estimated in Joint Typhoon Warning Center (JTWC), and made landfall in Philippines on November 8 (Figure 1A), causing catastrophic destruction and thousands of casualties (Lander *et al*, 2014). The intensity of Haiyan is much higher than majority of recorded TCs worldwide (Knapp *et al*, 2010; Lin *et al*, 2014). In Saffir-Simpson scale (Table 1), there are about 20 knots variance between adjacent categories, while Haiyan's peak exceeds the maximum of category 5 (135 knots) by 35 knots. Following Lin, Pun and Lien (2014), we classify Haiyan as "category 6". The question on why Haiyan can reach such high intensity is interesting for us to explore.

Most of TCs formed over the Warm Pool which characterizes with thick warm water and a fresh surface layer. Between the bottom of mixed layer (ML) and the top of thermocline, there is usually a barrier layer (BL) existing (Kara *et al*, 2000; Maes *et al*, 2006; Bosc *et al*, 2009). BL has the same temperature as ML but higher salinity. These two layers compose an isothermal layer (IL). BL plays a "barrier" role on vertical mixing and entrainment, and impedes the heat exchange between ML and thermocline (Sprintall and Tomczak, 1992).
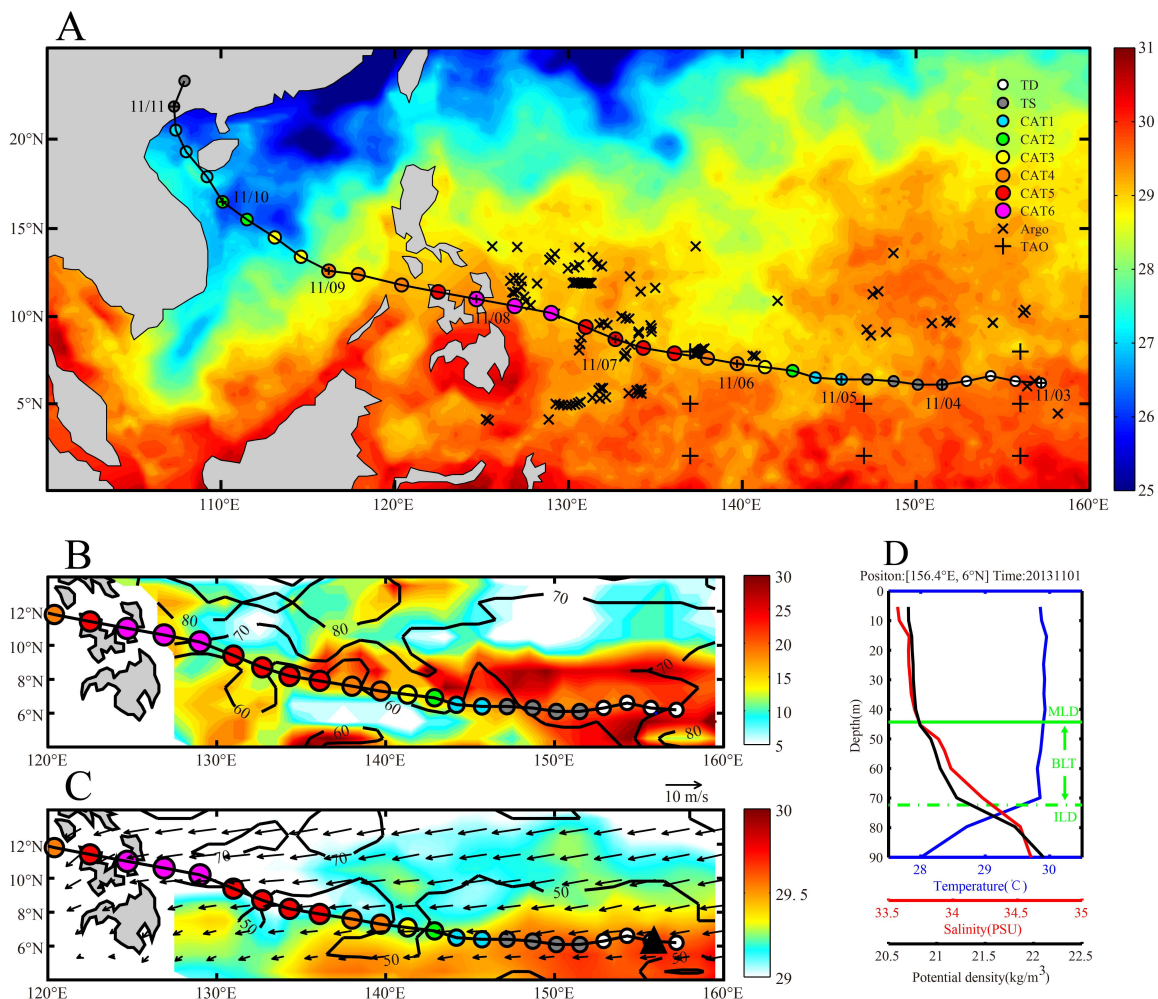
Figure 1. (A) Track of typhoon Haiyan (circles) and TRMM Microwave Imager（TMI）Sea surface temperature (SST) averaged in November 3−11 (shaded, unit: °C). The circles with + inside indicate 0:00. (B) Distribution of BLT (shaded, unit: m) and ILD (contours, unit: m), (C) MLD (contours, unit: m) and ML mean temperature (shaded, unit: °C) from Argo and ASCAT wind field (vector) in November 2013. Triangle indicates the position of the Argo float; (D) The T/S profile from Argo float.

Table 1. Saffir-Simpson scale from category 1 to 5 and the unofficial category 6

Type	Category	Winds (knots)
Depression	TD	< 34
Tropical Storm	TS	34-63
Hurricane	1	64-82
Hurricane	2	83-95
Hurricane	3	96-113
Hurricane	4	114-135
Hurricane	5	> 135
Hurricane	6 (unofficial)	>155

A majority of Typhoon-Ocean interaction studies focused on the processes how the atmosphere acts on ocean. However, previous investigations showed that TCs- induced sea surface temperature (SST) cool-ing could feedback on their intensity (Lloyd and Vecchi, 2011; Vincent *et al*, 2012; Ma *et al*, 2013). Emanuel (1999) argued that the air-sea enthalpy difference decides the intensity of a TC. It implies that more factors, including wind mixing and entrainment, could influence TC's intensification (Shay *et al*, 2000; Shen and Ginis, 2003; Lin *et al*, 2005; Balaguru *et al*, 2012). In this study, we demonstrate that the presence of BL sustains high SST along the track of Haiyan and favors an extraordinary "Category 6" super typhoon in an ocean perspective.

2. Data and Methods

2.1 Data

TC's track and intensity data from https://www.ncdc.

noaa.gov/ibtracs/ is used. For historical data, the Joint Typhoon Warning Center (JTWC)'s best track data was used, including TC Haiyan's position, maximum sustained wind speed, and sea level pressures for every 6 hours.

The daily upper ocean temperature and salinity data from HYCOM (HYbrid Coordinate Ocean Model) were downloaded from http://hycom.org/dataserver. The HYCOM+NCODA global 1/12° reanalysis assimilates satellite altimeter observations and *in situ* SST, plus *in situ* vertical temperature and salinity profiles from expendable bathythermographs (XBT) and array for real-time geotropic oceanography (ARGO) floats and moored buoys. Based on HYCOM temperature and salinity data, we calculated daily barrier layer thickness (BLT), mixed layer depth (MLD), and isothermal layer depth (ILD) in the region 110°~160°E, 0°~20°N.

Monthly Argo 1° gridded temperature and salinity data were obtained from Scripps Institution of Oceanography (http://sio-argo.ucsd.edu/RG_Climatology.html) to verify the BLT, MLD, and ILD results from HYCOM. Temperature and salinity profiles from the Argo floats are used in this study to estimate the upper ocean condition along the track of Haiyan.

TMI (Tropical Rainfall Measuring Mission's microwave imager) SST data is from RSS (Remote Sensing Systems), with daily and 0.25° grid resolution, obtained from ftp:ftp.discover-earth.org/sst/daily_v04.0/. The daily 0.25° grid ASCAT (the Advanced SCATterometer) wind field data obtained from ESA (European Space Agency, ftp://ftp.ifremer.fr/ifremer/cersat/products/) was used to calculate TC's intensity. Latent heat flux data from WHOI (Woods Hole Oceanographic Institution) OAFlux (Objectively Analyzed air-sea Fluxes), with daily and 1° grid resolution, were obtained from ftp:// ftp.whoi.edu/pub/science/oaflux/data_v3.

2.2 Calculation of Barrier Layer Thickness (BLT)

BLT is defined as ILD minus MLD (de Boyer Montégut *et al*, 2007). The calculation of MLD is based on a variable potential density (σ_θ) criterion (Lukas and Lindstrom, 1991; Sprintall and Tomczak, 1992), which determines the depth as where σ_θ is equal to the sea surface σ_θ plus the increment in σ_θ equivalent to a desired net decrease of 0.8℃ in temperature (Kara, Rochford and Hurlburt, 2000). The criteria is given by de Boyer Montégut, Mignot, Lazar *et al.* (2007) with a temperature difference of 0.2℃ from a near-surface

value at 10 m. Based on this study about TC in Northwest Pacific, we used de Boyer Montégut, Mignot, Lazar *et al.* (2007)'s criteria with the temperature difference of 0.6℃.

# 3. Barrier Layer and Typhoon Haiyan Intensification

Typhoon Haiyan originated in the eastern part of the Northwest Pacific Warm Pool (4°~8°N, 140°~160°E), where the BLT was more than 20 m and the maximum was close to 40 m when Typhoon Haiyan passed by (Figure 1B). The results from HYCOM show the same large BLT alone the track of Typhoon Haiyan (figure not shown). In general, with intense atmospheric deep convection and heavy rainfall, the BLT in this region is more than 50 m in winter (Kara *et al*, 2000). Over the BL (Figure 1C), weak wind leads to weak vertical mixing, sustain high SST in a thin ML. In addition, thick salt-stratified barrier layers in the upper 150 m impede the cold entrainment into the ML from the thermocline (Bosc *et al*, 2009; Maes *et al*, 2006). An Argo float (ID: 591687) recorded a T/S profile on November 1, 2013, providing the upper ocean condition before the generation of Haiyan (Figure 1D). In Figure 1D, low salinity (<33.7 PSU) water was found in upper 50 m while uniform temperature at ~30℃ deep to 70 m. Before Haiyan generates, there was a thick BL over 20 m.

Haiyan formed as tropical depression on November 3 over warm water (Figure 2A) and moved westward. Two days later, Haiyan developed to a category-3 TC. Along the track of TC Haiyan, BL was thicker than 20 m, consistent with large latent heat flux releasing (Figure 2B). At the sea surface, latent heat flux releasing increased and so did the wind field around the Haiyan's cyclone eye. On November 7, Haiyan reached its peak of 170 knots and became a category-6 TC (Figure 2C). Haiyan developed quickly from tropical depression to peak intensity in 5 days. In general, internal dynamics and external forcing of environmental flow determines the intensity of TC. As external factor, SST matters most.

Warm SST provides a favorable condition for the evolution and intensification of tropical cyclones (Emanuel, 2005; Webster *et al*, 2005). Along Haiyan's path (Figure 3A), 26.5℃ isothermal layer was more than 70 m deep and SST was more than 29℃ which are favorable for Haiyan's evolution.
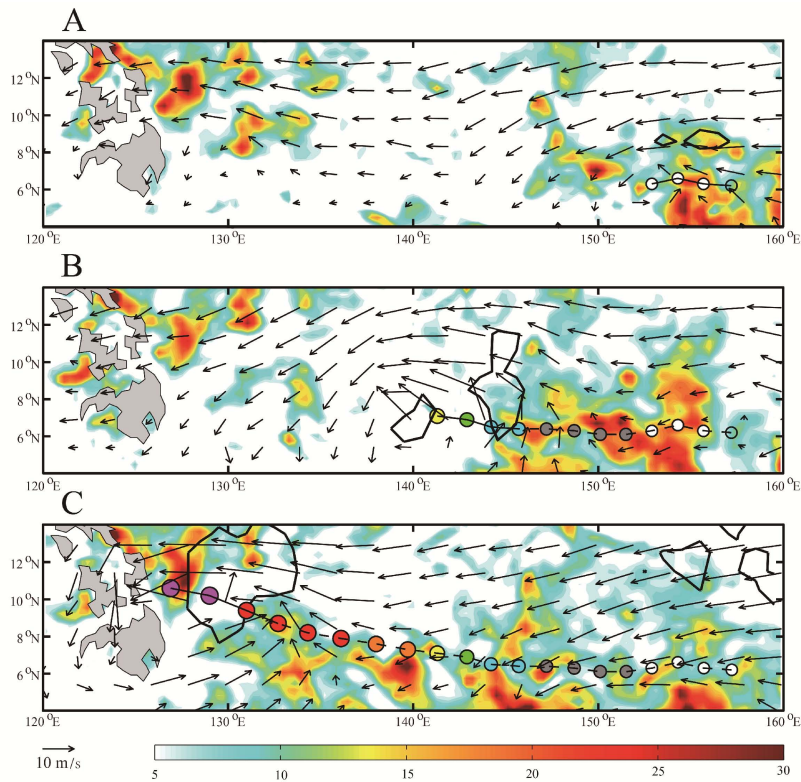
Figure 2. HYCOM BLT (shaded, unit: m), ASCAT winds (vectors, unit: ms^{-1}) and OAFlux latent heat flux (200 Wm^{-2} contour only) during the developing phases of typhoon Haiyan, superimposed with the typhoon track (Real line is the track of the day and dotted line is the day passed). (A) November 3, (B) November 5, (C) November 7.
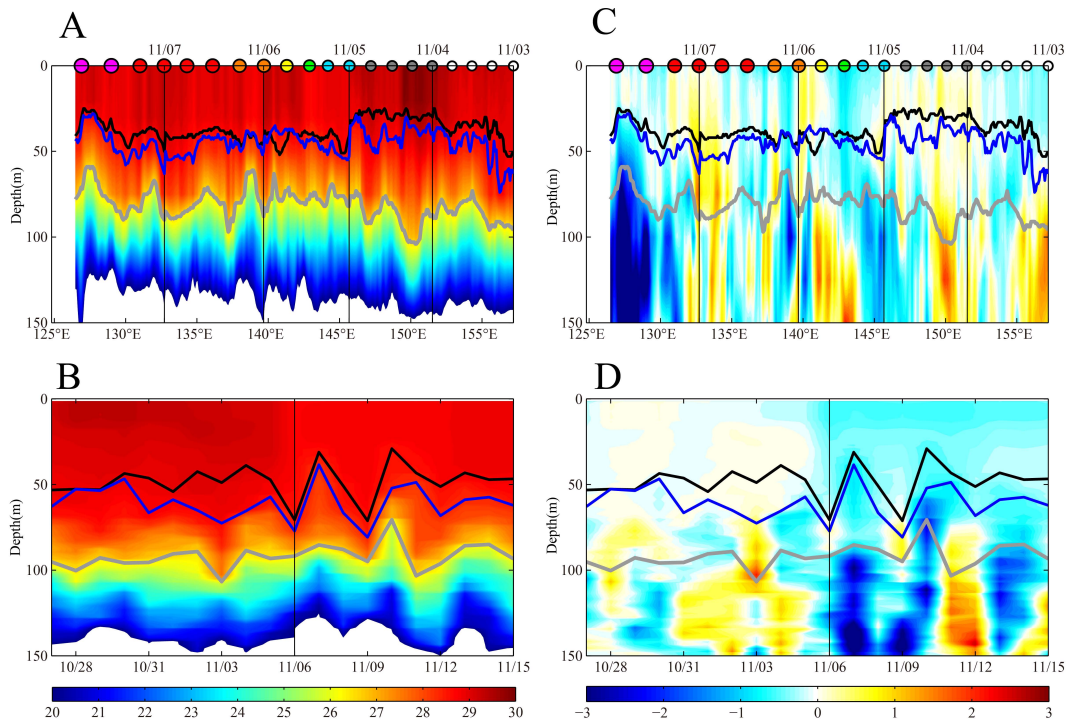

Figure 3. (A) HYCOM Temperature (shaded, unit: ℃) and (C) the anomaly (remove 10/27-11/2 mean) alone the track of typhoon Haiyan (circles) center; (B) Temperature and (D) the change for an Argo float near the track of typhoon Haiyan (137°E, 8°N). Black line is MLD. Blue line is ILD. Grey line is 26.5℃ isothermal layer.

When Haiyan passed by, due to the existence of BL, ocean surface temperature cooled within 1℃, and even slightly increases 1℃ in some regions (Figure 3C). Along the track of typhoon Haiyan, an Argo float (ID: 5904871) (137°E, 8°N) recorded the upper ocean condition before and after Haiyan passing by. BLT was about 20 m and IL was about 100 m existing prior to Haiyan (Figure 3B), which are consistent with above results from HYCOM. Further, the surface temperature cooling recorded by this Argo float was also within 1℃, which conforms the result from the HYCOM (Figure 3D).

The existence of BL acts as a heat reservoir for SST. With relatively fast translational speeds, the vertical mixing induced by Haiyan did not penetrate into the deep ocean, thus hardly introduced the direct thermal feedback from the thermocline. After Haiyan passed by, the upper ocean temperature decreased slightly by less than 1℃ (Figure 3D). While with high SST, the release of latent heat flux contributed to Haiyan's evolution.

Figure 4 shows variables in the Haiyan intensification. In 5 days, Haiyan's intensity increased 150 knots rapidly from 20 knots to 170 knots and scale increased from tropical depression to category 6 (Figure 4A).

The minimum atmospheric pressure at the sea level decreased with the intensification of Haiyan (Figure 4B). Low vertical wind shear provided a favorable environment to the genesis and evolution of Haiyan until its landfall (Figure 4C). Sea surface latent heat flux increased to approximately 200 Wm⁻². In the first 3 days, ML was relatively thin while BL was relatively thick (Figure 4D). When Haiyan passed over the region with thick BL, the reduction of vertical mixing and entrainment prevented the cold thermocline water into the ML. As a result, sea temperature cooling associated with Haiyan was suppressed (Balaguru *et al*, 2012). In addition, high sea temperature continued to provide heat to Haiyan via latent heat flux releasing, which favors the Haiyan's rapid intensification. In the following 2 days, for the thicker ML of over 40 m (Figure 4D), cold thermocline water was blocked from entraining into upper ocean (Lin *et al*, 2005; Wu *et al*, 2007). Thus, SST and latent heat flux releasing remained at a high value (Figure 4E and 4F). BL controlled ambient SST and SST cooling under TC eye, which are two external factors about TC intensity (Vincent *et al*, 2012). Thus, Haiyan's intensity increased continually and reached rapidly to its peak.
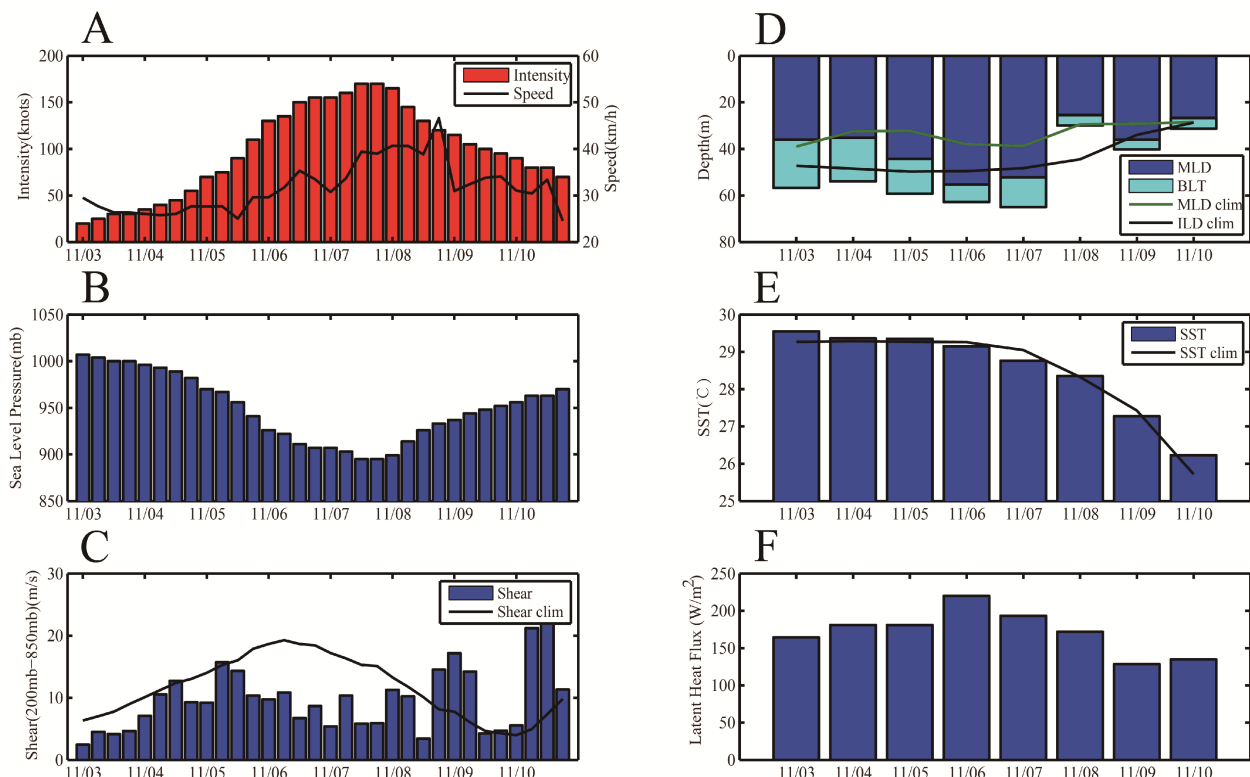
Figure 4. Evolution of (A) TC intensity and translational speed, (B) sea level pressure, (C) vertical wind shear, and daily average of (D) MLD and BLT, (E) SST from HYCOM, and (F) latent heat flux along the track of typhoon Haiyan center. The climatological mean values are superimposed in (C), (D), and (E) with bold curves.

4. Discussion and Conclusion

Haiyan's intensity with 170 knots sustained speed was much higher than most, if not all, of recorded TCs over the study region. SST, atmospheric boundary layer temperature, and humidity are crucial for TCs' evolution in general. This study suggested another factor which significantly contributes to the intensification of Haiyan in its developing phase. BL played a "barrier" role on the vertical mixing and entrainments, which prevented cold water from cooling SST. The increasing air-sea heat flux releasing enhanced the evolution of Haiyan. This process contributed to Haiyan's intensity. A different case shows in the Coral Sea that storm-induced cooling and consequent negative feedback is stronger in regions with thin or absent BL (Jullien *et al*, 2014). Though the influence of BL on TCs intensification is hard to be estimated from the observations, its role in the evolution in a super typhoon should not be overlooked.

Haiyan shares many similarities with Super Typhoon Bopha which one-year proceeded in early December 2012. Both of them formed at unusual low latitude (i.e.,~5°N), but developed to become high intense TCs. Besides, they shared similar track and made landfall in the Philippines with catastrophic and deadly power (Lander *et al*, 2014). Bopha was a low-latitude storm, one of typhoons in the historical record to reach over 110 knots south of 5°N latitude, and the only typhoon in the historical record to reach over 130 knot south of 7°N before Haiyan. In general, low-latitude forbids the Coriolis Effect to deflect winds blowing towards the low pressure center and creating a cyclone. In the Indian Ocean, low-latitude and low-level westerly wind bursts associated with the Madden-Julian oscillation can create favorable conditions for tropical cyclones by initiating tropical disturbances (e.g., Kikuchi *et al*, 2009).

The fast translational speed of about, ~9 ms^{-1}, is another extraordinary feature of Haiyan. In the Pacific, TCs' translational speed is 5 ms^{-1} in general (Lin *et al*, 2014). Due to Haiyan's fast translational speed, there was not much time for the deep ocean to respond to Haiyan. Consequently, the directly thermocline cooling feedback was absent (Lin *et al*, 2009). On the contrary, if the storm moves slowly, the surface flux or ocean induced sea surface cooling may lead to appreciable reduction of storm intensity (Shen and Ginis, 2003).

TC brings heavy precipitation along its path, which could feedback to the formation of the BL (Bosc *et al*, 2009; Maes *et al*, 2006). Comparing the BLT from Figure 2A to 2C, larger BLT appeared after the TC Haiyan than before it at nearly 140°E, which implies that the heavy precipitation caused by TC play an important role on the formation of the BL. Further, the new BL may influence the intensity of upcoming TC. Balaguru *et al.* (2014) found that TCs may self-regulate their activity through cold wake generated by previous TCs. Based on their theory, TCs may become less intense after encountering linger wakes with experiencing cool SSTs. However, the results in Northwest Pacific show the opposite comparing to Atlantic and eastern Pacific. The new formed BL probably plays a role on this process, which needs further investigation in the future.

Conflict of Interest

No conflict of interest was reported by all authors.

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