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Key Points:
- Aerosols enlarge the tropical cyclone rainfall area in the western North Pacific, which is about 9–20 km for each 0.1 increase in AOD
- The location of the maximum TC rainfall rate, i.e., TC eyewall, moves farther away from the TC center as AOD increases
- Total rainfall amount of TC is also found to increase with AOD

Supporting Information:
- Table S1
- Figure S1

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Enlarging Rainfall Area of Tropical Cyclones by Atmospheric Aerosols

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Abstract The size of a tropical cyclone (TC), measured by the area of either rainfall or wind, is an important indicator for the potential damage by TC. Modeling studies suggested that aerosols tend to enhance rainfall in the outer rainbands, which enlarges the eyewall radius and expands the extent of rainfall area. However, no observational evidence has yet been reported. Using TC rainfall area and aerosol optical depth (AOD) data, we find that aerosols have a distinguishable footprint in the TC size. Other dynamical factors for TC size, such as relative SST and Coriolis parameter, are also quantified and discussed. We show that, on average, TC rainfall size increases 9–20 km for each 0.1 increase of AOD in the western North Pacific. This finding implies that anthropogenic aerosol pollution can increase not only TC rainfall rate, but also TC rainfall area, resulting in potentially more destructive flooding affecting larger areas.

Plain Language Summary The size of a tropical cyclone (TC), measured by the area of either rainfall or wind, is an important indicator for the potential damage by TC. No observational evidence about the impact of aerosols on the TC size has yet been reported. Using TC rainfall area and aerosol optical depth (AOD) data, we find that aerosols have a distinguishable footprint in the TC size. On average, TC rainfall size increases by 9–20 km for each 0.1 increase in AOD in the western North Pacific. This finding implies that anthropogenic aerosol pollution can increase not only the TC rainfall rate as found in previous studies, but also the TC rainfall area, resulting in potentially more intensive flooding affecting larger areas. It is worthy to note that factors other than the aerosols, such as relative sea surface temperature, could also contribute to the changes of TC rainfall area.

1. Introduction

Understanding tropical cyclone (TC) rainfall characteristics is essential since TCs can induce heavy precipitation and flooding in addition to damages associated with strong winds and storm surges (Kunkel et al., 2013). Previous studies have shown that TCs are affected by many factors including sea surface temperature (SST), wind shear, lower-to-middle-level relative humidity (RH), aerosols, and so on (Chiacchio et al., 2017; Guo & Tan, 2017; Rosenfeld et al., 2012; Tao et al., 2012; Yoshida et al., 2017). In general, there are relatively less studies regarding the TC rainfall area compared to the TC intensity. A recent study (Lin et al., 2015) noted a robust dependence of the TC rainfall area or size on relative SST with respect to the tropical mean SST. Another study (Chavas et al., 2016) also noted that the relative SST is a determinant factor for TC size measured in wind fields. In addition to the relative SST, are there any other factors, especially anthropogenic ones, which also influence the TC rainfall area?

Numerous model studies have investigated the impacts of aerosols on TC. They showed that aerosols could affect precipitation-forming processes, the distribution of TC precipitation and the intensity of TCs (Hazra, Goswami, et al., 2013; Khain et al., 2008; Rosenfeld et al., 2008, 2012; Tao et al., 2012; Wang, Zhang, et al., 2014; Zhang et al., 2009). For example, the model studies have indicated that aerosols can invigorate the convection within TC outer rainbands through an increase in anvil coverage, enlarging the TC eye radius, thus reducing the TC intensity (Reale et al., 2014; Rosenfeld et al., 2012; Wang, Lee, et al., 2014; Zhang et al., 2009). It has also been suggested that anthropogenic aerosols can reduce the frequency of TCs through their radiative effect by cooling SST (Dunstone et al., 2013). The aerosol invigoration effect, which is invigoration of deep convective clouds by aerosols, occurs when aerosols serving as cloud condensation nuclei (CCN) enter the bottom of deep convective clouds near the periphery of TC. The elevated CCN concentration fosters vapor condensation in warm phase and droplet freezing in the cold phase aloft, resulting in additional significant latent heat release and boosting deep convection (Fan et al., 2018; Li et al., 2008; Rosenfeld et al., 2008; Wang et al., 2011). Associated with this mechanism called microphysical effects of aerosols on TCs (Wang, Zhang, et al., 2014), model simulations have shown enlarged rainband and increased precipitation under polluted conditions. If light-absorbing aerosols exists, the aerosol radiative effects can cause warming in the lower troposphere, which further strengthens the lower-level convection and enhances precipitation in the rainband region (Wang, Lee, et al., 2014). Typically, TC can suck in air mass from the distance three times of its radius, so continental aerosols in a polluted region like China have great chances of getting into the periphery of TCs before their landing. However, no systematic investigations of the aerosol impact on the TC rainfall area, which is often as important as the intensity of a TC, based on observations have been reported.

Using the TC radius objectively determined from Tropical Rainfall Measuring Mission (TRMM) satellite rainfall retrievals (Huffman et al., 2010; Lin et al., 2015), combined with the aerosol optical depth (AOD) obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) (Levy et al., 2013) and by the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) (Gelaro et al., 2017; Molod et al., 2015) from 2000 to 2015, we examine the relationship between AOD and TC rainfall radius in the western North Pacific (WNP) region to the south of 30°N. Asia is heavily polluted along with their fast-developing economy, particularly in East Asia. These aerosols could be transported into the WNP and have strong impacts on the TC rainfall area in this region.

The paper is organized as follows. Section 2 describes the data and methods. The results are shown in section 3. And section 4 provides the summary and discussions.

2. Data and Methods

The tropical cyclone cases considered in this study are those with maximum wind speed larger than 17.5 m s^{-1}. Only the TC cases observed within the tropical domain are analyzed. Those TC cases that went through extratropical transition are not included in our analysis since their rainfall characteristics could be more associated with extratropical transition (Knaff et al., 2014; Lin et al., 2015).

We use daily MODIS AOD retrieval from National Aeronautics and Space Administration (NASA) Terra at 1° resolution and 6-hourly AOD from MERRA2 Aerosol Reanalysis at 0.625° resolution. In order to be consistent, we linearly interpolated MERRA2 AOD to 1° resolution as well. Compared to MODIS, MERRA2 provides all-weather instead of clear-sky-only AOD data and thus much larger sample volume could be examined. The study period is from 2000 to 2015 when both AOD and TC rainfall radius data were available. For each TC, MODIS and MERRA2 AOD within the 1° × 1° grid measured one day before the arrival of the TC are used to represent the AOD for that location so that the effect of TCs on aerosols is minimized. Since the TC size is generally larger than the grid size, we here adopted AOD at the grid that the TC center would pass in one day. Using AOD that averaged within a 3° × 3° region that TC would pass, it gave similar results (not shown here). The TC rainfall radius is objectively determined from TRMM rainfall retrievals combined with TC tracks following the method in Lin et al. (2015), where the TC rainfall area was defined as the region that contains most of TC rainfall by meeting three criteria: azimuthal-mean rainfall greater than 0.5 mm h^{-1}, fractional standard deviation of rainfall less than 1.0 and a negative radial gradient of azimuthal-mean rainfall. Same as the TC rainfall area, TC rainfall radius is azimuthally averaged value at each time step. Note that TC rainfall area determined is sensitive to the criteria used, but it probably will not influence the results unless the impact of aerosol on TC rainfall has significant radial inhomogeneity.

Based on the climatological distribution of TC occurrence (Knapp et al., 2010) and the spatial distribution of averaged AOD observed by MODIS between 2000 and 2015, we identified the tropical region in the WNP region with frequent aerosol pollution events and sufficient TC occurrences, which is with latitudes between 10.0°N and 30.0°N and longitudes between 125.0°E and 178.0°E. We limited our analysis to this region for minimizing the variability due to factors other than aerosols. To remove the influence of SST, We use monthly SST data set from Hadley Centre at 1° resolution to isolate the changes of relative SST (Lin et al., 2015), which is defined as the SST in the TC environment minus the tropical (30°S-30°N) mean SST.

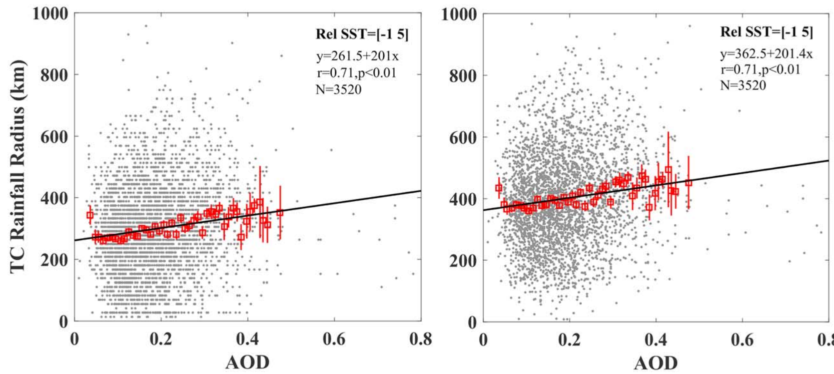

Figure 1. Scatterplot of TC rainfall radius as a function of MODIS AOD for the western North Pacific region a with and b without the impacts of relative sea surface temperature (SST) between -1 °C and 5 °C. The gray dots represent observation data. The red squares represent the mean TC rainfall radius in AOD bins that have more than five samples and the vertical red lines represent root-mean-square errors. The AOD bin width is 0.01. The solid black lines are the linear regression fits through the data. R is the Spearman's rank correlation coefficient based on the bin-averaged values (red boxes). The p-value is calculated using the Student's t-test.

In the WNP study region, aerosols or particulate pollution from mega-cities in Eastern China can be transported to the vast oceanic area. The primary aerosol type in this region is soluble aerosols such as sulfate or nitrate (Chin et al., 2004), which can serve as cloud condensation nuclei (CCN). All types of aerosol reduce the surface solar radiation by scattering and absorbing solar radiation, while their radiative effects in the atmosphere differ considerably. The total number of TC samples at a temporal resolution of three hours during the 15-year period is 14494. The number of TC rainfall radius samples matched with MODIS AOD (MERRA2 AOD) values reduces to 3585 (14045). The mean and standard deviation of MODIS AOD during the study period are about 0.19 and 0.10; and the mean and standard deviation of MERRA2 AOD during the study period are about 0.21 and 0.17.

3. Results

We divide the relative SST into six bins going from -1 °C to 5 °C in 1 °C intervals, and AOD into 6 bins with an interval of 0.1. The mean TC rainfall radii within each relative SST bin and AOD bin for the WNP region are shown in Tables S1 and S2, respectively. The TC rainfall radius generally increases with increasing relative SST (Table S1) except for some bins with small sample sizes. Moreover, the TC rainfall radius increases with increasing AOD for all bins having sample sizes greater than 100.

The correspondence between AOD and TC rainfall radius is evident over the WNP (Figure 1a for MODIS AOD and Figure S2a for MERRA2 AOD). A student t-test has been carried out for the relationship between AOD and TC rainfall radius. The low p-value ($p < 0.01$) indicates that there is a strong significant linear relationship between AOD and TC rainfall radius. This dependence becomes more evident when the TC radius is divided into different AOD bins. Since the relative SST is an important factor determining the TC size, this dependence may be a coincidence if AOD correlates well with the relative SST. This is not the case because the correlation (r) between the two is only 0.09 (0.05 for MERRA2 AOD) and not statistically significant. However, there is still a possibility that the aerosol radiative effect affects the SST although their time scales are different, which may lessen their correlation.

Another way to isolate the influence of relative SST is to take the relative SST impact into consideration. The increase in TC rainfall radius to relative SST is ~30–40 km K^{-1} (Lin et al., 2015). To roughly exclude the impact of relative SST on the TC rainfall radius, we use 35 km K^{-1} to adjust the TC rainfall radius as follows:

$$R_N = R + SST_{rel} \times 35, \quad (1)$$

where SST_{rel} is the relative SST in units of K. R_N and R are the adjusted and original TC rainfall radii, respectively, in units of km.

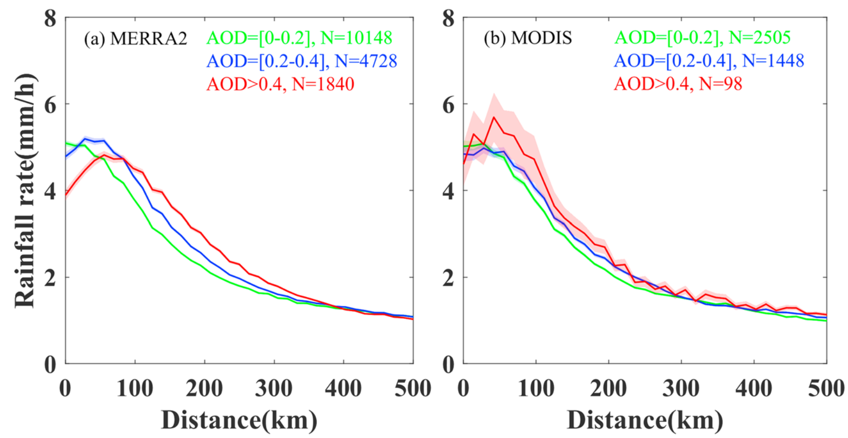

Figure 2. Azimuthally-averaged radial rainfall rate for three different AOD bins from a MERRA2 and b MODIS. The green, blue, and red lines represent data for AOD intervals 0–0.2, 0.2–0.4, and greater than 0.4, respectively. Sample sizes (N) are given. The color shading represents one standard error of the mean.

The dependence of the TC rainfall radius on MODIS AOD still remains using the adjusted radius (Figure 1b). Note that similar findings have been found when other values between 30 km K^{-1} and 40 km K^{-1} instead of 35 km K^{-1} are used in Eq. (1). The linear fit to the data binned by AOD shows a similar dependence between the two. Significant positive relationships between TC rainfall radius and AOD are found above the 95% confidence level when using both the original and adjusted TC radii. This suggests that the dependence of the TC rainfall radius on aerosols is robust, at least over the WNP. As shown in Figure S1, the positive dependence still remains within each bin of relative SST, although it is only statistically significant when the sample size is greater than 100.

We also examined the relationship between AOD and TC rainfall radius over the WNP using AOD from MERRA2 instead of MODIS (Figure S2). Similar results as those shown in Figure 1 were found: both original and adjusted TC rainfall radii increased significantly with increasing AOD over the WNP. Figure S3 further shows that the positive dependence of the TC rainfall radius on MERRA2 AOD still remains in each bin of relative SST, similar to that seen in Figure S1 using MODIS AOD. Rosenfeld et al. (2012) have shown that aerosols can also significantly reduce the TC intensity, associated with the enlarged TC eye radius by aerosols' invigoration effect. Thus, with the increase of AOD, TC rainfall radius increases and TC intensity decreases. Regarding the TC rainfall radius and TC intensity, Lin et al. (2015) have shown that they have no relationship. We here find that the positive relationships between AOD and TC rainfall radius remain while the slope changes for binned TC intensity (not shown here).

Figure 1 shows that the linear regression slope is ~200 km per AOD unit, i.e., 20 km per 0.1 AOD, over the WNP. Figure S2 shows a linear regression slope of around 88–97 km per unit of AOD over the WNP. In general, the sensitivity of the TC rainfall radius to AOD ranges from ~9 to 20 km per 0.1 AOD. Note that the change in TC rainfall radius by relative SST is about 30–40 km K^{-1}. The contribution of AOD to TC rainfall radius is thus also significant.

Theoretical arguments and numerical simulations have suggested that the TC size is inversely proportional to the Coriolis parameter (Chavas & Emanuel, 2014; Khairoutdinov & Emanuel, 2013). Accordingly, we next examined the latitudinal variation in TC rainfall radius and AOD over the WNP. As shown in Figure S4a, the TC rainfall radius decreases slightly with increasing latitude over the oceanic region. However, there is no significant variation in MODIS AOD with latitude (Figure S4b). Therefore, the increasing trend in TC rainfall radius with increasing AOD over the WNP is not likely related to the impact of the Coriolis force that might correlate with changes in AOD. Interestingly, MERRA2 AOD increases with latitude (Figure S4c). We then expect that the increase in TC size with AOD should be smaller when using MERRA2 data than when using MODIS data. This is actually the case as shown in Figure 1 and Figure S2.

We further examine the variation in TC rainfall radial profiles with AOD over the WNP (Figure 2). The outward expansion of TC rainfall with increased AOD is evident for both MODIS and MERRA2 AOD. This is

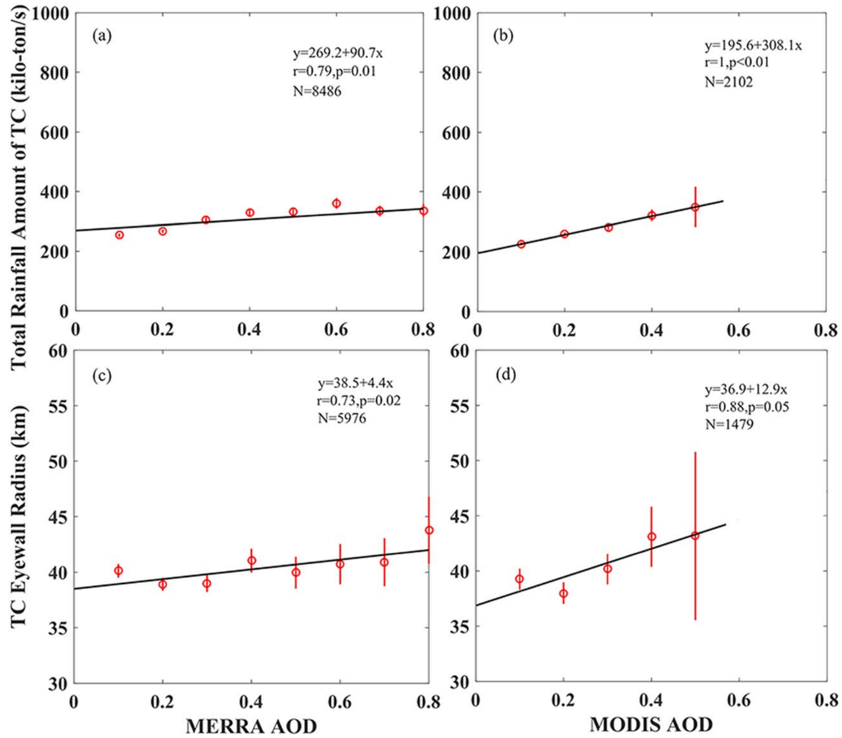

Figure 3. TC's total rainfall amount as a function of a MERRA2 AOD and b MODIS AOD and TC eyewall radius as a function of c MERRA2 AOD and d MODIS AOD. Only TCs with maximum winds $>$17.5 m/s are selected. The eyewall radius is calculated as the distance between the maximum azimuthally-averaged rainfall rate and the TC center. The circles and bars represent the means and standard deviations of the TC eyewall radius in each AOD bin. The AOD bin width is 0.1. The solid black lines are the linear regression fits through the data. The fitting functions, Spearman's rank correlation coefficients (r), p-values, and sample sizes (N) are shown in each panel.

consistent with the expanded rainfall fields noted in previous numerical simulations. It also shows that the TC rainfall rate increases with AOD in the outer regions of the TC on some expense of the inner region, which suggest that the aerosol invigoration effect is occurring (Wang, Lee, et al., 2014). Slight difference also exists for the response of rainfall rates to AOD at inner core (radial distance $<$100 km) between MODIS and MERRA2. For example, the change pattern of rainfall rates for MODIS AOD from [0.2 0.4] to $>$0.4 is similar to that for MERRA2 AOD from [0 0.2] to [0.2 0.4] at inner core of TCs. One likely explanation is the difference of AOD observations from MERRA2 and MODIS: the MODIS AOD is observed from satellite which could include the contribution from water vapor, making it likely larger than actual column aerosol amount. Figure 1 and Figure S2 also demonstrate that there are much less observations with AOD $>$ 0.4 for MODIS than MERRA2, which could be another reason causing the different responses found above. Note that the increased TC rainfall rate with AOD will be more pronounced if we consider that the TC rainfall coverage is also enhanced by aerosols. Associated with the increasing precipitation rate and expanded rainfall fields, the total precipitation amount for TCs with maximum winds larger than 17.5 m/s (Klotzbach, 2006) increases with both MODIS and MERRA AOD, as suggested by Figures 3a and b. Note that stronger TCs tend to have a well-defined precipitation structure for identification. Same as the AOD-bin-average total precipitation amount, the AOD-bin-median total precipitation amount also increases with both MODIS and MERRA2 AOD as shown in Figure 4. Increasing precipitation rates and amounts with increased aerosol loading have also been found for deep convective clouds and mid-latitude cyclones over the mid-latitude land and ocean areas (Li et al., 2011; Wang, Zhang, et al., 2014; Zhang et al., 2007).

Figure 2 also shows that the location of the maximum TC rainfall rate (which generally corresponds well with the TC eyewall) moves farther away from the TC center as AOD increases, implying that the TC eyewall radius also increases with increasing AOD. This increase in eyewall diameter was shown to be

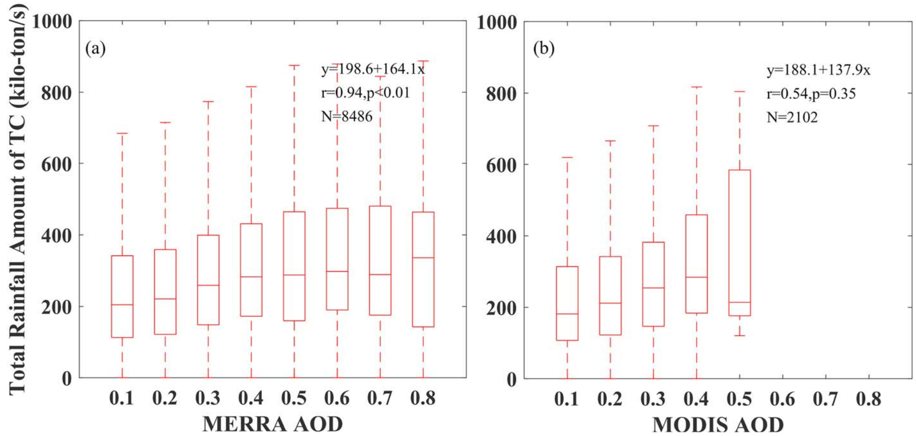

Figure 4. Boxplots of TC's total rainfall amount as a function of a MERRA2 AOD and b MODIS AOD. The fitting functions, Spearman's rank correlation coefficients (r), p-values, and sample sizes (N) are shown in each panel.

associated with decrease in the maximum wind of the TC (Rosenfeld et al., 2012). Figures 3c and d show the variation in eyewall radius with MERRA2 and MODIS AOD for TCs with maximum winds larger than 17.5 m/s because the structure of eye is more obvious in mature tropical cyclone. There is a significant increasing trend in TC eyewall radius with AOD. Thus, an increase in aerosol concentrations most likely induce increases in the TC flood area (increasing the rainfall radius as shown in Figure 2), total precipitation amount, and the radius of the TC eyewall, consistent with the findings from previous model simulation studies and expectations from both microphysical effects and radiative effects of aerosols (Hazra, Mukhopadhyay, et al., 2013; Lynn et al., 2016). This occurs despite a possible decrease in the maximum wind speed. These findings are not consistent with the findings from a few studies such as an idealized simulation by Herbener et al. (2014), who found that the storm intensity increased and the storm size decreased with increasing aerosol number concentration. Note that in the idealized simulation by Herbener et al. (2014), the aerosols were put directly into eyewall regions, whereas we assume aerosols enter eyewall from outside here. By contrast, our finding are consistent with and support the mechanisms and findings found by most previous studies (Carrio & Cotton, 2011; Evan et al., 2011; Hazra, Goswami, et al., 2013; Reale et al., 2014; Rosenfeld et al., 2012; Wang, Lee, et al., 2014; Yang et al., 2018; Zhang et al., 2009).

4. Summary and Discussions

This study has shown a robust dependence of the TC rainfall radius on AOD over the WNP. Although various modeling studies have investigated the impacts of aerosol on TC properties, including its intensity, precipitation and size, this is the first study to explore the potential impact of aerosol on TC size measured in rainfall area based on available observations. Efforts are paid to isolate some potential factors influencing TC sizes, such as the relative SST and Coriolis parameter, but the results presented in the paper are mainly based on correlation analyses.

A likely physical explanation is that anthropogenic aerosols serving as CCN intrude into the TC outer rainbands and invigorate the vertical development of the outer rainbands with intensified ice particle detrainment aloft. The expanded convective clouds consequently increase the rainfall area outward of the rainbands and thus increase the rainfall area and wind field as suggested by numerical simulations (Khain et al., 2010; Zhang et al., 2009) and satellite measurements (Reale et al., 2014). Numerical simulations have found that the aerosol invigoration effect (Rosenfeld et al., 2008) occurring in the outer rainbands tends to reduce the TC strength with increased TC rainfall rate and size (Reale et al., 2014; Zhang et al., 2009). The analysis here thus provides observational evidence for the aerosol impact on the TC structure. This study implies that increases in anthropogenic aerosols will cause increases not only in TC precipitation rate as found in previous studies, but also in the TC rainfall area over the WNP, which may potentially result in more severe flooding once landfall is made.

The observational finding may provide key observational support to modeling results (Wang, Lee, et al., 2014) regarding aerosol effects on the development and structure of TCs, while most of existing studies focused more on the TC intensity rather than the TC rainfall area and size (Reale et al., 2014; Rosenfeld et al., 2012; Zhang et al., 2009). Our findings may help us improve understanding of the aerosol impacts on the development of severe tropical storms through microphysical-radiative interactions. While East Asia and the adjacent western North Pacific (WNP) is generally polluted with high AOD climatology, severe pollution usually occurs episodically. The finding of an enlarged rain band and a decreased intensity of TCs under polluted conditions suggests that we might need to account for both the concentration and variability of aerosols in predicting TCs.

The possible other factors at play will be investigated vigorously in our future modeling study. TC size and structure can vary substantially during its life cycle because of various environmental impacts and its internal dynamics, such as the eyewall replacement, rainband generation and dissipation, among others (Houze 2010). As a result, the aerosol impact is hard to be completely isolated and quantified. Nevertheless, the distinguishable dependence found here suggests that aerosols probably have a non-negligible impact on TC rainfall area.

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