Eyewall Evolution of Typhoons Crossing the Philippines and Taiwan: An Observational Study

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Abstract

This study examines the statistical characteristics of the eyewall evolution induced by the landfall process and terrain interaction over Luzon Island of the Philippines and Taiwan. Interesting eyewall evolution processes include the eyewall expansion during landfall, followed by contraction in some cases after re-emergence in warm ocean waters. Best track data, advanced satellite microwave imagers, high spatial and temporal ground-observed radar images and rain gauges are utilized to study this unique eyewall evolution process. An examination of the available microwave images of 23 typhoons crossing the Philippines between 2000 and 2010 shows that most typhoons experienced this kind of eyewall evolution, i.e., the radius of the eyewall for 87% of landfall typhoons increased during landfall; and, the radius of the eyewall for 57% of the cases contracted when the typhoons reentered the ocean after they crossed the Philippines. Furthermore, analyses of large-scale environmental conditions show that small vertical wind shear, high low-level relative humidity and sea surface temperature are important for the reorganization of the outer eyewall and the subsequent eyewall contraction when the typhoons reentered the ocean.

For typhoons that crossed Taiwan, based on the microwave and radar images, 89% of the cases show an expansion of the eyewall during landfall. However, the reorganization of the outer eyewall and subsequent contraction were rarely observed due to the small fraction of the ocean when the typhoons entered the Taiwan Strait. In addition, observed rainfall shows an expansion in the rainfall area induced by terrain.

Key words: eyewall contraction, eyewall breakdown, eyewall reorganization

I. Introduction

The eyewall of a tropical cyclone (TC) consists of deep convective clouds surrounding the eye that contains only light winds and almost no precipitation. The most severe weather, such as maximum winds and torrential rains, occurs in the eyewall. It is generally believed that the evolution of the eyewall is responsible for the intensity change of a TC. An important factor affecting the eyewall evolution is the topography that a TC encounters. Brand and Blelloch (1973) was the first to document the effect of the Philippine Islands on the changes in the track, eye diameter, storm intensity and size of TCs during 1960-70 based on the Annual Typhoon Reports of Joint Typhoon Warning Center (with aircraft reconnaissance available during that period). It was indicated that the frictional effect of land mass and the reduction in heat and moisture supply by the ocean are the primary causes of the above changes (Wu et al. 2009).

There have been limited numbers of studies focusing on the eyewall dynamics of typhoons making landfall at the Philippine Islands, whose terrain has horizontal scales about equivalent to the size of the TC. The eyewall evolution of Typhoon Zeb (1998) before, during, and after its landfall at Luzon was documented from both the satellite observation and numerical simulation (Wu et al. 2003). It is proposed that the terrain plays a critical role in such an eyewall evolution wherein first the eyewall contraction just before landfall, its breakdown after landfall, and then the reorganization of a larger outer eyewall after the storm returns to the ocean. Further detailed numerical examination of this unique eyewall evolution was documented in Wu et al. (2009). It was shown that the presence of Luzon plays a critical role in the observed eyewall evolution. The eyewall replacement occurred in Typhoon Zeb was triggered by the mesoscale terrain that has a horizontal scale similar to the core of the typhoon. Furthermore, based on several sensitivity experiments, it was shown that both diabatic heating and surface friction are key factors for the maintenance and the reorganization of the outer eyewall when Zeb reentered the ocean.

In addition to Typhoon Zeb (1998) over Luzon, similar scenarios have also been observed in other storms, such as Typhoon Dan (1999) over Luzon, Typhoon Talim (2005) over Taiwan, and Hurricane Gilbert (1988), Wilma (2005) and Dean (2007) over the Yucatan Peninsula (Chou and Wu 2008). Since any changes in the eyewall structure would lead to or be accompanied by change in the storm intensity, it is believed that a better understanding of such terrain-induced eyewall evolution could improve our understanding of a TC structure and intensity changes, especially for TCs making landfall and interacting with mesoscale terrains (Wang and Wu 2004). Furthermore, the question of intensity and inner-core structure change, and the associated precipitation pattern of a landfalling TC is very important for operational forecasts.

The main objective of this study is to document the statistical characteristics of the eyewall evolution induced by the landfall process and terrain interaction over Luzon Island of the Philippines and Taiwan based on advanced satellite microwave imagers and high spatial and temporal radar images. The difference between the typhoons with and without reorganization of the outer eyewall when typhoons reentered the ocean will be examined. Furthermore, the differences in eyewall evolutions between the typhoons crossing the Philippines and those crossing the Taiwan are also identified.

II. The eyewall evolution scenarios for typhoons crossing Taiwan

There were 19 typhoons crossing Taiwan from 2000-2010. Figure 1 shows the radar reflectivity evolutions of the same six typhoons crossing Taiwan. Following the subjective definition of the outer eyewall by Kossin and Sitkowski (2009), the major convective ring is identified and plotted in the figure when there is at least 75% of a complete circular band with 0.5 degree width. Taking Typhoon Talim in 2005 as an example (Figs. 1a and 1b), the major convective ring before landfall and after the storm reentered the ocean was located at the radii of 0.6 and 1.7 degree latitude from the storm center, respectively. Based on these radar images, the convective rings are usually located within a 1.0 degree radius from the storm center before landfall, and they shift to the outer area ranging between 1.0 and 2.0 degree radii from the storm center after reentering the ocean. In the cases of Talim, Sepat, Kroa, Jangmi, Morakot, and Fanapi, the landfall of the typhoons in Taiwan lead to increment of the radius of the major convective ring by 0.9, 0.7, 1.4, 1.2, 1.4, and 0.2 degrees, respectively. These results are consistent with the eyewall evolution as depicted by the microwave images (figures not shown), while a quantitative analysis is preformed based on radar images with high temporal and spatial resolution.

Detailed evaluations of the eyewall evolution for typhoons crossing Taiwan are analyzed by the radius-time Hovmöller diagrams of the azimuthally-averaged radar reflectivity as shown in Fig. 2. It can be found that most typhoons (53%) showed a contraction of the inner eyewall and the presence of concentric eyewall before landfall over Taiwan (Figs. 2a, 2b, 2e, 2f, 2h, 2j, and 2l). The inner eyewalls in most cases are located within a 1.0 degree radius from the storm center, while the outer eyewalls are located at a radius about 1.0-2.0 degrees from the storm center. Both the inner and outer eyewalls obviously collapsed, and the convection areas shifted inward at the beginning of the landfall. Thereafter, the inner eyewall gradually weakened and the outer eyewall reorganized several hours later after the storms made landfall. The radii of the reorganized outer eyewall range were between 1.0-2.2 degrees, with the smallest and largest being in Pabuk in 2007 and Haitang in 2005 (as shown in Fig.1d and Fig. 2a). Note that except for Sinlaku, Jangmi, and Fanapi, the reorganized eyewall did not contract when the storms cross the Taiwan Strait.

Overall, results from these Hovmöller-diagram analyses are not only consistent with those depicted by the microwave images, but also provide a high temporal and spatial observational evidence in demonstrating the terrain-induced eyewall evolution when typhoons cross islands as indicated earlier in Wu et al. (2003). Furthermore, the contraction of the eyewall before the storms made landfall at Taiwan was also consistent with the observational analyses (Willoughby and Black 1996; Chang et al. 2009) and the numerical simulations (Wu et al. 2009).

Figure 3 shows the radius-time Hovmöller diagrams of the azimuthally-averaged (relative to the storm center) rainfall rate observed hourly for typhoons crossing Taiwan during 2005-2010. The azimuthally-averaged rainfall rate is calculated from the storm center to a 5 degree radius with a bin size of a 0.1 degree radius. It should be noted that since the frequency of rainfall data is observed hourly, the distance between each rain gauge and the location of the storm center is calculated every hour, while the hourly location of the storm center is interpolated from 3-hourly CWB best track. It can be found that before the landfall and first several hours during the landfall period, except for Pabuk in 2007 and Kalmaegi in 2008 (Figs. 3d and 3g), the areas with larger rainfall rate were always located within a 0.5 degree radius from the storm center. Then, the rainfall rate in the storm core gradually vanished and the locations of the maximum rainfall rate shifted outward to a 1.0-2.0 degree radius from the storm center when the storms left Taiwan. These results are consistent with the analyses of the radius-time Hovmöller diagrams of radar reflectivity. Furthermore, these rainfall analyses indicate that the topography of Taiwan not only alters the evolution of the eyewall, but also modifies the rainfall pattern of landfall typhoons. Note that Pabuk passed through the southern part of Taiwan in just one hour. Therefore, the modulation of the eyewall and rainfall pattern for Pabuk may not be as significant as the other cases. The unique rainfall patterns induced by Kalmaegi and Morakot are related to the confluent region associated with the storm circulation and the environmental southwesterly monsoon flows as proposed in Ge et al. (2010) and Hong et al. (2010). However, the rainfall pattern expanding outward from the storm center caused by the terrain effect is consistent with the process revealed in this study.

III. Concluding remarks

The statistical characteristics of the terrain-induced eyewall evolution when a typhoon makes landfall, as in the discussion about Typhoon Zeb (1998) over Luzon Island by Wu et al. (2003, 2009), are examined based on the best track data, advanced satellite microwave imagers, high spatial and temporal ground-observed radar images and rain gauges in this study. Based on the analyses of JTWC best track data from 1945-2010, it is found that annually at least 3.0 TCs with sustained surface maximum winds larger than 64 knots passed through the Philippine islands and 1.3 through Taiwan. During the eleven-year period from 2000 and 2010, the eyewall evolution associated with the 23 and 19 typhoons respectively making landfall in the Philippine islands and Taiwan, were detected by the 85-91 GHz brightness temperature satellite microwave imagers. Based upon these available microwave images for typhoons crossing the Philippine islands, the results indicate that the radius of the eyewall increased during landfall in 87% of the landfalling typhoons, while in 57% of the cases the radius of the eyewall contracted when the typhoon reentered the ocean. For typhoons crossing Taiwan, both the microwave images from satellites and the reflectivity images from ground-based radar observations are applied to analyze the eyewall evolution. It is found that 89% of cases show an expansion of the eyewall during the landfall period. However, reorganization of the outer eyewall is seldom observed due to the limited time the typhoon spends over the Taiwan Strait before making landfall in Mainland China. Furthermore, based on the observed rainfall analyses, an expansion of the rainfall pattern due to the effect of terrain is also revealed. These results provide a conceptual model that may help improve the forecast of severe weather associated with such type of landfall storms. It should be noted that the findings of this study could provide more insights into the impact of terrain on rainfall caused by landfall TCs. In a traditional view, a landfall TC provides stronger wind on the windward side, which then enhances the orographic lifting, thereafter producing more rainfall (Wu and Kuo 1999). Large-scale environmental conditions are examined to investigate the differences between contracted and non-contracted outer eyewall cases. The results show that small vertical wind shear, high low-level relative humidity, and warm sea surface temperatures are important for the reorganization of the outer eyewall after the landfall typhoons reenter the ocean.

The eyewall evolution examined by the satellite microwave imagers is consistent with the finding by Brand and Blelloch (1973), who indicated that the islands of the Philippines affected the eye diameter of passing typhoons based on aircraft reconnaissance data. Although this special eyewall evolution had been identified by Brand and Blelloch (1973), we have documented the climatological aspects of such eyewall evolution and also shown that advanced satellite microwave imagers can depict the eyewall evolution for almost all cases selected. Furthermore, this study also shows that this special eyewall evolution can also be found in typhoons making landfall in Taiwan from high spatial and temporal radar images.

Although this terrain-induced eyewall evolution has been better documented, some issues remain unsolved and are yet to be addressed in future studies. (1) How is such an eyewall evolution influenced by the size of the land, the height of the terrain, and the size and intensity of the landfalling storm? (2) What determines the timing for the inner eyewall to break down after the storm makes landfall? (3) What is the relationship between land with different surface roughness, latent heat flux supply, and topography? (4) How does the environmental vertical wind shear affect this eyewall evolution? It is expected that more insight can be obtained from more well-designed sensitivity numerical experiments with high-resolution cloud-resolving models. Detailed discussion of this study could be refereed in Chou et al. (2011).

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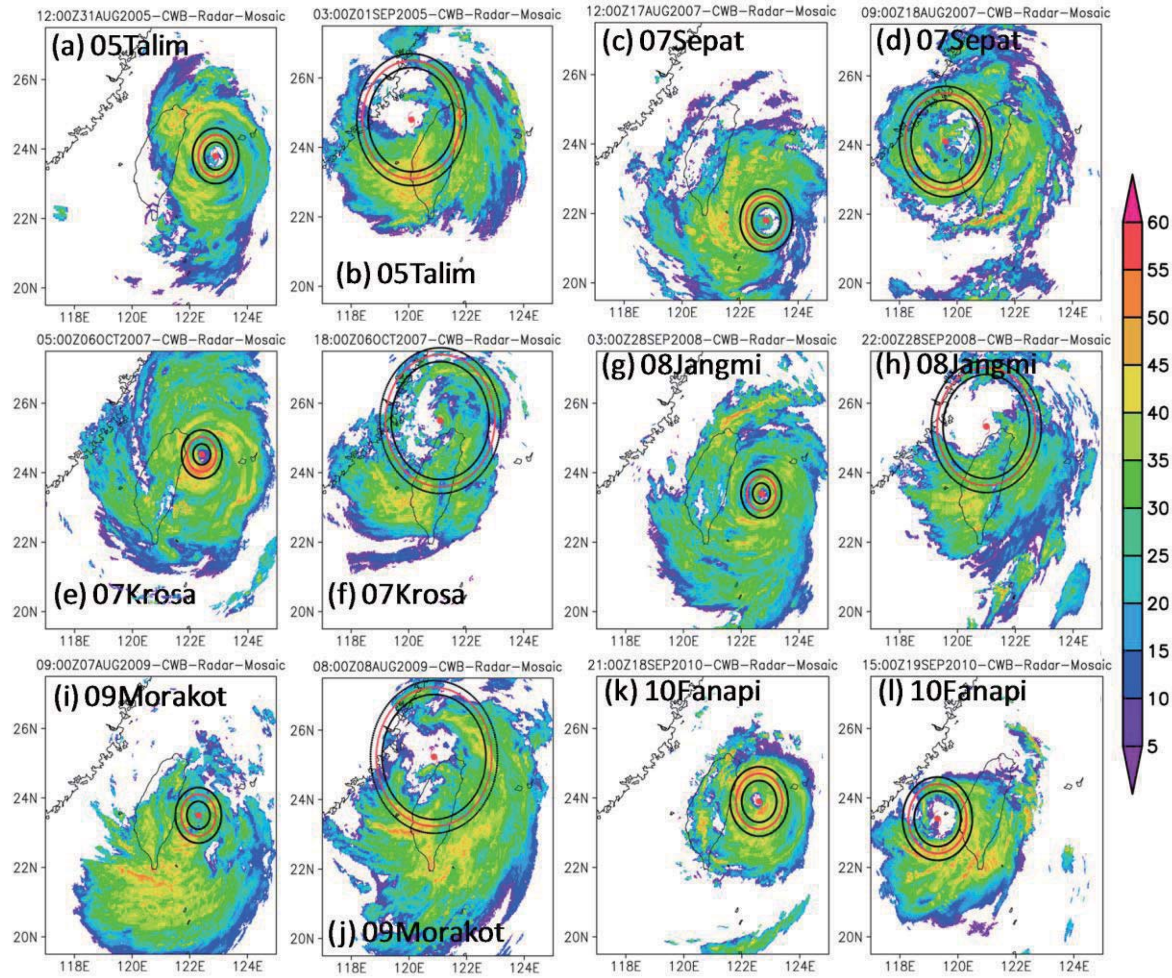

Fig. 1. The radar reflectivity evolutions of six particular typhoons (Talim in 2005, Sepat and Krosa in 2007, Jangmi in 2008, Morakot in 2009, and Fanapi in 2010) that crossed Taiwan. Each case contains three individual images, showing the inner-core structure changes when typhoons moved into and away from Taiwan. Three solid rings with a 0.5 degree radius are shown for identifying the maximum convection regions near the core of the typhoons. The locations of typhoons are interpolated from 3-h best track of CWB

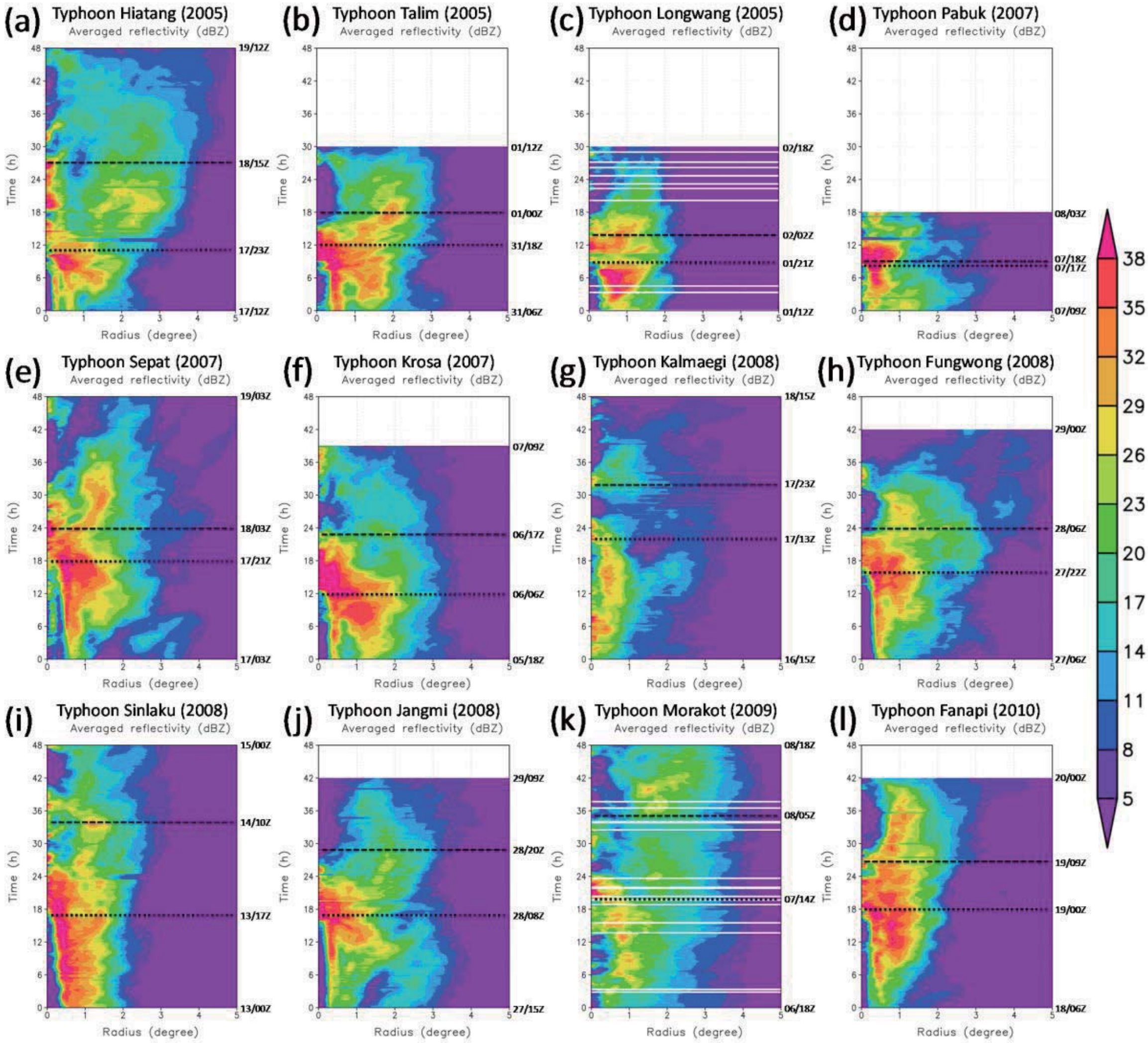

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Fig. 2. Radius-time Hovmöller diagram of the azimuthally-averaged radar reflectivity (dBZ) for 12 typhoons that crossed Taiwan. The dotted (dashed) horizontal line indicates the time when typhoons made landfall at (exited from) Taiwan.

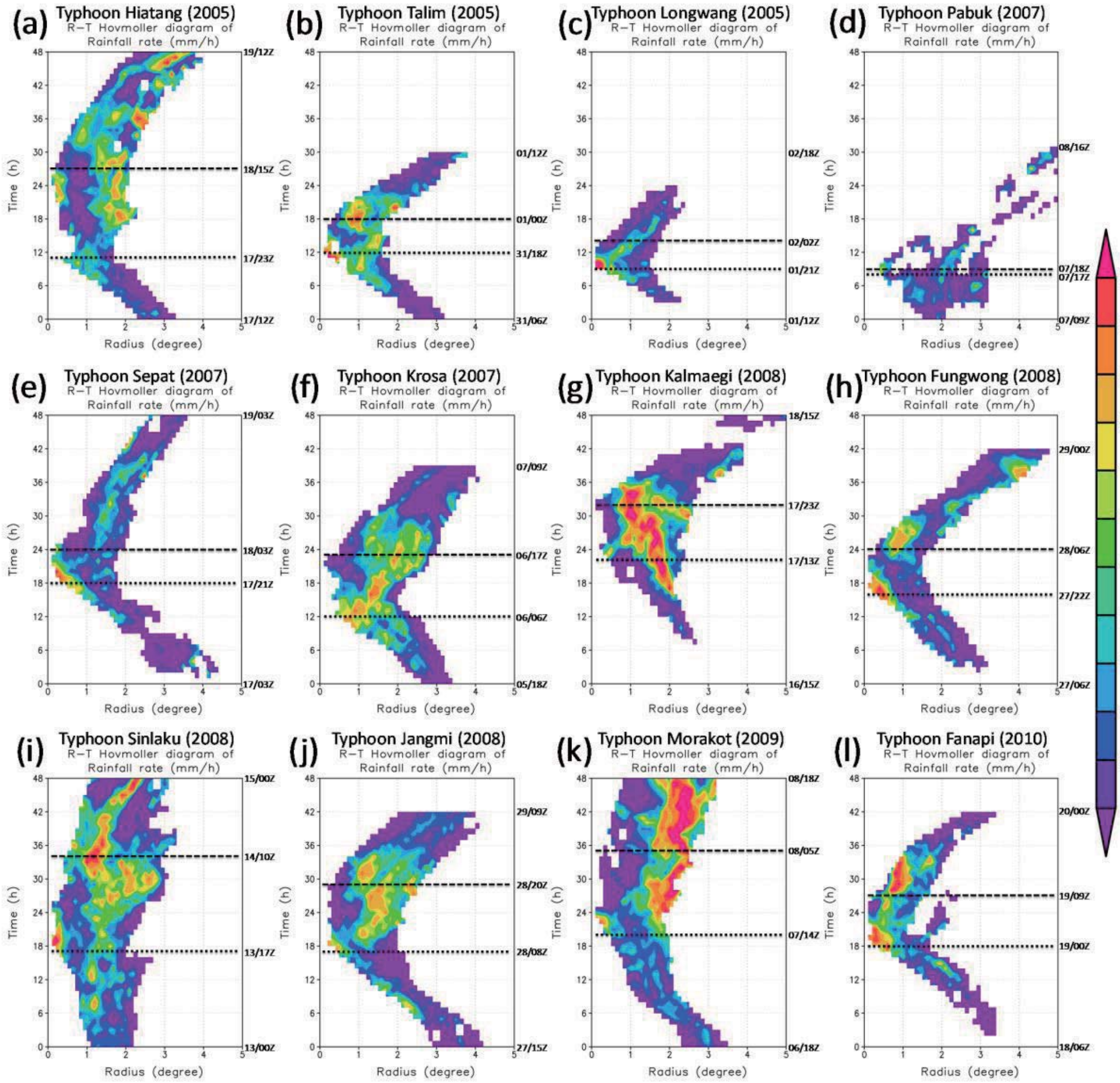

Fig. 3. Radius-time Hovmöller diagram of the azimuthally-averaged (relative to the storm center) observed rainfall rate (mm h^{-1}) for 12 typhoons that crossed Taiwan. The dotted (dashed) horizontal line indicates the time when typhoons made landfall at (exited from) Taiwan. The observed rainfall rates are calculated from the CWB automatic rain gauge.