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Key Points:
- More precipitation and colder high clouds with 208 K < IR BT < 240 K are found as TCs intensify
- Intensifying TCs follow the occurrence of colder temperature and greater coverage of very deep convection with IR BT < 208 K
- Clouds with IR BT < 208 K are a good predictor of TC intensity change

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Precipitation, Convective Clouds, and Their Connections With Tropical Cyclone Intensity and Intensity Change

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Abstract In this paper, satellite-based precipitation, clouds with infrared (IR) brightness temperature (BT), and tropical cyclone (TC) data from 2000 to 2015 are used to explore the relationship between precipitation, convective cloud, and TC intensity change in the Western North Pacific Ocean. An IR BT of 208 K was chosen as a threshold for deep convection based on different diurnal cycles of IR BT. More precipitation and colder clouds with 208 K < IR BT < 240 K are found as storms intensify, while TC 24 h future intensity change is closely connected with very deep convective clouds with IR BT < 208 K. Intensifying TCs follow the occurrence of colder clouds with IR BT < 208 K with greater areal extents. As an indicator of very deep convective clouds, IR BT < 208 K is suggested to be a good predictor of TC intensity change. Based upon the 16 year analysis in the western North Pacific, TCs under the conditions that the mean temperature of very deep convective clouds is less than 201 K, and the coverage of this type of clouds is more than 27.4% within a radius of 300 km of the TC center, will more likely undergo rapid intensification after 24 h.

1. Introduction

The accuracy of tropical cyclone (TC) track forecasting improved by nearly 50% for lead times of 24–72 h between 1990 and 2008; over the same period forecasting of TC intensity showed only limited improvement (Rappaport et al., 2009). Although guidance on the intensity of TCs has seen significant improvements, forecasting the intensification of TCs is still a real challenge (DeMaria et al., 2014). Although it is well known that TC intensification occurs more readily under conditions of higher sea surface temperature, lower vertical wind shear, and higher low troposphere moisture (DeMaria et al., 2005), and these environments are critically important to the prediction of TC intensity change in general and more specifically rapid intensification (RI) (DeMaria et al., 2005; Kaplan et al., 2015, 2010), studies have shown that these environmental conditions alone are not sufficient to explain changes in TC intensity. Hendricks et al. (2010), for example, found that the environmental conditions for rapid intensifying and intensifying TCs are similar and concluded that the rate of TC intensification might not be critically reliant on environmental conditions. Forecasts obtained from the Statistical Hurricane Intensity Prediction Scheme, a statistical model of TC intensity change using climatology and a persistence predictor, together with synoptic predictors, are found to explain only about 50% of the variability in observed TC changes (DeMaria & Kaplan, 1994).

Given the limited prediction skill of models of TC intensity based on environmental properties, there have been a wealth of studies of the role of internal dynamical processes of TCs, which are largely linked to precipitation properties and convective processes. The release of latent heat by convection in the inner core of a TC is considered crucial to TC intensification (Simpson et al., 1998). Through analysis of an 11 year Tropical Rainfall Measuring Mission (TRMM) precipitation data set, Jiang (2012) found that extremely intense convection in the inner core increases the possibility of RI, but the difference is not substantial. Using the same data set, Jiang and Ramirez (2013) found that rapidly intensifying TCs are associated with a large area of rainfall with heavy rain in the inner core. By compositing 22 year passive microwave satellite overpasses, Harnos and Nesbitt (2011) detected a convective ring forming 6 h before the onset of RI. Using a 14 year TRMM precipitation radar (PR) data set, Tao and Jiang (2015) found that RI is more likely to be caused by shallow-moderate precipitation, while moderate to very deep convection observed during an RI is more likely to be a response. With two more years of TRMM PR data, Tao et al. (2017) claimed that RI follows significant increases in the occurrence and coverage of stratiform rain, thus stressing the importance of this type of rainfall. In a comparison with TCs with slow intensification rates, Alvey et al. (2015) used 15 year multisatellite passive microwave data to show that storms with higher intensification rates have more symmetric distributions and a larger overall coverage of precipitation prior to the onset of intensification.

Satellite-based statistical studies can be used to draw more robust conclusions through analysis of more data sets. However, consensus on the importance of different properties of convection on TC intensity change, especially RI, has not yet been reached despite the extensive use of satellite data by the authors of these cited works. The extent to which convection is a precursor, or simply a reflection of other processes occurring during RI, is also unclear.

Studying the diurnal variations in TC convective cloud systems for the period 2000–2013, Wu and Ruan (2016) found that clouds with IR BT < 208 K have a maximum coverage in the morning, and clouds with 208 K < IR BT < 240 K have a maximum coverage in the afternoon. An IR BT of 208 K was chosen as a threshold to identify very deep convection within IR data (Chen & Houze, 1997; Hall & VonderHaar, 1999). Clouds with IR BT < 208 K and 208 K < IR BT < 240 K are termed "very cold deep convective clouds" and "cold high clouds," respectively, influenced by different diurnal cycles (Wu & Ruan, 2016). Different diurnal cycles and different underlying physical mechanisms associated with these two types of TC clouds suggest that they might play different roles in TC intensity change. In this paper we use 16 year (2000–2015) precipitation data, IR BT data, and TC information to examine the relationships between precipitation, very deep convective clouds, high clouds, and TC intensity changes.

2. Data and Methods

Best track data were provided by the United States Navy Joint Typhoon Warning Center (Chu et al., 2002). The 6-hourly records of the position of the TC center, the intensity of the TC, and other important parameters were included in the best-track data, typically at 0000, 0600, 1200, and 1800 UTC. TCs for the period 2000–2015 were analyzed, in which period both high-resolution precipitation and IR BT data are available. The 6-hourly TC centers were linearly interpolated to give the 3-hourly and hourly TC center positions, to match the temporal resolution of the precipitation and IR BT data, respectively. A total of 437 storms in the western North Pacific were analyzed for the period 2000–2015. The precipitation data used in this paper are rates of rainfall from the NASA TRMM Multisatellite Precipitation Analysis (TMPA). TMPA is a four-stage calibration-based sequential scheme for combining precipitation estimates from multiple satellites and gauge analyses (Huffman et al., 2007, 2010). It is a TRMM standard product computed for the entire TRMM period (January 1998 to present). The TMPA operational product used in this paper is 3B42 (version 7) and has a horizontal resolution of 0.25° × 0.25° between 50°N and 50°S, with a temporal resolution of 3 h. Half-hourly global merged IR BT data were obtained from the United States National Centers for Environmental Prediction Climate Prediction Center (Janowiak et al., 2001). The IR BT data were computed by merging data from all the available geostationary satellites. The IR BT data have a pixel size of 4 km by 4 km between 60°N and 60°S. The half-hourly IR BT data were averaged to hourly data to fill gaps in the data.

All precipitation and IR BT images were evaluated in terms of TC intensity (maximum sustained wind) and 24 h future intensity changes. The five intensity categories are classified at comparable sample sizes, as follows: $V_{max} < 32$ kt (tropical depression, TD), 33 kt $< V_{max} <$ 64 kt (tropical storm, TS), 65 kt $< V_{max} <$ 82 kt (CAT 1 TCs), 83 kt $< V_{max} <$ 113 kt (CAT 2 and CAT 3 TCs), and $V_{max} >$ 113 kt (CAT 4 and CAT 5 TCs). RI was first defined by Kaplan and DeMaria (2003) as the 95th percentile of all 24 h overwater intensity changes of 30 kt or greater in 24 h for the North Atlantic. Jiang (2012) defined five separate intensity change categories, namely rapidly intensifying, slowly intensifying, neutral, slowly weakening, and rapidly weakening. In order to compare all intensity changes using similar sample sizes, the following criteria are used in this paper: RI ($V_{24} - V_0 \geq$ 30 kt), slow intensification (SI, 10 kt $\leq V_{24} - V_0 <$ 30 kt), intensifying neutral (IN, 0 kt $\leq V_{24} - V_0 <$ 10 kt), weakening neutral (WN, −10 kt $\leq V_{24} - V_0 <$ 0 kt), slow weakening (SW, −30 kt $\leq V_{24} - V_0 <$ −10 kt), and rapid weakening (RW, $V_{24} - V_0 <$ −30 kt). All satellite images must show the best-track position 300 km or more away from land to remove any influence from it. The wind fields were obtained from the 0.75° resolution European Centre for Medium Range Weather Forecasts interim reanalysis data set (Simmons et al., 2007). In this paper, each image is evaluated using wind shear relative coordinates, with wind shear defined as the difference between 850 and 200 hPa winds averaged at a radius of 200–800 km from the TC center, as described in Harnos and Nesbitt (2011). The 6-hourly wind shear data were linearly interpolated to give hourly data to match the temporal resolution of IR BT data.

3. Results

The 16 year shear-relative composites of precipitation, very deep convective clouds, and high clouds for each of the five intensity classifications within 300 km from the TC center in the western North Pacific are shown in Figure 1. These reveal large variations within a 300 km radius from the TC center associated with TC intensity and TC intensity change. The mean precipitation rate increases significantly with increased TC intensity. The average rate of rainfall within a 100 km radius of the TC center increases from about 2 mm/h up to as much as 10 mm/h, when storms intensify from weakest TDs to strongest CAT 4 and CAT 5 TCs. A 100 km radius from the TC center can be roughly defined as the inner core. Unlike precipitation, the relationship between very deep convective clouds and TC intensity is somewhat less straightforward. Deep convective clouds have coldest temperatures in their inner core and largest coverage for clouds less than 200 K in categories TS and CAT 1 TC. The variations in temperature and area of cold high clouds as a function of TC intensity show similar patterns to precipitation. The temperature of this type of clouds in the inner core decreases, and the coverage of colder clouds increases as storms intensify.

Although Figure 1 shows clear relationships in which TC intensity increases with precipitation and with colder high clouds, we are unable to distinguish either precipitation or high clouds as a precursor or a response to TC intensity change. To investigate the relationship for precipitation, two types of clouds, and TC 24 h future intensity change, Figure 2 shows the shear-relative composites of precipitation, very deep convective clouds, and high clouds for each of the six intensity change classifications within 300 km of the TC center. For both weakening (rapid weakening and slow weakening) and RI categories, the mean rainfall rates in the inner core are high and the coverage of rates greater than 5 mm/h is high. The mean rainfall rates in the inner core in the rapid weakening case are the highest, at up to 7 mm/h. This can be partially explained by the fact that the most rapid weakening occurs when TCs are intense.

Unlike precipitation, the presence of very deep convective clouds is closely linked with TC 24 h future intensity change. Intensifying TCs follow the occurrence of colder temperature in the inner core and the larger areal extent of this type of clouds. Weakening TCs follow the occurrence of relatively warm temperature in the inner core and the smaller areal extent of this type of clouds. Figure 1 shows that very deep convective clouds have the coldest temperature in their inner core and the largest coverage in the categories of TS and CAT 1 TCs. This phenomenon can be explained by the connection between the coldest temperature and largest areal extent of very deep convective clouds with RI, and the fact that TS and CAT 1 TCs are those most likely to show RI (Kaplan & DeMaria, 2003, also see Table 1). The variations in temperature and area of high clouds as a function of TC 24 h future intensity share similar patterns with precipitation as well. The temperatures of this type of clouds in the inner core are cold in both the rapid weakening and rapid intensification categories, with the coldest mean BT occurring in rapid weakening cases. The results shown in Figure 2 demonstrate that deep convective clouds, unlike precipitation and high clouds, can be a precursor to TC intensity change.

Table 1 summarizes the TC statistics according to different TC intensity change categories in the western North Pacific. The sample size in Table 1 is the total number of satellite images that fall in each category. For both IR BT and precipitation data, TCs in intensifying neutral and slow intensifying have the largest sample size. The mean wind shear for rapid weakening TCs is the largest. It is about twice as large as the mean wind shear for TCs under RI. TCs under RI have the weakest wind shear. The mean wind shear for TCs under RI is 1.38 kt weaker than that for TCs under slowly intensifying. Considering the large sample size, the differences in wind shear are significant, but that such differences are not definitive regarding whether or not RI occurs. The mean intensity 24 h before TCs undergo rapid weakening is about 111.11 kt. It indicates that TCs stronger than CAT 3 are most likely to have rapid weakening. The mean intensity 24 h before TCs undergo RI is 60.73 kt. It indicates that TS and CAT 1 TCs are most likely to have RI.

The role of diabatic heating associated with convection in TC intensification is also dependent on the orientation of the heating relative to the radius of maximum winds (Nolan et al., 2007). Figure 3 presents the shear-relative frequency distribution of precipitation, very deep convective clouds, and high clouds with respect to TC intensity change classification. For the precipitation, the occurrence rates are high for weakening and intensifying storms, with the highest occurrence in the inner core. The occurrence rate of very deep convection in the inner core is significantly higher for RI than for other states, being greater than 70%. However, the occurrence rate of very deep convection in the inner core for rapid weakening TCs is the

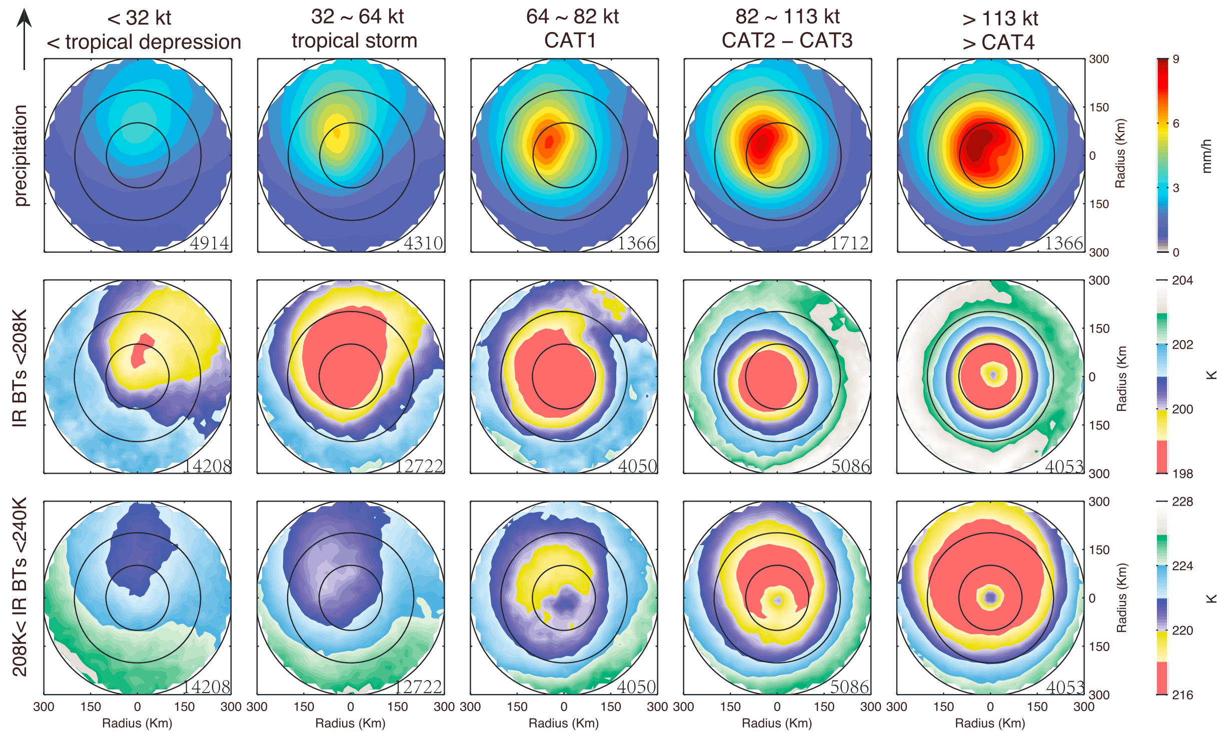

Figure 1. Shear-relative composites of precipitation and BT of very deep convective clouds and high clouds according to different TC intensity categories in the western North Pacific. Black circles represent 100, 200, 300 km radii from the TC center. The arrow represents the direction of wind shear. The sample sizes are shown at the bottom right-hand corner of each panel.

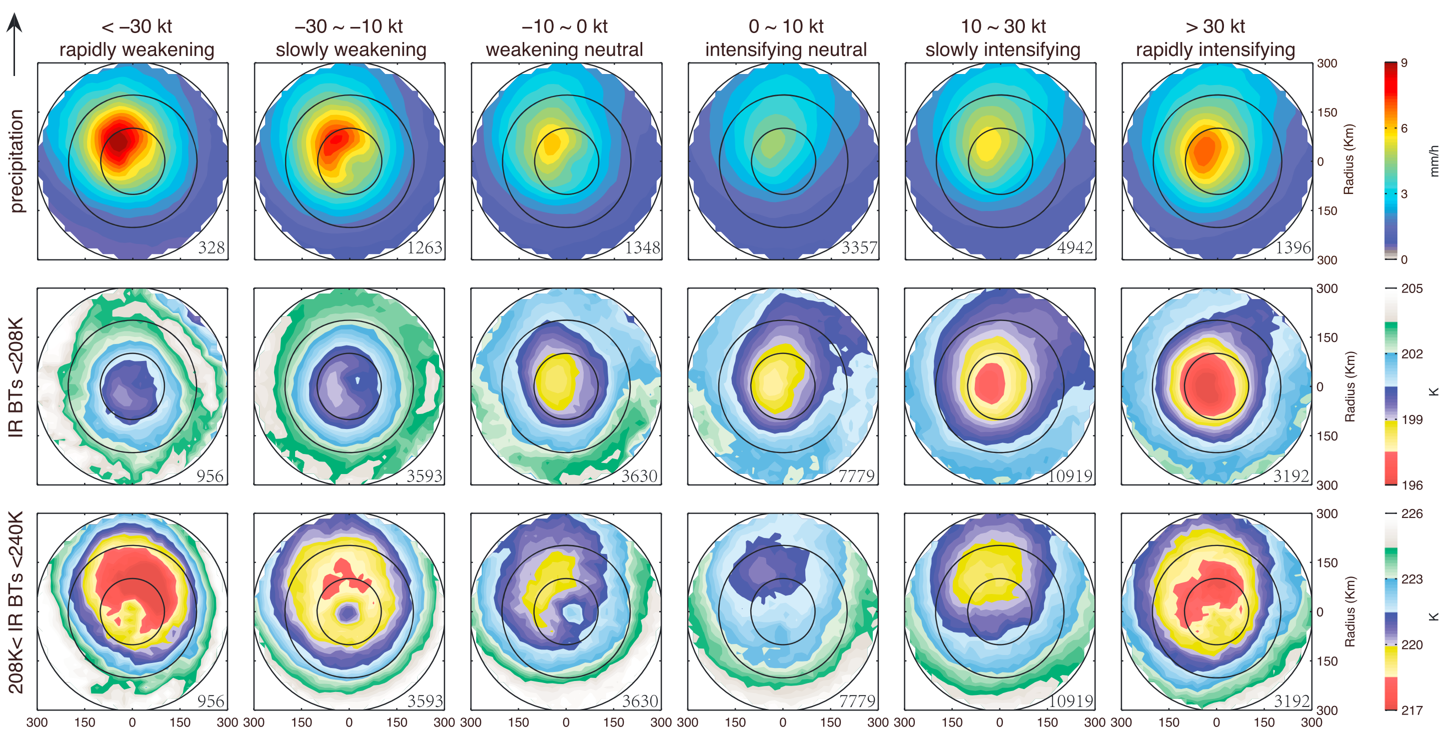

Figure 2. As Figure 1 but the composites are based on TC intensity change.

Table 1
TC statistics according to different TC intensity change categories in the western North Pacific

		Sample size		Shear(kt)		Initial intensity(kt)	
	Defination (kt)	BT	Precipitation	Mean	SD	Mean	SD
RW	$V_{24}-V_0 < -30$	956	328	19.04	8.85	111.11	22.57
SW	$-30 \le V_{24}-V_0 < -10$	3,593	1263	15.27	8.49	99.48	30.97
WN	$-10 \le V_{24}-V_0 < 0$	3,630	1348	14.59	7.74	68.84	37.56
IN	$0 \le V_{24}-V_0 < 10$	7,779	3357	12.93	6.80	42.50	31.38
SI	$10 \le V_{24}-V_0 < 30$	1,0919	4942	11.14	5.71	44.82	28.16
RI	$V_{24}-V_0 \ge 30$	3,192	1396	9.76	5.41	60.73	23.42

second highest. In combination with the composite of very deep convective clouds with respect to six intensity change classifications in Figure 2, this indicates that having the largest overall fractional areas of very deep convection, and therefore colder mean IR BT, appears to provide better means of distinguishing TC intensity change. The occurrence rate of high clouds in the inner core is lowest for RI, which is due to the high occurrence rates of very deep convection in the inner core for RI. The high clouds have high occurrence rates in the outer rain bands for both rapidly weakening and weakening TCs.

To provide a quantitative demonstration of the variations in precipitation, very deep convective clouds and high clouds as a function of TC intensity, the 16 year mean precipitation and rainfall area, the mean temperature, and area of very deep convective clouds and high clouds within 300 km of the TC center are shown in Figure 4a. Both mean rainfall rate and rainfall area increase simultaneously as TCs intensify. Rainfall rate increases from 1.6 mm/h to 3.6 mm/h, and rainfall areas increase from 65.6% to around 91.0% when the TCs intensify from TD to CAT 4 and CAT 5 TC. Similar to precipitation, the mean temperature of high clouds decreases from 223.9 K to 221.4 K and the area increases from 32.6% to 49.3% simultaneously as TCs intensify from the weakest to the strongest category. Neither mean temperature nor area of very deep convective clouds show the linear evolution associated with TC intensity demonstrated in Figure 1. The coverage of clouds colder than 208 K (13.8%, 20.2%, 22.8%, 20.9%, and 27.7%, respectively) is only about half of that of clouds between 208 K and 240 K (32.6%, 36.7%, 43.8%, 48.6%, and 49.3%, respectively) in all intensity

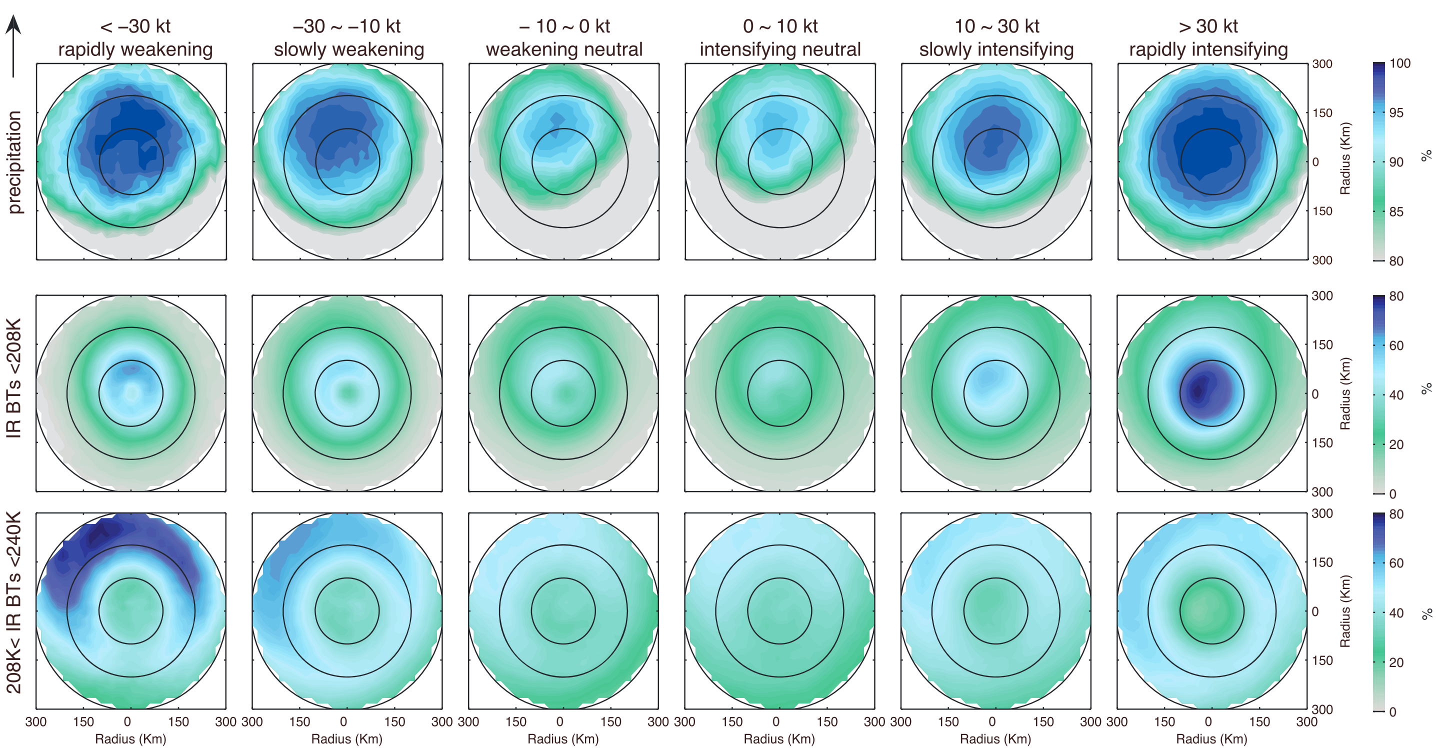

Figure 3. As Figure 2 but the colors show occurrence frequency for precipitation and BT of very deep convective clouds and high clouds.

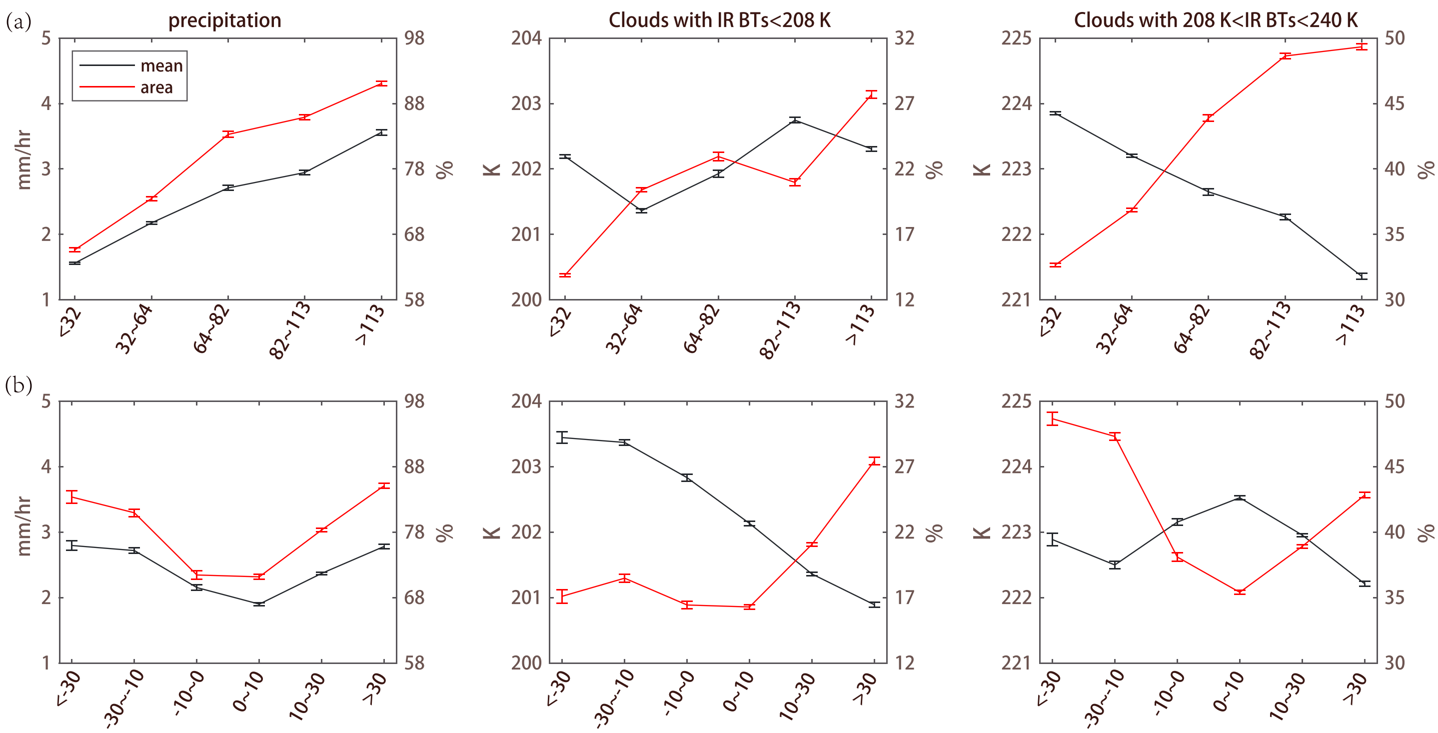

Figure 4. The 16 year mean rain rate (black) and rainfall area (red) of precipitation, and mean temperature (black) and area (red) of very deep convective clouds and high clouds according to different TC (a) intensity categories (kt) and (b) intensity change categories, within 300 km of the TC Center. Error bars (vertical lines) are based on standard error.

categories. Therefore, the distribution of precipitation is largely under the influence of high clouds in all intensity categories, which explains the similar patterns of precipitation and high clouds associated with varying TC intensity in Figure 1.

The 16 year mean precipitation and rainfall area, the mean temperature, and area of two types of clouds within 300 km of the TC center associated with 24 h future TC intensity change are shown in Figure 4b. The mean rainfall rate (about 2.8 mm/h) and rainfall area (83.3% and 85.5%, respectively) are high in both the rapidly weakening and rapidly intensifying cases. Similarly, the mean temperature is warmest and the coverage is smallest in the neutral categories for high clouds. No linear relationship between precipitation, high clouds, and 24 h future TC intensity change is found. As for very deep convective clouds, the mean temperature decreases from 203.5 K to 201 K as the 24 h future TC intensity change varies from rapidly weakening to rapidly intensifying. While the coverage of this type cloud does not change much from rapid weakening, weakening, to a neutral state (about 17% of the total area), intensifying and RI TCs do have a larger coverage, of 21.0% and 27.4% of the total area, respectively. The coverage of very deep convective clouds (high clouds) ranges from 16.2% to 27.4% (35.3% to 48.7%) for different intensity change categories. Comparing to the very deep convective clouds, the high clouds have about twice the coverage in all intensity change categories. Therefore, the distribution of precipitation is largely associated with high clouds in all intensity change categories, as shown in Figure 2.

4. Summary and Discussion

Precipitation and convective cloud properties associated with TC intensity and intensity change in the western North Pacific Ocean have been investigated using satellite and best-track data. Because different physical mechanisms are associated with very deep convective clouds with IR BT $<$ 208 K and high clouds with 208 K $<$ IR BT $<$ 240 K, the effects of these two types of clouds on TC intensity changes have been evaluated separately. As storms intensify, the mean rate of rainfall and area of rainfall increase, the mean temperature of high clouds decreases, and the coverage of this type of clouds increases. Such a relationship was not found between TC intensity and very deep convective clouds. Although TC intensity increases with precipitation and with colder high clouds, we are unable to distinguish either precipitation or high clouds as a precursor or a response to TC intensity change. TC 24 h future intensity changes are not found to be directly associated with precipitation and high clouds but are found to be closely related to very deep convection. Intensifying TCs follow the occurrence of colder temperature and larger areal extent for this type of very deep convective clouds. Based upon the 16 year analysis in the western North Pacific, TCs under the conditions that the mean temperature of very deep convective clouds is less than 201 K, and the coverage of this type of cloud is more than 27.4% within a radius of 300 km of the TC center, are more likely going to undergo RI after 24 h.

The relationship between precipitation and TC intensification is generally associated with the release of latent heat in the TC inner core. Stratiform rain in the tropics is produced by convection. This study shows that deep convection is a precursor of RI, and the stratiform rain that was observed in Tao et al. (2017) with TRMM may have been associated with deep convection of too short of a lifetime to be observed by TRMM's snapshots. It is essential to identify different convection processes in the satellite data in order to study the impacts of convection on TC intensification. Very deep convection has been defined as being colder than a given threshold from satellite IR images (e.g., Alvey et al., 2015; Gettelman et al., 2002; Jiang & Tao, 2014). The threshold used to define very deep convection can be arbitrary; here 208 K is used, based on different diurnal cycles of IR BT. The selection should be made according to its underlying physical mechanism, which provides a more reasonable threshold for defining very deep convection and a more reliable precursor to TC intensity change.

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