Role of Submonthly Disturbance and 40–50–day ISO on the Extreme Rainfall Event Associated with Typhoon Morakot (2009) in Southern Taiwan

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Abstract

Typhoon Morakot that made landfall on Taiwan during 7–9 August 2009 caused record–breaking rainfall in Southern Taiwan and nearly 700 deaths from mudslides. It was the most severe natural disaster in Southern Taiwan caused by a typhoon in 50 years. Different from typical typhoon cases, characterized by an isolated vortex, Typhoon Morakot was embedded in a large–scale convection region with monsoon circulation of different time scales in the tropical western North Pacific. Morakot's landing on Taiwan occurred concurrently with the arrival of a large–scale cyclonic circulation in a submonthly wave pattern (10–30–day) during the cyclonic phase of the 40–50–day ISO (intraseasonal oscillation). It is suggested that the abundant moisture supply from the southwesterly embedded in the multiscale large–scale circulation and the topographic lifting effect of steep terrain resulted in the record–breaking rainfall in Southern Taiwan.

Key word: Typhoon, submonthly wave pattern, 40-50-day ISO, topographic lifting effect

1. Introduction

On 3 August 2009, Typhoon Morakot formed in the tropical western North Pacific (TWNP) and made landfall on Taiwan on 8 August. Typhoon Morakot, a category 2 (maximum wind speed 40 m s^{-1}) typhoon, took more than two days to pass through Northern Taiwan and soaked Southern Taiwan with record–breaking rainfall when curving northward. The 3–day accumulated rainfall exceeded 2000 mm at many rainfall stations in Southern Taiwan and caused deadly mudslides in the mountains, leading to 618 deaths and 67 missing. The southern plain was flooded and covered in 2–3 meters of mud after the flood retreated. More than one hundred bridges were broken and the agriculture and fishery loss was over US$4.7 billion. Typhoon Morakot caused the most severe natural disaster in Taiwan by a typhoon in 50 years.

This special event reveals again that rainfall, not wind, is often the major factor causing the disaster in Taiwan. The rainfall is usually sustained by the abundant moisture supply from the southwesterly flow that intensifies during the passage of typhoon. As shown below, such a strong southwesterly flow is also observed in the Morakot event. This study attempts to understand the nature of this southwesterly by examining the relationship between Typhoon Morakot and the large–scale background circulation.

Previous studies showed that the genesis and movement of tropical cyclones (TCs) are significantly affected by large–scale circulation such as the intraseasonal oscillation (ISO, e.g., Liebmann et al. 1994; Gray 1978; Elsberry 2004). The active ISO phase, which is characterized by cyclonic circulation and enhanced convection, provides a favorable environment for the genesis, growth and movement of TCs (e.g., Gray 1978; Nakazawa 1986; Liebmann et al. 1994; Maloney and Dickinson 2003; Hsu 2005; Hsu et al. 2008). Ko and Hsu (2006, 2009) recently found that recurving TCs tend to embed in the cyclonic circulation of a submonthly (10–30 days) large–scale wave pattern, which is in turn modulated by the ISO activity in the TWNP. This multiscale characteristic was clearly identified during the life cycle of Typhoon Morakot in 2009, and was responsible for the strong southwesterly. It is suggested that the abundant moisture supply from the southwesterly embedded in the multiscale large–scale circulation and the topographic lifting effect of steep terrain in Southern Taiwan resulted in the record–breaking rainfall in Southern Taiwan.

2. Data and Methodology

The daily datasets used in this study include 1) wind of NCEP/NCAR Reanalysis I (2.5°x 2.5°, Kalnay and Coauthors, 1996), 2) outgoing longwave radiation (OLR, 2.5°x 2.5°; Liebmann and Smith, 1996), 3) TRMM–TMI (Tropical Rainfall Measuring Mission–Tropical Microwave Imager) satellite products (Huffman et al. 2007), 4) ECMWF high resolution (25–km) Year of Tropical Convection (YOTC) global analysis, and 5) rainfall from the Central Weather Bureau in Taiwan. Wavelet analysis was applied to analyze the multiscale nature of disturbances. The western North Pacific summer monsoon (WNPSM) index, which is defined as U_{850}(5–15°N,100–130°E)–U_{850}(20–30°N,110–140°E) (Wang and Fan 1999) is used to represent the strength of monsoon trough in the TWNP.

3. Large–scale circulation associated with Typhoon Morakot

The mean 850–hPa stream function during 1–10 August is presented in figure 1 to illustrate the large–scale background circulation in which Typhoon Morakot evolved. A cyclonic circulation extending from the South China Sea (SCS) to almost 150°E is clearly seen in Fig. 1a. This organized circulation is often referred to as monsoon gyre, which occurs roughly once per year for two or three weeks during the WNPSM (Lander 1994). Once this large–scale cyclonic vortex is established, it often becomes a prolific generator for meso–scale vortices or tropical depressions. This is indeed the case in early August 2009, when three TCs (including Typhoon Morakot) appeared within the monsoon gyre.

The accumulated TRMM rainfall during the passage of Typhoon Morakot through Taiwan shown in Figure 1b indicates the occurrence of maximum rainfall in Southern Taiwan, which is about 300 km to the south of the typhoon track. Instead of collocating with the typhoon vortex as in most typhoon cases, the maximum rainfall occurred to the south of the vortex and appeared to be part of a large–scale convection/cyclone system that extended from 110°E to 140°E. This unusual characteristic of Typhoon Morakot implies the important contribution of the large–scale circulation to the record breaking rainfall.

The QuikScat near–surface wind (Fig. 1b) indicated that this record breaking rainfall was associated with the low–level convergent zone near the southwest coastline of Taiwan. It is interesting to note that this low–level convergent zone is established by the northwesterly and southwesterly winds. The former is part of the typhoon circulation and the latter is part of the southwesterly monsoon flow. While the monsoon gyre provided a favorable environment for the Morakot genesis, the corresponding large–scale southwesterly monsoon flow also enhanced the moisture flux transport to the windward side of the Central Mountain Range (CMR, the south–north oriented mountains in Taiwan, 2000 m high on average) in Southern Taiwan. These results suggest the combination of the large–scale forcing, typhoon vortex, and mountain lifting effect to accommodate the unusual rainfall.

4. The role of submonthly disturbance and 40–50–day ISO

The effect of large–scale flow on Typhoon Morakot is illustrated in this section. The WNPSM index shown in Figure 2a exhibits notable oscillation during the 2009 summer compared to the climatological evolution. The oscillation of the WNPSM index between positive/large and negative/small values reflects the strengthening and weakening cycle of the TWNP monsoon trough. Three ups and downs were observed between July and September. The sudden strengthening of the monsoon trough in late July and remaining strong in early August (upper–left figure in Fig. 2a) is particularly interesting, because of the coincidence with the life cycle of Morakot and the favorable environment the monsoon trough created for the development of Morakot.

The wavelet analysis reveals two significant intraseasonal oscillations, submonthly disturbance (10–30 day) and 40–50 day oscillation (Fig. 2b). The submonthly disturbance was initiated in early July and peaked in late August, while a 30–60–day ISO appeared as early as April and narrowed the period to 40–50 days in July and August. The co–existence of 10–30–day and 40–50–day fluctuation in late July and early August suggests that Typhoon Morakot was under the influence of two distinctive lower frequency fluctuations.

The 10–30–day filtered 850–hPa wind and moisture anomalies presented in Figure 3a–c show that a southeast–northwest orientated wavelike disturbance occurred in the TWNP from late July to early August. The submonthly disturbance, with a wavelength about 4000 km and a speed about 5 m s^{-1}, propagated northwestward in the Philippine Sea toward Taiwan. It exhibited the characteristics of the TC/submonthly wave pattern identified by Ko and Hsu (2006). The submonthly wavelike disturbance in late July (figure 3a) was characterized by a moist cyclonic anomaly in the Philippine Sea, indicating a strengthened monsoon trough, and dry anticyclonic anomalies near Taiwan and the equator. The wavelike disturbance moved northwestward toward Taiwan in the next few days. On 5 August, the moist cyclonic anomaly moved to 20°N (Fig. 3b), reflecting the enhancement of the monsoon trough between 10°N and 30°N. Also noted is the large extent of the moist southwesterly, which can be traced all way to the Bay of Bengal. The cyclonic anomaly moved further northwestward in next few days and resulted in the strong southwesterly impinging upon Taiwan on 8 August (Figure 3c). It is evident that the monsoon gyre establishment was caused by the arrival of the cyclonic circulation in the submonthly wavelike disturbance. Such a moist cyclonic environment is favorable for the genesis and development of three typhoons in early August (Fig. 1a), and also the moisture transport to Taiwan by the prevailing southwesterly. The 2–8 day perturbation shown in Figure 3d, which reflects the typhoon circulation on 5 August, exhibits an east–west wave–like pattern north of 20°N and from 110°E to 150°E. The two cyclonic anomalies reflect the circulation of Typhoon Goni and Morakot. A cyclonic circulation, which developed into Typhoon Etau few days later, can also be seen near 140°E, 15°N. This wave–like pattern with a much smaller spatial scale appears to embed in the 10–30 day cyclonic anomaly. The cyclonic anomaly associated with Typhoon Morakot continued moving westward to Taiwan in next few days, resulting in the strengthening of local southwesterly near Taiwan on 8 August (Figure 3e). Note that the spatial scale of the anomalous southwesterly directly associated with Morakot was much smaller than that of the 10–30 day perturbation.

The above results suggest that the record–breaking rainfall was likely a result of the combined effect of Typhoon Morakot and the submonthly disturbance. Wavelet analysis was further applied to rainfall averaged over Southern Taiwan (20°–22°N, 120–122°E, Fig. 4a) to obtain the temporal fluctuation of rainfall contributed by each frequency band. The percentage contributed by each frequency band (e.g., 2–8 day, 10–30 day, and 40–50 day) was then calculated as the ratio of spectrum power at each frequency band to total spectrum power. The typhoon circulation (2–8–day) and the submonthly disturbance (10–30–day) contribute 56% (585 mm) and 37% (381mm) of total rainfall, respectively, during the landfall period (Table 1). The same analysis applied to the TRMM rainfall yielded a similar result. The wavelet analysis shows that the typhoon circulation and submonthly wavelike disturbance together led to the extreme rainfall in Southern Taiwan.

Although the relative contribution of the 40–50–day ISO to the extreme rainfall in Southern Taiwan is insignificant, the ISO contributed notably to the circulation. When computed in 850–vorticity averaged over the monsoon gyre (15–30°N, 110–140°E), the 40–50–day ISO contributed almost the same amount of amplitude as the submonthly disturbance during early August (not shown). The 40–50–day filtered wind and specific humidity anomalies on 5 August are presented in Figure 3f. It was characterized by a positive specific humidity anomaly, anomalous cyclonic circulation, and westerly anomaly in the SCS and TWNP. This result is consistent with the finding by Ko and Hsu (2009) that the cyclonic phase of ISO creates favorable environment for the development of the TC/submonthly wave pattern.

5. Local topographic effect

The above shows that the typhoon and 10–30–day disturbances together contribute to the heavy rainfall in Southern Taiwan. In this section, the topographic effect on the record–breaking rainfall is explored. As shown in Figure 4a, the maximum 3–day (7–9 August) rainfall exceeding 2000 mm occurred in the windward side of the CMR. The high–resolution YOTC data show two paths of moisture flux on 8 August, which led to large moisture convergence along the southwestern coast of Taiwan: the northwesterly one associated with Typhoon Morakot and the southwesterly one associated with large–scale monsoon southwesterly (Fig. 4b). Significant moisture convergence is observed at the windward side of the CMR in Southern Taiwan where maximum rainfall occurred (Fig. 4a). The vertical cross section of moisture flux and horizontal convergence along 23°N shown in Figure 4c illustrates that the moisture was transported upslope over the steep terrain toward the CMR (Fig. 4c). This topographic effect led to strong moisture convergence in Southern Taiwan, which is 2–3 times larger than the convergence over Taiwan Strait, and presumably strengthened rainfall intensity. The mountain effect on rainfall in strong southwesterly associated with a typhoon was well explored in previous studies (e.g., Wu el al. 2002; Chen and Chen 2003). A recent numerical study (Ge et al. 2009) also confirms that the interaction between TC, monsoon system and local terrain led to the record–breaking rainfall in Southern Taiwan.

6. Conclusion

Typhoon Morakot, which made landfall on Taiwan 8 August 2009, caused record breaking rainfall in Southern Taiwan and nearly 700 deaths by mudslide. Different from many typhoon cases that were characterized by an isolated vortex, Typhoon Morakot was embedded in a large–scale convection region and monsoon circulation of different time scales in the TWNP. This study demonstrates the role of multiscale circulations and the local terrain effect in causing the extreme rainfall in Southern Taiwan during the Morakot event. The main results are summarized as below.

1) The genesis of Typhoon Morakot was concurrent with the arrival of a large–scale low–level cyclonic circulation, which was part of a 10–30–day wave–like disturbance that propagated northwestward toward Taiwan in the TWNP. The large–scale cyclone enhanced the WNP monsoon trough and provided a favorable environment for typhoon genesis and development. Three typhoons formed in this large–scale cyclonic flow in late July and early August 2009.

2) The wavelet analysis shows that the WNPSM was dominated by the submonthly (10–30–day) wavelike disturbance and 40–50–day ISO. Further calculation revealed that the record–breaking rainfall was resulted primarily from the typhoon vortex and the submonthly large–scale cyclonic disturbance. The former contributed about 56% and the latter contributed 37% of total rainfall. Although the 40–50–day ISO contributes relatively little to the extreme rainfall in Southern Taiwan, its contribution to the large–scale vorticity was equivalent to that of the submonthly disturbance. The ISO modified the slow–varying large–scale circulation that enhanced the monsoon trough to create a favorable environment for the development of the TC/submonthly wave disturbance.

3) Two paths of significant moisture flux resulted in anomalous moisture convergence along the Southwestern Taiwan: the northwesterly one associated with Morakot and the southwesterly one associated with the strengthened monsoon southwesterly impinging upon Taiwan. Much larger moisture convergence occurred in South Taiwan when abundant moisture was transported upslope over the steep terrain toward the CMR. The lifting effect of local topography contributes significantly

to the record–breaking rainfall under strong southwesterly that was enhanced due to the arrival of the cyclonic anomaly in the submonthly perturbation.

This study demonstrates the role of large–scale circulation anomaly and the local terrain in the record–breaking rainfall in Southern Taiwan. The observed evidences clearly show, consistent with the finding of Ko and Hsu (2006, 2009) based on long–term statistics, that the submonthly and 40–50 day wavelike disturbance played an essential role in setting up the environment for extreme rainfall. While the large–scale monsoonal southwesterly transported abundant moisture to the region and set up a favorable condition for the occurrence of heavy rainfall, the lifting effect of steep terrain contributed significantly to the unusual heavy rainfall. The Typhoon Morakot case presented here and in recent studies (e.g., Ko and Hsu 2006, 2009) reveals the importance of treating TC and large–scale circulation as an integrated entity and exploring the multiscale interaction effect to further our understanding of typhoon activity in the TWNP.

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Table 1 The relative contributions of multiscale on the total rainfall over Southern Taiwan (20°–22°N, 120–122°E) when the Typhoon Morakot made landfall in Taiwan during 7–9 August 2009. The wavelet analysis is used for the estimation.

Catalog	relative contribution	accumulated contribution
2–8–day	585 mm (56%)	585 mm (56%)
10–30–day	381 mm (37%)	966 mm (93%)
40–50–day	36 mm (3%)	1002 mm (96%)
others	48 mm (4%)	1050 mm (100%)

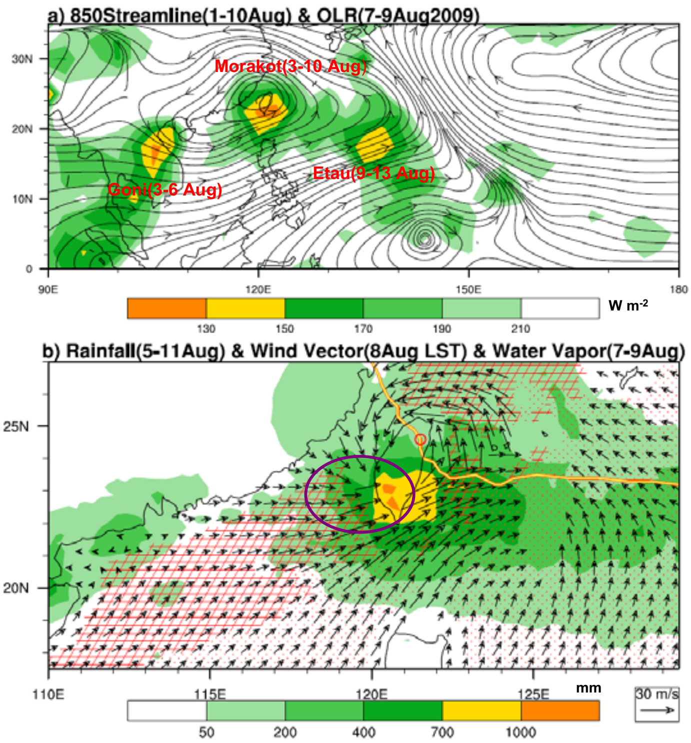

Figure 1 (a) 850–hPa streamline (1–10 August) and OLR anomalies averaged over 7–10 August. The date in bracket represents the duration of three typhoons, respectively. (b) TRMM–TMI rainfall (5–11 August), atmospheric water vapor (7–9 August) and QuickSCAT near–surface wind (8 August). The purple elliptical line denotes the convergent zone of northwesterly typhoon circulation and southwesterly monsoon flow. Area where atmospheric water vapor is greater (less) than 65 mm is hatched (dotted) in red, while blank indicates the location of missing data. The yellow curve and red circle in b) denote Morakot's track and its center on 8 August, respectively.

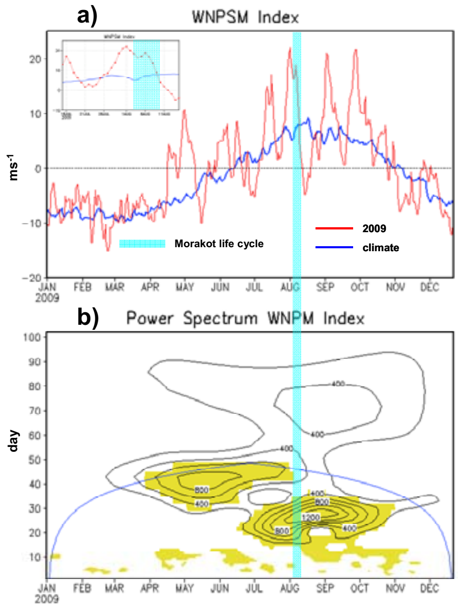

Figure 2 a) Time series of daily WNPSM index for 2009 (red curve) and the corresponding climatological values (blue curve). A blown–up image of the curves in late July and early August is shown in the upper left corner. b) Power spectrum of the WNPSM index derived from wavelet analysis (basis function "Morlet" with parameter 6). The cone of influence of wavelet power spectrum is shown in blue curve and the spectrum exceeding 95% confidence level is shaded. The blue bar denotes the period of Typhoon Morakot.

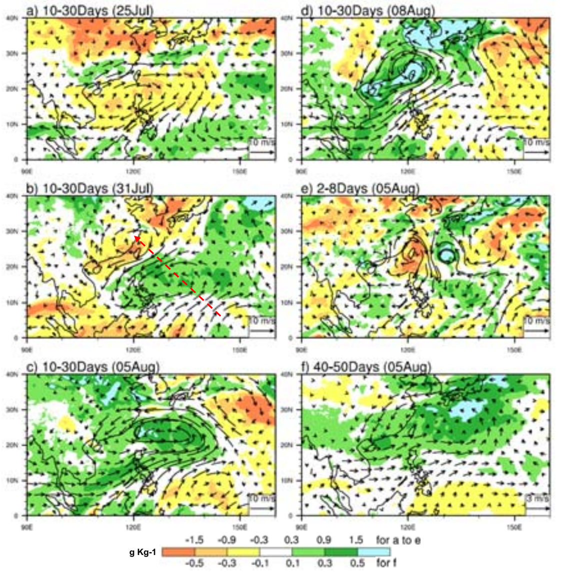

Figure 3 (a–c) YOTC–25km 10–30–day filtered 850–hPa wind and moisture anomalies on 31 July, 5 August, and 8 August, respectively. The dashed arrow in b) denotes the propagation direction of submonthly wave pattern. (d–e) and (f) are same as in (a–c) but for the 2–8–day perturbation on 5 and 8 August and the 40–50–day perturbation on 5 August, respectively.

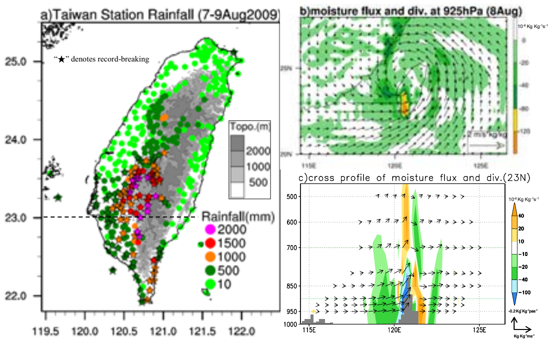

Figure 4 a) Accumulated rainfall observed at meteorological stations in Taiwan during 7–9 August 2009 when Morakot made landfall. b) YOTC–25km 925–hPa moisture flux and convergence (shading) on 8 August. c) Height–longitude cross section of zonal and vertical moisture flux and horizontal moisture flux convergence at 23°N.