Environmental Influences on the Intensity and Configuration of Tropical Cyclone Concentric Eyewalls in the Western North Pacific

Xue-Song ZHU and Hui YU

Shanghai Typhoon Institute, China Meteorological Agency, China
Key Laboratory of Numerical Modeling for Tropical Cyclone, China Meteorological Agency, China

(Manuscript received 29 March 2018, in final form 9 October 2018)

Abstract

Using brightness temperature data from passive microwave satellite imagery, this study examines tropical cyclones (TCs) with concentric eyewall (CE) in the western North Pacific between 1997 and 2011. The identified CEs are divided into two types according to the characteristics of the eyewall replacement cycle (ERC) in the microwave imagery: a CE with a typical ERC (T-ERC) and a CE without an ERC (N-ERC). It is indicated that 88% T-ERCs reach peak intensity near (0.2 h after on average) CE formation, whereas 90% N-ERCs reach peak intensity prior to (22.0 h on average) CE formation.

In general, N-ERCs tend to occur when there are strong interactions between the environment and the CE, whereas T-ERCs occur in a relatively quiet environment. The three-dimensional conceptual models of the environmental configurations for both CE types are proposed. Specifically, N-ERCs are accompanied by stronger southwesterly and southeasterly inflows, active low-level trough, and stronger subtropical high (SH) and South Asia high (SAH), compared with T-ERCs. For N-ERCs, the stronger inflows may bring in a large amount of moisture, and the active low-level trough may result in a large vertical wind shear (VWS). The stronger SH and SAH may contribute to changes in the intensity and direction of the VWS for N-ERCs, and hence trigger the development of local convection in the outer eyewall. The asymmetries in the convection of the outer eyewall may weaken the ability to cut off the radial inflow to the inner eyewall. Consequently, N-ERCs fail to finish the ERC and weaken rapidly in intensity, even though the moisture remains sufficient after CE formation.

Keywords concentric eyewall; tropical cyclone; intensity change; environmental configuration

Citation Zhu, X.-S., and H. Yu, 2019: Environmental influences on the intensity and configuration of tropical cyclone concentric eyewalls in the western North Pacific. J. Meteor. Soc. Japan, 97, 153–173, doi:10.2151/jmsj.2019-008.

1. Introduction

Eyewalls and spiral rainbands are the most significant characteristics of tropical cyclones (TCs). A fully-developed TC sometimes forms a new outer eyewall, which is often, but not always, collocated with the secondary wind maximum (Samsury and Zipser 1995). Moreover, the convective activities between the inner and outer eyewalls are suppressed. This double-eyewall structure was first referred to as a concentric eyewall (CE) by Willoughby et al. (1982), and its three-dimensional structure was first reported in detail by Houze et al. (2007) during the Hurricane Rainband and Intensity Change Experiment.

After CE formation, the outer eyewall may cut off the environmental energy that is previously supporting the inner eyewall (Houze et al. 2007; Rozoff et al. 2008). As the outer eyewall develops and migrates inward, the inner eyewall may weaken and even dis-
appear. When the inner eyewall dissipates, the ability to produce or maintain the intense TC warm core might be temporarily lost. However, the TC would reintensify after the inner eyewall is replaced by the outer eyewall (Willoughby et al. 1982; Shapiro and Willoughby 1982; Willoughby et al. 1985). The entire process is known as the eyewall replacement cycle (ERC).

Using aircraft, radar, and satellite data, Chen (1986) proposed that 76 out of 1268 TCs over the western Pacific Ocean between 1949 and 1983 had formed CEs. Based on aircraft and satellite observations, Hawkins and Helveston (2008) indicated that approximately 70% of intense TCs (maximum wind speed $> 50 \text{ m s}^{-1}$) between 1997 and 2006 in the North Atlantic, 50% in the eastern Pacific, and 80% in the western Pacific had CE structures. Moreover, triple eyewall configurations were observed (McNoldy 2004; Tsujino et al. 2017; Zhao et al. 2016) in Hurricane Juliette (2001), and typhoons Bolaven (2012) and Usagi (2013). It is considered that a stronger TC often has a higher probability of having a CE configuration (Kossin and Sitkowski 2009). Kuo et al. (2009) examined western North Pacific TCs between 1997 and 2006 and noted that 57% of category 4 and 72% of category 5 TCs exhibited CE structures during their lifetimes.

It is believed that both internal and external factors play important roles in CE formation. This includes vortex Rossby waves (Montgomery and Kallenbach 1997; Martinez et al. 2010, 2011; Qiu et al. 2010), the local accumulation of potential vorticity (Judt and Chen 2010), the interactions between vortices (Kuo et al. 2004, 2008), the positive feedback between the balanced response to the convective heating and the unbalanced dynamics (Sun et al. 2013), wind expansion (Rozoff et al. 2012; Bell et al. 2012), the local enhancement of the vorticity gradient (Ooyama 1969; Kepert 2001, 2013; Kepert and Wang 2001), the inner-core moisture environment (Wang 2009), and the wind-induced sea surface heat exchange (Nong and Emanuel 2003).

The observed intensity changes of TCs with CE often vary considerably and are sometimes inconsistent with that of a TC undergoing the ERC (Willoughby et al. 1982). For example, Hurricane Gilbert (1988) formed a CE structure 12 h after reaching its maximum intensity, whereas Hurricane Anita (1977) continuously strengthened during the ERC. Based on microwave satellite observations, Kuo et al. (2009) found that only 51% of CE intensity changes over the western North Pacific between 1997 and 2006 agreed with the ERC concept (Willoughby et al. 1982) that a TC strengthened before CE formation but weakened afterwards.

Spiral rainbands of a TC may exhibit various patterns, which in turn have different effects on its intensity (Dvorak 1975; Wang 2009; Xu and Wang 2010). Similarly, different CE structures and evolutions may result in different intensity changes. As passive microwave satellite imagery has become increasingly available in past decades, greater details of CE structures have been revealed. It is evident that CE structures have various modes. Hawkins and Helveston (2008) gave some examples of different CE structures, including the ERC, triple eyewalls, multiple CE formations, ERCs that are interrupted by vertical wind shear (VWS) and land condition, and CE cases that have large outer eyewalls and maintain for long periods. Yang et al. (2013) classified CEs into three types: a CE with ERC, a CE with no ERC, and a CE that was maintained for an extended period. Moreover, CE evolutions may be distinctive in a single TC with multiple CE formations (Zhu et al. 2016). For example, CE structures formed three times (Figs. 1b–d) during the lifetime of Super Typhoon Muifa (2011). A typical ERC, including CE formation, outer eyewall strengthening, and the inner eyewall replacement were only accomplished for the first CE formation of Muifa. The other two CE structures of Muifa ended with no eyewall replacements.

Synoptic and underlying surface conditions have been found to be related to the CE type. Hawkins and Helveston (2008) indicated that most nontypical ERC cases were dominated by strong VWS. Yang et al. (2013) showed that high VWS, low sea surface temperature (SST), and low relative humidity acted to favor nontypical ERC cases, which were defined as the cases in which part of the outer eyewall dissipated within 20 h and that environments with high SST, high relative humidity, and low VWS were favorable to the formation of long-lived (> $20 \text{ h}$) CEs. In addition, Yang et al. (2015) indicated that the long-lived (> $20 \text{ h}$) CE cases and the multiple CE formation cases tended to occur in warm episodes of the El Niño Southern Oscillation (ENSO). It was considered (Tsujino et al. 2017) that sufficient entropy supply from the outer eyewall in the boundary layer may contribute to the longer maintenance of the inner eyewall in the long-lived CE of typhoon Blaven (2012). However, how the three-dimensional configurations of the environmental fields are related to the different CE types is still largely unknown.

The purpose of this study is to examine the intensity
changes and environmental configurations for different CE types, which may be beneficial for forecasting in the CE structural evolution and its intensity change. The data and methodology are described in Section 2. CE classification and related intensity change are studied in a more detailed manner than in previous studies (Kuo et al. 2009; Yang et al. 2013), and are presented in Sections 3 and 4, respectively. Section 5 presents the SST and VWS conditions. Section 6 shows the configurations of the dynamical and thermodynamical synoptic fields for different CE types. The summary and discussion are presented in Section 7.

2. Data and methodology

2.1 Microwave satellite data

Radiance data from passive microwave satellite sensors in the Naval Research Laboratory (NRL) (Hawkins et al. 2001) were used to identify TCs with CE in the western North Pacific between 1997 and 2011. These sensors include the passive Special Sensor Microwave Imager (SSM/I; 85 GHz), the Special Sensor Microwave Imager Sounder (SSMIS; 91 GHz), the passive Tropical Rainfall Measuring Mission (TRMM), Microwave Imager (TMI; 85 GHz), the Advanced Microwave Sounding Unit (AMSU; 89 GHz), and the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E; 89 GHz). The brightness temperature (TB) from the 85, 89, and 91 GHz horizontal polarized channels is more sensitive to convective activities and therefore can be used to identify the TC eyewall structure. In addition, in order to capture the structural details of the inner core (Hawkins and Helveston 2004; Hawkins et al. 2006), these microwave satellite images were reprocessed (Poe 1990) to 1–2 km spatial resolution on the NRL website from the original resolutions of 5, 12.5, 16, 12.5, and 5.4 km for the TMI, SSM/I, AMSU, SSMIS, and AMSR-E, respectively.

Fig. 1. (a) Best-track intensity trace of Typhoon Muifa (2011) from JTWC. The vertical lines labeled b, c, and d represent three CE formation times, and the corresponding microwave images from the NRL are shown in panels (b), (c), and (d), respectively. The microwave satellite observed CE structure first forms at (b) 0411 UTC on July 31, and the TC intensity at 0000 UTC on July 31 is 69 m s⁻¹ according to the best-track data from the JTWC. Similarly, the second and third CEs form at (c) 2017 UTC on August 2 and (d) 1127 UTC on August 4 in the microwave observations, and the nearest TC intensities are 54 m s⁻¹ and 46 m s⁻¹, respectively. The spacing of the latitude-longitude lines is 2°.
CE observations have become increasingly available because of the addition of microwave satellite sensors. In general, more than half of the CEs were observed by microwave satellites for 10 to 22 times per day during 1997 and 2011. One microwave sensor (SSMI) was available in 1997, but there were only five satellite overpasses for a CE per day on average. The TMI was added in 1998, and its average number of overpasses was between 7.7 and 9.3. The AMSU and the AMSR-E were added in 2001 and 2003 respectively. By early 2005, the number of microwave sensors has increased to five (SSM/I, SSMIS, TMI, AMSR-E, and AMSU). As a result, the microwave satellite observation frequency for CE reached more than 10 per day on average after 2000, and has been maintained at approximately 20 since 2006.

Numerous products for TC monitoring from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) are available for identifying CE, for example, the Morphed Integrated Microwave Imagery at CIMSS (MIMIC). MIMIC is a synthetic blend of TC imagery based on the TB measured from microwave satellite instruments (Wimmers and Velden 2007), including SSM/I (85 GHz channel), SSMIS (91 GHz channel), TRMM TMI (85 GHz channel), and Aqua AMSR-E (89 GHz channel). The time intervals between separate TC observations by these microwave satellites are irregular and range from 0.5 h to 25 h. Therefore, MIMIC creates a morphed image sequence with a fixed time step (15 min) to show successive changes in the TC inner-core-induced convection. The MIMIC products have been available since 2004 and can be downloaded from http://tropic.ssec.wisc.edu/real-time/mimic-tc/tc.shtml.

2.2 CE definition

CE structure and its evolution have various patterns, which are more complex than the existing classifications (e.g., classical ERC and non-classical ERC). However, as there is no appropriate objective method for this kind of CE definition and classification, each available microwave overpass for a TC is examined manually, one by one in this study. We adopted a CE definition similar to that of Kuo et al. (2009). First, a quasi-circular convective ring that is separated from the original eyewall is necessary. A ring with TB < 230 K should form at least three-fourths of a complete circle. The three-fourth criterion here is stricter than the two-third criterion of Kuo et al. (2009) and the five-eighth coverage in criterion 4 of Yang et al. (2013). Second, the TB within the moat region located between the original eyewall and the quasi-circular ring (at least three-fourths coverage) should be higher than 250 K. As indicated by Rozoff et al. (2006), the strain-dominated flow in the moat provided an unfavorable environment for deep convection. Therefore, the moat region is echo-free and may only be covered by light convection in the microwave images. In total, 67 CE TCs out of 80 CE cases, including 11 double CE formation1 TCs and one triple CE formation TC (Muifa 2011) were identified. The time when a CE structure initially forms in the microwave imagery is considered to be the CE formation time in this study. The position and intensity at the CE formation time are determined from the nearest 6-h-interval best-track data from the Joint Typhoon Warning Center (JTWC).

As examples, Figs. 1b–d show the microwave images of three CE formations for Typhoon Muifa (2011). The first CE formed at 0411 UTC on July 31 and had an intensity of 69 m s\(^{-1}\) at 0000 UTC on July 31 according to the JTWC best-track data. The duration of the first CE was approximately 41 h. The second CE of Muifa (labeled Muifa-2) was maintained between 2055 UTC on August 2 and 0443 UTC on August 3, and the third CE (labeled Muifa-3) was maintained between 1127 UTC on August 4 and 1753 UTC on August 4.

A total of 13 CE TCs are excluded due to a lack of coverage in the microwave imagery for 12 h in the CE classification. According to Yang et al. (2013), the radius of an outer eyewall could be larger than 300 km. To avoid the landing and terrain effect, a further 12 CE cases were removed due to their landing or their short distance (< 300 km) from land during a 60 h period before or after CE formation. In total, 48 CE TCs, or 55 CE cases in final, are included in this study.

2.3 Reanalysis data

The reanalysis data is from the Climate Forecast System of the National Center for Environmental Prediction (NCEP). The NCEP Climate Forecast System Reanalysis (CFSR) dataset between January 1979 and December 2010 was created from NCEP Climate Forecast System (Saha et al. 2010), and the data after January 2011 was produced from Climate Forecast System version 2 (Saha et al. 2014) as the system was upgraded to this version on March 30, 2011.

---

1Sometimes, a CE evolution cycle, including CE formation, weakening, and dissipation could be observed more than once during a TC’s lifetime. Therefore, double or triple CE formation indicates that there are two or three CE evolution cycles during the lifetime of a single TC.
dataset used in this study has a 0.5° latitude horizontal resolution and 37 vertical levels.

Storm-following coordinates was used with the center determined by the nearest TC position in the JTWC best-track data, and the time frame generally ranges from 60 h before (−60 h) CE formation to 60 h after CE formation (60 h). In the storm-following coordinates, composite analyses were performed for moisture flux and its convergence, horizontal wind, and geopotential height based on the NCEP/CFSR dataset. It should be noted that the TC motion and its circulation have not been subtracted in the following calculation, and the directions of TC motion and VWS were also not considered in the storm-following coordinates.

2.4 SST and VWS

The area-averaged SST and VWS (850–200 hPa) for a TC were calculated in a radius of 500 km surrounding the TC center with the CFSR data. The 850 hPa wind vectors were subtracted from the 200 hPa wind vectors. Note that the TC circulation was not removed in the VWS calculation, and the result may be impacted by the vortex circulation. However, since a TC with CE is more symmetric in vortex, it is expected that the existence of the TC vortex may not have a significant influence on the result.

3. CE Structural classifications

As indicated by Willoughby et al. (1982), a typical ERC includes three distinct phases of CE structural change: formation of the outer eyewall, outer (inner) eyewall contraction (dissipation), and replacement and reorganization. In contrast to the objective method of Yang et al. (2013), we examined each NRL microwave image and MIMIC animation for the identified CE cases manually, one by one. According to the characteristics of the three phases of an ERC, a CE is classified as a typical ERC (T-ERC) case with the microwave imagery. A total of 25 T-ERC cases were identified and the rest of the 30 CEs were recognized as nontypical ERC (N-ERC) cases. Similar to the three phases in the ERC definition, the structural evolution of an N-ERC case can also be divided into three phases, including CE formation, weakening, and dissipation. Based on the characteristics during the three phases in the microwave imagery, the N-ERC cases can be classified as four sub-categories. The definitions are given below, and the examples are shown in Fig. 2.

a. N-ERC-Weakened Pattern (20 Cases)

Both the inner and the outer eyewalls were average-ly organized in radii and convection at CE formation. After that, convection within the inner and outer eye-walls simultaneously decayed during the weakening phase. Finally, a part of the inner and outer eyewalls remained at the end of the dissipation phase. These cases are similar to the shear-stop ERC mode defined by Hawkins and Helveston (2008) and the nontypical ERC cases in Yang et al. (2013).

b. N-ERC-Large Pattern (7 Cases)

The outer eyewall convection was strong and ax-isymmetric and was formed at a relatively large radius when CE formed. Meanwhile, the moat region was obvious with a clear sky. During the weakening phase, the inner eyewall continuously weakened and even faded away, whereas the outer eyewall remained unchanged with no obvious strengthening or contraction. This CE ended with a single large outer eyewall. This pattern includes CE cases with large outer eyewalls and longer durations (Hawkins and Helveston 2008), and the long-lived (more than 20 h) CE cases (Yang et al. 2013).

c. N-ERC-Multiple Pattern (2 Cases)

The inner eyewall convection was relatively strong at the CE formation; meanwhile (or a few hours later), the weak outer eyewall was wrapped by another outer rainband. The outer eyewall continued to weaken in the weakening phase and was replaced by the outermost rainbands in the dissipation phase, whereas the inner eyewall remained unchanged. Aircraft (McNoldy 2004; Sitkowski et al. 2011) and radar (Zhao et al. 2016) observations have determined that some CE TCs (e.g., Hurricanes France 2004 and Ivan 2004) had triple wind maxima. This N-ERC-Multiple pattern might be related to the triple wind maxima configuration: the inner wind maximum corresponds to the inner eyewall, the middle maximum forms when the CE forms, and the outer maximum is related to spiral rainbands that evolve into the outer eyewall.

d. N-ERC-Degenerated Pattern (1 Case)

When a CE forms, the inner and outer eyewalls are formed at large radii and are not completely closed. A few hours later, the CE structure degenerated directly into spiral rainbands with no obvious weakening phase. This N-ERC-Degenerated Pattern was only observed during the third CE evolution of Typhoon Muifa (2011). This pattern may be distinct from the classical CE structure and has rarely been mentioned.
Fig. 2. Microwave images of CE formation, weakening, and dissipation for examples of the N-ERC-Weakened, N-ERC-Large, N-ERC-Multiple, and N-ERC-Degenerated patterns. The corresponding CE formation times and TC intensity are shown at the top of each panel. The spacing of the latitude-longitude lines is 2°.
in previous studies.

4. Intensity changes

4.1 Relationship between CE formation and peak intensity time for individual CEs

Time difference (DT) is defined as the difference between the CE formation time and the peak intensity time. The peak intensity is the peak sustained winds in the JTWC best-track. Therefore, a negative value of DT indicates that the CE formation occurred earlier than the peak intensity, whereas a positive DT indicates a later CE formation time. For a case that has secondary peak intensity, DT was calculated as the time from the CE formation to the nearest peak intensity.

On average, DTs of the T-ERC and N-ERC cases are −2.6 h and 17.1 h, respectively. It is shown in Fig. 3a that for the T-ERC cases, half of the DTs are between 4 h and −8 h, and approximately 75% of the DTs are between −10 h and 10 h. The minimum DT is −49 h, which is recognized as an extreme outlier. While in the N-ERC cases, DTs cover a wider range than in the T-ERC cases. More than 75% of N-ERC cases have positive values in DT, implying that in most N-ERC cases, CE forms after the TC has reached its peak intensity. T-test shows that the difference in DT between the T-ERC and N-ERC cases is statistically significant at a 95% confidence level. In other words, the two CE groups are different in the CE formation time relative to the peak intensity time. To be specific, the T-ERC cases tend to have their peak intensity around the time of CE formation, whereas the N-ERC cases often intensify to peak intensity prior to CE formation.

Time gap between the microwave satellite observations is the main factor that affects the accuracy of the CE formation time and the DT. However, for the running mode of the microwave satellite, the gaps from one microwave sensor for a CE are irregular. Therefore, the averaged time gap for a CE per day was calculated by dividing the averaged microwave observation frequency (as discussed in Section 2.1) over 24 h. It is shown that the averaged time gaps for all the T-ERC and N-ERC cases (Fig. 3b) range from 0.9 h to 4.8 h and more than 50% of the gaps are between 1.2 h and 2.7 h. Specifically, the averaged time gaps are from 1.0 h to 3.1 h for the T-ERC cases, except for one extreme value (4.8 h), whereas those of the N-ERC cases are from 0.9 h to 4.8 h. As mentioned in Section 2.2, CEs with missing coverage in the microwave imagery for 12 h or more are excluded in this study. Therefore, the errors in the CE formation time from the microwave satellite observation are within 6 h (+/− 6 h), with the tendency being 0.5 h to 1.6 h for the T-ERC cases and 0.5 h to 2.4 h for the N-ERC cases. Because the maximum winds in the best-track are at 6-h-interval, the errors in DT are basically 3 h more than those in the CE formation time.

4.2 Temporal evolution of mean intensity around CE formation

The mean intensities of the T-ERC and N-ERC cases...
cases are calculated from 60 h before CE formation to 60 h after CE formation (Fig. 4). It shows that the mean intensity of the T-ERC cases is weaker than that of the N-ERC cases before CE formation, but it increases rapidly to the peak intensity (63 m s\(^{-1}\)) at CE formation, and subsequently maintains a stronger intensity than that of the N-ERC cases. Even though the N-ERC cases have a stronger mean intensity in the beginning, they dropped quickly in intensity after reaching the peak intensity (61 m s\(^{-1}\)) at CE formation. Besides, out of the 25 T-ERC cases, 22 reached the peak intensity (−0.2 h on average in DT) around CE formation except for Yagi (2006), Nabi (2005), and Danas (2001). They continuously intensified until approximately 30 h after CE formation (Fig. 4a), and their DTs are −29, −30, and −49 h (Fig. 3a), respectively. While 27 of the 30 N-ERC cases reached the peak intensity (22.0 h on average in DT) before CE formation, except for Amber (1997), Dianmu-2 (2004; the second CE of Diammu), and Chaba-2 (2004; the second CE of Chaba). They reintensified to a secondary peak intensity after CE formation, and the corresponding DTs are −25, −14, and −20 h, respectively.

Typhoon Yagi (2006) experienced two CE formations and the second CE formation may contribute to the continuous intensification after the first CE formation. The duration of the first CE of Yagi was between 0920 UTC and 2153 UTC on September 20. The second CE formed at 0041 UTC on September 22, 39 h after the first CE appeared in the microwave imagery. Yagi continued to intensify until it reached its maximum intensity 27 h after the first CE formation (Fig. 4a).

The intensities of Nabi (2005) and Danas (2001) are 41 m s\(^{-1}\) and 46 m s\(^{-1}\) respectively at CE formation, much weaker than the mean T-ERC intensity (64

Fig. 4. Intensity (m s\(^{-1}\)) time series for (a) composite T-ERC (25 cases), Danas (2001), Nabi (2005), and Yagi (2006), and (b) composite N-ERC (30 cases), Amber (1997), Dianmu-2 (2004), and Chaba-2 (2004). The composite is calculated relative to the CE formation time (Time = 0).

Fig. 5. Time series of the area-averaged (a) SST (°C) and (b) 850–200 hPa VWS (m s\(^{-1}\)) within 500 km from the TC center of the T-ERC (red) and N-ERC (blue) cases. Those for Nabi (2005), Dianmu-2 (2004), Amber (1997), and Chaba-2 (2004) are also plotted with dashed lines on the charts. The average is calculated relative to the CE formation time.
m s$^{-1}$). To understand the possible reason for Nabi’s continuous intensification, the average SST and 850–200 hPa VWS within a 500 km radius of the TC center were calculated. It is obvious that Nabi has a higher SST and a lower VWS than the mean values of the T-ERC cases (Figs. 5a, b), both of which are favorable conditions for the intensification of a TC.

Two vortices are located to the southwest of Danas (2001)’s core 30 h before CE formation (Fig. 6a), one of which is stronger in intensity but smaller in size compared with the TC core. These vortices are usually related to the convective activities in the outer rainbands (Didlake and Houze 2009; Powell 1990; Montgomery et al. 2006) and their interactions with the TC core can result in a CE structure (Kuo et al. 2004, 2008). It is evident from the vorticity evolution (not shown) that the two vortices are absorbed into the TC core later on and that the TC completed its axisymmetrization in vorticity on August 5 (Fig. 6c) when the CE formed (Fig. 6d). After the CE forma-

Fig. 6. Low-level (850 hPa) vorticity ($10^{-4}$ s$^{-1}$) of Typhoon Danas (2001) in the storm-following coordinates (degrees from center) at (a) −30 h and (c) 0 h. The nearest microwave observations at 2353 UTC on September 3 and 0456 UTC on September 5 are shown in panels (b) and (d), respectively. The spacing of the latitude-longitude lines in the satellite images is 2°.
tion, a tight and small TC core was maintained until August 8.

All the three N-ERC exception cases, Amber (1997), Dianmu-2, and Chaba-2, have large and long-lived outer eyewalls. The CE of Amber formed at 1126 UTC on August 26 and maintained for over 26 h. The CE durations in Dianmu-2 and Chaba-2 are 43 h and 44 h, respectively. Both the SST and VWS favor the development and intensification of the three cases, with the SST (VWS) higher (lower) than the mean of the N-ERC cases after CE formation (Figs. 5a, b).

The N-ERC-Large pattern in this study is similar to the long-lived (> 20 h) CE case in Yang et al. (2013). They proposed that the long-lived CE case had a lower VWS and higher SST than the typical ERC type, which are consistent with the environmental conditions of the N-ERC-Large pattern.

Compared with the first CE of Dianmu, Dianmu-2 has a larger outer eyewall radius and its CE structure is maintained for a longer period. However, as the CE decays in the northern portion, strong convection forms in the southeastern part of Dianmu’s circulation (Fig. 7d), which results in an asymmetric vorticity (Fig. 7c). The dissipation of the CE structure of Dianmu-2 may be induced by the approaching subtropical high from the southeast (not shown).

In conclusion, 22 out of 25 T-ERC cases reached their peak intensity near the CE formation time, and 27 out of 30 N-ERC cases were in their weakening stage at the CE formation time. The 27 N-ERC cases include 19 N-ERC-Weakened, five N-ERC-Large, two N-ERC-Multiple, and one N-ERC-Degenerated case. Because each of the last three patterns has very few samples, only the 19 N-ERC-Weakened cases will be studied in the following sections for comparison with the 22 T-ERC cases.

The ERC experiences three distinct phases of intensity change: intensification, weakening, and reintensification (Willoughby et al. 1982). Sitkowski et al. (2011) validated the intensity changes of the ERC based on aircraft measurements of the inner-core intensity and wind structure for 24 CEs in the Atlantic between 1997 and 2007. The intensity changes around CE formation of the T-ERC cases in the present study are consistent with that of the ERC (Willoughby et al. 1982) and the results of Sitkowski et al. (2011).

Willoughby et al. (1982) indicated that a TC would reintensify after the eyewall replacement and the amount of reintensification may depend on the situation. In the present study, there are 11 out of the 25 T-ERC cases that exhibit the reintensification, and the other 10 T-ERC cases maintain the intensity after the eyewall replacement.

The N-ERC cases in the present study are distinctive in DT from the ERC indicated in Willoughby et al. (1982). However, the N-ERC cases were mentioned in the observations of Sitkowski et al. (2011), who found that 7 of their 24 CE cases did not contain an intensification phase because they were at peak intensity before the outer wind maxima formed (DT > 0). These cases are very similar to the N-ERC cases in the present study.

5. **SST and VWS**

Warm SST and low VWS are generally recognized to be favorable environmental conditions for CE formation and were calculated and analyzed in the T-ERC and N-ERC cases.

The area-averaged SST of the T-ERC cases is generally higher than that of the N-ERC cases, which is consistent with the result of Yang et al. (2013). The decreasing trends in SST are clear for both the T-ERC and N-ERC cases, with the decreasing rate being slower for the T-ERC cases than that for the N-ERC cases. The SST still remains above 26°C at 60 h after CE formation for the T-ERC cases, but drops rapidly to below 26°C just 24 h after CE formation for the N-ERC cases. It has been shown in Fig. 5b that the area-averaged VWS is lower for the T-ERC cases than for the N-ERC cases, which is consistent with the results of previous studies (e.g., Yang et al. 2013). The VWSs of both the T-ERC and N-ERC cases decreased from −60 h to a value of ~ 5 m s$^{-1}$ at CE formation and then increased. The differences in VWS between the two CE types are minimal prior to CE formation compared with those after CE formation. Furthermore, the VWS of the T-ERC cases remained below 7.0 m s$^{-1}$ between −60 h and 60 h, which is obviously less than that of the N-ERC cases, in particular, after CE formation time. On the other hand, the VWS increased rapidly to > 10 m s$^{-1}$ by 30 h after CE formation for the N-ERC cases.

6. **Environmental configurations**

6.1 **Moisture transport and flux convergence**

Figure 8 highlights the composite low-level (850 hPa) wind, geopotential height, and moisture flux for the T-ERC and N-ERC cases. It is shown that both the T-ERC and N-ERC cases have two low-level transport channels. One is the west channel lying in the southwest flow of a northern hemisphere low-pressure system. The other is the east channel associated with the easterly flow of a northern hemisphere high-pressure system. The composite moisture flux...
averaged within a 500 km radius from TC center is strong in the lower atmosphere for both CE types (Figs. 9a, b). The largest flux at 850 hPa is confined to the east of the TC center (Figs. 9c, d), where the moisture flux is stronger and strengthens more rapidly for the N-ERC cases.

Nong and Emanuel (2003) indicated that the simulated CE formation in their simple TC model was very sensitive to the initiation of environmental moisture. Wang (2009) also showed that the deep moist layer in the near-core environment might modify the heating/cooling rate in the outer rainbands and favor CE formation. Moisture input could enhance latent heat release, which can increase the vertical velocity. Dynamically, the vertical updraft acceleration could in turn enhance the low-level convergence to strengthen the vortex. Consequently, in contrast to the T-ERC type, the strengthening of the peak intensity prior to CE formation for the N-ERC type may result from a more moist environment.

Fig. 7. As in Fig. 6 but for Typhoon Dianmu (2004) at (a) 0 h and (c) 42 h. The nearest microwave observations at 2136 UTC on June 17 and 1656 UTC on June 19 are shown in panels (b) and (d), respectively. The spacing of the latitude-longitude lines in the satellite images is 2°.
The maximum of the low-level (850 hPa) moisture flux convergence for the T-ERC cases is consistently smaller than that for the N-ERC cases during −60 and 60 h (Fig. 10a). On average, the maximum of the moisture flux convergence for the T-ERC cases is approximately $64 \times 10^{-6}$ g (hPa cm$^2$ s)$^{-1}$, which is much weaker than the $94 \times 10^{-6}$ g (hPa cm$^2$ s)$^{-1}$ for the N-ERC cases. The time series shows that the convergence maximum of the T-ERC cases increases from −12 h to 24 h and then decreases, whereas that of the N-ERC cases fluctuate prior to CE formation but increases continuously after CE formation (Fig. 10a). Moreover, the locations of the convergence maximum for the T-ERC cases are in the southwest quadrant of the storm-following coordinates both before and after CE formation, but shift a little bit radially inward after CE formation. However, most of the convergence maxima for the N-ERC cases shifted from the southwest to the northeast quadrant and farther away from the TC center after CE formation (Fig. 10b). Such shifts in azimuth and radius for the N-ERC cases may be related to the activities of the local convection in the northeast quadrant within the outer rainbands.

The shifts in radius of the convergence maximum for the N-ERC cases (Fig. 10b) may have an effect on its sharp weakening in intensity (Fig. 4b), even though the moisture remains sufficient after CE formation (Figs. 9b, d). These convergence maxima are highly correlated with the strong convective activities induced by atmospheric heating. Owing to hydrostatic adjustments, diabatic heating would decrease the surface pressure at the lower level. However, the decrease in surface pressure due to the heating in the outer rainbands may be distinctive at different radial distance. As indicated by Wang (2009), the decrease is significant on the inward side of the rainbands where the inertial stability is generally strong, while it is relatively small outside the rainbands, where the inertial stability is weak and the heating is almost lost to gravity wave radiation. As a result, heating in the...
Fig. 9. Height-time diagrams of the composite moisture flux (g (hPa cm s)^{-1}) averaged within a 500 km radius from TC center for the (a) T-ERC and (b) N-ERC cases. Time-azimuth diagrams of the composite low-level (850 hPa) moisture flux averaged within a 500 km radius from TC center for the (c) T-ERC and (d) N-ERC cases. The “N”, “E”, “S”, and “W” indicate north, east, south and west quadrants in the storm-following coordinates.

Fig. 10. (a) Temporal and (b) spatial evolutions of the maximum convergence of the low-level (850 hPa) moisture flux (10^{-6} g (hPa cm^2 s)^{-1}) for the T-ERC and N-ERC cases. The gray circles in (b) are 150 km and 250 km from the TC center. For the T-ERC cases, the solid triangles and circles represent the maximum convergence no later than and after CE formation time, respectively, while the hollow triangles and circles are those for the N-ERC cases.
outer rainbands/eyewall may reduce the horizontal pressure gradient across the radius of maximum wind, and thus, the TC may weaken in terms of the maximum tangential wind.

The shifts in azimuth (from southwest to northeast quadrant) of the composite convergence maximum for the N-ERC cases (Fig. 10b) may have two explanations. The first is that these shifts may be induced by changes in the environmental VWS. Using ten years of TRMM data, Hence and Houze (2012) analyzed the vertical structure of TCs undergoing ERC and showed that the convective processes within the CEs were highly resistant to environmental VWS and that the left-of-shear sides were observed to favor intensive convection. The calculations in this study confirmed the environmental VWS changes in strength (Fig. 5b) and direction (from southeast-to-northwest to northwest-to-southeast; not shown) after CE formation for the N-ERC cases. Yang et al. (2013) showed that the non-ERC cases experienced larger VWS. Hawkins and Helveston (2008) also introduced a nontypical ERC mode, which may be related to the strong VWS. The definitions of the non-ERC case by Yang et al. (2013) and the nontypical ERC by Hawkins and Helveston (2008) are similar to that of our N-ERC cases. The second explanation is that the shifts are partially due to the changes in the direction of storm motion. Corbosiero and Molinari (2003) found that violent convection (e.g., lightning) in TCs occurred predominantly in the right-front quadrant of the TC motion. The locations of CE formation and TC motion from −12 h to 12 h show that at least half of the N-ERC cases shift clockwise in moving direction after CE formation, while little has been changed for the T-ERC cases (Fig. 11). Accordingly, the convergence maximum for the N-ERC cases change to northeast quadrant (Fig. 10b). It was considered (Corbosiero and Molinari 2003; Chen et al. 2006) that VWS and storm motion are two of the most important factors contributing to convection asymmetries in TCs, but the dominant factor may depend on the situation.

6.2 Synoptic fields of the wind and geopotential height

To evaluate the three-dimensional configurations of the environmental fields for the T-ERC and N-ERC cases, the composites, as well as the differences (N-ERC minus T-ERC) in the horizontal wind and geopotential height were calculated in the storm-following coordinates. The analyses at 850 hPa, 500 hPa, and 100 hPa are given as examples of the low, middle, and upper levels, which are shown in Figs. 12–14, respectively.

Three low-level (850 hPa) regions with salient
and long-duration significant difference between the T-ERC and N-ERC cases, labeled D1, D2, and D3, can be identified (Fig. 12). D1 forms in the southwest quadrant of the storm-following coordinates. The low-level southwesterly flow within D1 indicates greater water vapor inflow for the N-ERC cases, as discussed in Section 6.1 (Fig. 9). D2 initiates in the east quadrant at −36 h and strengthens after −12 h. Region D3 appears in the northwest quadrant at −54 h and gradually moves 20° eastward from −36 h (Fig. 12a) to −12 h (Fig. 12b). Finally, D3 remains stationary after −12 h forming a dipole structure together with the southern D2 (Fig. 12c). The cyclonic circulation within D3 is noticeable at the lower levels and represents the difference in the short-wave trough, which may be accompanied by the westerlies in the middle latitudes. The cyclonic circulation in D3 indicates that the low-level trough is more active for the N-ERC than for the T-ERC cases, which could partially explain the larger VWS for the N-ERC cases (Fig. 5b).

The middle-level (500 hPa) significant differences within region D2 begin to appear at −36 h and become most significant at −24 h (Fig. 13c). The composite indicates that the subtropical high (SH) as represented by the coverage of the 5880 gpm contour is moderate in intensity and lies approximately 600 km to the east of the TC center at CE formation (Fig. 13a), compared with a stronger SH (5900 gpm) at a shorter distance.

---

**Fig. 12.** Low-level (850 hPa) composite differences of the horizontal wind (vectors; m s⁻¹) and the geopotential height (contours; gpm) between the N-ERC and T-ERC cases (N-ERC minus T-ERC) at (a) −36 h, (b) −12 h, and (c) 0 h in the storm-following coordinates (degrees from center). The contour intervals are 10 gpm. The gray and black shaded regions are areas with significant differences (95% confidence) in geopotential height and horizontal wind, respectively. The interested regions are included in the black rectangles labeled as D1, D2, and D3.
(500 km) for the N-ERC cases (Fig. 13b). Therefore, the SH is stronger for the N-ERC cases than for the T-ERC cases, which is evident in D2 (Fig. 13c). The stronger SH for the N-ERC cases may partially be the result of being located further north on average (Fig. 8b).

The upper-level (100 hPa) significant differences within region D4 maintain from −60 h to 60 h. An example of the significant difference within D4 at CE formation time is shown in Fig. 14c with its center located approximately 25°N 90°E on average. Figures 14a, b are the composites for the T-ERC and N-ERC cases at CE formation, respectively. The 16600 gpm at 100 hPa is often used as a reference height (Zhang et al. 2000; Zhou et al. 2006) to evaluate the strength of the South Asia high (SAH). It appears that the SAH is stronger for the N-ERC cases, which is evident from the anti-cycloic circulation within D4 in Fig. 14c.

The combination of environmental differences in the low-level southwest flow, low-level short-wave trough, SH, and SAH may contribute to the different CE evolutions between the T-ERC and N-ERC cases.

The significant differences at the middle-level within D2 may be partially related to those at the upper level within D4. Note that the significant difference in geopotential height within D4 at 100 hPa deepens and moves eastward from −30 h (Fig. 15a) to −24 h (Fig. 15b). Consequently, the relative circula-
tions are induced below 100 hPa, and eventually the significant difference in geopotential height within D2 at 500 hPa strengthens and extends to the west (Fig. 13c). Therefore, the results in Fig. 15 confirm the synoptic perspective that the strengthening and eastward approach of the SAH would attract a westward extension of the SH.

7. Summary and discussion

Based on the brightness temperature data from the SSM/I, SSMIS, TMI, AMSU, and AMSR-E micro-wave sensors, as well as the MIMIC animations, subjective methods of CE structure identification and its structural classification were used to examine TCs in the western North Pacific between 1997 and 2011. A total of 67 CE TCs (out of 80 CE cases), including 11 multiple CE formation cases, were identified. After removing the cases that lack coverage in the microwave imagery for 12 h in CE classification and the cases that are close (< 300 km) to land during the 60 h period before and after CE formation, 48 CE TCs, or 55 CE cases remained. A total of 25 CE cases with the T-ERC were identified, which resembled the classic ERC cases. The other 30 CE cases were N-ERC and can be further divided into four categories based on the phases of CE structure in the microwave imagery: N-ERC-Weakened, N-ERC-Large, N-ERC-Multiple, and N-ERC-Degenerated patterns. The intensity,
SST, VWS, moisture condition, horizontal wind, and geopotential height were analyzed for the T-ERC and N-ERC cases. The conclusions are as follows.

T-test showed that the two CE types were significantly different in intensity changes. For the T-ERC cases, 22 out of 25 (88%) reached peak intensity near (0.2 h after on average) CE formation, whereas 27 out of 30 (90%) N-ERC cases reached peak intensity before (22.0 h on average) CE formation.

Higher SST and lower VWS were observed within a radius of 500 km for the T-ERC cases, which may be related to their farther southward positions at CE formation.

The configurations of the horizontal wind and geopotential height are significantly different between the T-ERC and N-ERC cases, and associated three-dimensional conceptual models are proposed in Figs. 16a, and 16b, respectively. In general, the southwest flow and the middle-latitude trough at low-level (850 hPa), the SH at the middle-level (500 hPa), and the SAH at the upper level (100 hPa) for the T-ERC cases (Fig. 16a) are weaker than those for the N-ERC cases (Fig. 16b). For both the T-ERC and N-ERC types, two main low-level moisture inflows from the southeast and southwest are established and strong moisture fluxes appear within the eastern TC circulation. However, for the N-ERC cases, the southwesterly flow and SH are stronger; therefore, the environment is more moist in general. Strong convective activities are observed in the northeast quadrant within the outer eyewall for the N-ERC cases (Fig. 16b), whereas moderate convection develops in the southwest for the T-ERC cases (Fig. 16a). For the N-ERC cases, the low-level trough is more active in the middle latitude (Fig. 16b), and the middle-level SH is significantly stronger (Fig. 16b) compared with those for the T-ERC cases (Fig. 16a). Corresponding to the configuration of the SH at the middle-level for the N-ERC cases, the SAH is the most notable system at the upper level and is stronger and eastward-extending (Fig. 16b).

The dissipation of the inner eyewall during a typical ERC was thought to be related to the effects of the outer eyewall (Rozoff et al. 2008) and the moat (Shapiro and Willoughby 1982). Zhou and Wang (2011) emphasized the large negative radial advection of the axisymmetric equivalent potential temperature toward the inner eyewall. Finally, sufficient mixing of the enhanced potential vorticity in the CEs led to the formation of an annular TC (Zhou and Wang 2009). In addition to the typical ERC, we examined nontypical ERC evolution for the N-ERC-Weakened cases in this study. As the convection generates and develops locally within the outer eyewall, the outer eyewall be-
comes asymmetric. The ability of the outer eyewall to intercept the boundary layer inflow supply of entropy to the inner eyewall may be weakened. Consequently, the inner eyewall may not be replaced by the outer eyewall; instead, it (partially) remains for the net import of moist entropy. Note that the axisymmetrization of the outer eyewall is essential for the ERC and is often evident in the microwave imagery and MIMIC animations. Most of the outer eyewall must complete its axisymmetrization before strengthening and broadening inward.

Hawkins and Helveston (2008) introduced a CE case that was interrupted by strong VWS during the ERC. However, they did not mention whether the “interruption” is predictable due to the environment conditions or not. In this study, we presented two different CE types with distinctive environmental configurations. Given that the TC intensity changes are distinct for the two CE types, forecasters can benefit from utilizing information about current environmental configurations to forecast future intensity fluctuations.

Acknowledgments

We would like to thank Johnny Chan for his valuable suggestions that benefited this work. This research was supported and funded by the National Natural Science Foundation of China under Grant
References

Bell, M. M., M. T. Montgomery, and W.-C. Lee, 2012: An axisymmetric view of concentric eyewall evolution in Hurricane Rita (2005). J. Atmos. Sci., 69, 2414–2432.

Chen, S., 1986: Preliminary analysis on the structure and intensity of concentric double-eye typhoons. Adv. Atmos. Sci., 4, 113–118.

Chen, S. S., J. A. Knaff, and F. D. Marks, Jr., 2006: Effects of vertical wind shear and storm motion on tropical cyclone rainfall asymmetries deduced from TRMM. Mon. Wea. Rev., 134, 3190–3208.

Corbosiero, K. L., and J. Molinari, 2003: The relationship between storm motion, vertical wind shear, and convective asymmetries in tropical cyclones. J. Atmos. Sci., 60, 366–376.

Didlake, A. C., Jr., and R. A. Houze, Jr., 2009: Convective-scale downdrafts in the principal rainbow of Hurricane Katrina (2005). Mon. Wea. Rev., 137, 3269–3293.

Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. Mon. Wea. Rev., 103, 420–430.

Hawkins, J. D., and M. Helveston, 2004: Tropical cyclone multiple eyewall characteristics. 26th Conf. on Hurricane and Tropical Meteorology. Miami, FL, Amer. Meteor. Soc., P1.7. [Available at https://ams.confex.com/ams/26HURR/techprogram/paper_76084.htm.]

Hawkins, J. D., and M. Helveston, 2008: Tropical cyclone multiple eyewall characteristics. 28th Conf. on Hurricane and Tropical Meteorology. Orlando, FL, Amer. Meteor. Soc., 14B.1. [Available at https://ams.confex.com/ams/28Hurricanes/techprogram/paper_138300.htm.]

Hawkins, J. D., T. F. Lee, J. Turk, C. Sampson, J. Kent, and K. Richardson, 2001: Real-time internet distribution of satellite products for tropical cyclone reconnaissance. Bull. Amer. Meteor. Soc., 82, 567–578.

Hawkins, J. D., M. Helveston, T. F. Lee, J. J. Turk, K. Richardson, C. Sampson, J. Kent, and R. Wade, 2006: Tropical cyclone multiple eyewall configurations. Preprints. 27th Conf. on Hurricane and Tropical Meteorology. Monterey, CA, Amer. Meteor. Soc., 6B.1. [Available at http://ams.confex.com/ams/27Hurricanes/techprogram/paper_108864.htm.]

Hence, D. A., and R. A. Houze, Jr., 2012: Vertical structure of tropical cyclones with concentric eyewalls as seen by the TRMM precipitation radar. J. Atmos. Sci., 69, 1021–1036.

Houze, R. A., Jr., S. S. Chen, B. F. Smull, W.-C. Lee, and M. M. Bell, 2007: Hurricane intensity and eyewall replacement. Science, 315, 1235–1239.

Judt, F., and S. S. Chen, 2010: Convectively generated potential vorticity in rainbands and formation of the secondary eyewall in Hurricane Rita of 2005. J. Atmos. Sci., 67, 3581–3599.

Kepert, J. D., 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part I: Linear theory. J. Atmos. Sci., 58, 2469–2484.

Kepert, J. D., 2013: How does the boundary layer contribute to eyewall replacement cycles in axisymmetric tropical cyclones? J. Atmos. Sci., 70, 2808–2830.

Kepert, J. D., and Y. Wang, 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part II: Nonlinear enhancement. J. Atmos. Sci., 58, 2485–2501.

Kossin, J. P., and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. Mon. Wea. Rev., 137, 876–892.

Kuo, H.-C., L.-Y. Lin, C.-P. Chang, and R. T. Williams, 2004: The formation of concentric vorticity structures in typhoons. J. Atmos. Sci., 61, 2722–2734.

Kuo, H.-C., W. H. Schubert, C.-L. Tsai, and Y.-F. Kuo, 2008: Vortex interactions and the barotropic aspects of concentric eyewall formation. Mon. Wea. Rev., 136, 5183–5198.

Kuo, H.-C., C.-P. Chang, Y.-T. Yang, and H.-J. Jiang, 2009: Western North Pacific typhoons with concentric eyewalls. Mon. Wea. Rev., 137, 3758–3770.

Martinez, Y., G. Brunet, and M. K. Yau, 2010: On the dynamics of two-dimensional hurricane-like concentric rings vortex formation. J. Atmos. Sci., 67, 3253–3268.

Martinez, Y., G. Brunet, M. K. Yau, and X. Wang, 2011: On the dynamics of concentric eyewall genesis: Spacetime empirical normal modes diagnosis. J. Atmos. Sci., 68, 457–476.

McNoldy, B. D., 2004: Triple eyewall in Hurricane Juliette. Bull. Amer. Meteor. Soc., 85, 1663–1666.

Montgomery, M. T., and R. J. Kallenbach, 1997: A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricane. Quart. J. Roy. Meteor. Soc., 123, 435–465.

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. B. Saunders, 2006: A vertical hot tower route to tropical cyclogenesis. J. Atmos. Sci., 63, 355–386.

Nong, S., and K. Emanuel, 2003: A numerical study of the genesis of concentric eyewalls in hurricanes. Quart. J. Roy. Meteor. Soc., 129, 3323–3338.

Ooyama, K., 1969: Numerical simulation of the life cycle of tropical cyclones. J. Atmos. Sci., 26, 3–40.

Poe, G. A., 1990: Optimum interpolation of imaging microwave radiometer data. IEEE Trans. Geosci. Remote Sens., 28, 800–810.

Powell, M. D., 1990: Boundary layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale
rainfall and kinematic structure. *Mon. Wea. Rev.*, 118, 891–917.

Qiu, X., Z.-M. Tan, and Q. Xiao, 2010: The role of vortex Rossby waves in hurricane secondary eyewall formation. *Mon. Wea. Rev.*, 138, 2092–2109.

Rozoff, C. M., W. H. Schubert, B. D. McNoldy, and J. P. Kossin, 2006: Rapid filamentation zones in intense tropical cyclones. *J. Atmos. Sci.*, 63, 325–340.

Rozoff, C. M., W. H. Schubert, and J. P. Kossin, 2008: Some dynamical aspects of tropical cyclone concentric eyewalls. *Quart. J. Roy. Meteor. Soc.*, 134, 583–593.

Rozoff, C. M., D. S. Nolan, J. P. Kossin, F. Zhang, and J. Fang, 2012: The roles of an expanding wind field and inertial stability in tropical cyclone secondary eyewall formation. *J. Atmos. Sci.*, 69, 2621–2643.

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H.-Y. Chuang, H.-M. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J.-K. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C.-Z. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, R. W. Reynolds, G. Rutledge, and M. Goldberg, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.*, 91, 1015–1057.

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y.-T. Hou, H.-Y. Chuang, M. Iredell, M. Ek, J. Meng, R. Yang, M. P. Mendez, H. Van Den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System version 2. *J. Climate*, 27, 2185–2208.

Samsury, C. E., and E. J. Zipser, 1995: Secondary wind maxima in hurricanes: Airflow and relationship to rainbands. *Mon. Wea. Rev.*, 123, 3502–3517.

Shapiro, L. J., and H. E. Willoughby, 1982: The response of balanced hurricanes to local sources of heat and momentum. *J. Atmos. Sci.*, 39, 378–394.

Sitkowski, M., J. P. Kossin, and C. M. Rozoff, 2011: Intensity and structure changes during hurricane eyewall replacement cycles. *Mon. Wea. Rev.*, 139, 3829–3847.

Sun, Y. Q., Y. Jiang, B. Tan, and F. Zhang, 2013: The governing dynamics of the secondary eyewall formation of Typhoon Sinlaku (2008). *J. Atmos. Sci.*, 70, 3818–3837.

Tsujino, S., K. Tsuboki, and H.-C. Kuo, 2017: Structure and maintenance mechanism of long-lived concentric eyewalls associated with simulated Typhoon Bolaven (2012). *J. Atmos. Sci.*, 74, 3609–3634.

Wang, Y., 2009: How do outer spiral rainbands affect tropical cyclone structure and intensity? *J. Atmos. Sci.*, 66, 1250–1273.

Willoughby, H. E., J. A. Clos, and M. G. Schoreibah, 1982: Concentric eye walls, secondary wind maxima, and the evolution of the hurricane vortex. *J. Atmos. Sci.*, 39, 395–411.

Willoughby, H. E., D. P. Jorgensen, R. A. Black, and S. L. Rosenthal, 1985: Project STORMFURY: A scientific chronicle 1962–1983. *Bull. Amer. Meteor. Soc.*, 66, 505–514.

Wimmers, A. J., and C. S. Velden, 2007: MIMIC: A new approach to visualizing satellite microwave imagery of tropical cyclones. *Bull. Amer. Meteor. Soc.*, 88, 1187–1196.

Xu, J., and Y. Wang, 2010: Sensitivity of tropical cyclone inner-core size and intensity to the radial distribution of surface entropy flux. *J. Atmos. Sci.*, 67, 1831–1852.

Yang, Y.-T., H.-C. Kuo, E. A. Hendricks, and M. S. Peng, 2013: Structural and intensity changes of concentric eyewall typhoons in the western North Pacific basin. *Mon. Wea. Rev.*, 141, 2623–2648.

Yang, Y.-T., H.-C. Kuo, E. A. Hendricks, Y.-C. Liu, and M. S. Peng, 2015: Relationship between typhoons with concentric eyewalls and ENSO in the western North Pacific basin. *J. Climate*, 28, 3612–3623.

Zhang, Q., Y. Qian, and X. Zhang, 2000: Interannual and interdecadal variations of the South Asia high. *Chinese J. Atmos. Sci.*, 24, 67–78.

Zhao, K., Q. Lin, W.-C. Lee, Y.-Q. Sun, and F. Zhang, 2016: Doppler radar analysis of triple eyewalls in Typhoon Usagi (2013). *Bull. Amer. Meteor. Soc.*, 97, 25–30.

Zhou, N., Y. Yu, and Y. Qian, 2006: Simulations of the 100-hPa South Asian high and precipitation over East Asia with IPCC coupled GCMs. *Adv. Atmos. Sci.*, 23, 375–390.

Zhou, X., and B. Wang, 2009: From concentric eyewall to annular hurricane: A numerical study with the cloud-resolved WRF model. *Geophys. Res. Lett.*, 36, L03802, doi:10.1029/2008GL036854.

Zhou, X., and B. Wang, 2011: Mechanism of concentric eyewall replacement cycles and associated intensity change. *J. Atmos. Sci.*, 68, 972–988.

Zhu, X.-S., H. Yu, Z.-C. Mao, M. Xu, and J.-G. Tan, 2016: Satellite-based analysis on the concentric eyewall replacement cycles of super Typhoon Muifa (1109). *J. Trop. Meteor.*, 22, 330–340.