A Study on the Heavy Rainfall Event in Taiwan Associated with Typhoon Mindulle (2004) and the Accompanied Southwesterly Flow

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Abstract

The heavy rainfall event that occurred during 2–4 July 2004 in Taiwan associated with Typhoon Mindulle and the accompanied monsoonal southwesterly flow is diagnosed in this study using a range of observational data. Different dynamical factors were playing their role in each of the several rainfall periods. In the first period (30 June – 1 July) when Typhoon Mindulle was east of Taiwan, direct impact from the typhoon circulation brought rainfall to the eastern part of the Island. The second period (2 July) was when Mindulle's center stayed north of Taiwan. An east-west oriented convergence line formed between the dry northerlies (advected by the typhoon circulation from inland) and the warm, most southwesterlies. Following the northward motion of Mindulle, the convergence line and the convective cells embedded were also shifting northward, bringing heavy rainfall to the entire southwestern plain of Taiwan. In the third period (3–4 July), Typhoon Mindulle was further away from Taiwan and only the southwesterlies persisted in the area. The rainfall shifted to the north-south oriented central mountain range.

Four factors are identified to be essential determining the development of the entire rainfall event. These include the convergence between the southwesterly flow and Typhoon Mindulle's circulation, the warm and moist monsoonal southwesterly flow, the high-pressure system east of the Philippines, and Taiwan's orographic effect. The first three factors control the rainfall distribution during 2 July, while the orographic effect was dominating during 3–4 July. Based on these findings and comparison with some of the historical tropical cyclone-related rainfall cases in which strong southwesterlies also played important role, a conceptual model is built up for this kind of tropical cyclone-monsoon interaction.

Keyword: Typhoon rainfall, southwesterly flow

1. Introduction

Taiwan, being an island located at the western edge of the western North Pacific (WNP), is usually impacted by several tropical cyclones (TCs) every year. Some of these TCs affecting Taiwan formed in the monsoon trough east of the Philippines while the others formed in the South China Sea (SCS) and traveled northward or northeastward. The destructions brought by these TCs came from their strong winds, as well as flooding, landslides and debris flows caused by continuous heavy rainfall.

In general, the rainfall distribution brought by a TC depends much on the internal structure of the TC such as the size of the eye wall controls the location of the deep convections around. Degree of asymmetry in the off-wall convections and existence of mesoscale convective systems (MCSs) embedded in the TC are also important factors. For the Taiwan Island, two other factors are long recognized to be modifying the local TC-related rainfall to a large extent and cause much forecast difficulty. These are the topography of the Central Mountain Range (CMR) in Taiwan and interaction of an approaching TC with the Asian monsoon system. The CMR has an average height of about 3 km, it can deflect the motion of a pass-by TC, and even modify its structure and rainfall distribution. Therefore, the interaction-with-topography problem has attracted a lot of studies (e.g., Chang et al. 1993; Lin et al. 2002 and Lin et al. 2005). Comparatively, systematic studies on the problem of interaction with the monsoon system are quite few. When a TC occurs near the boundary between the WNP and SCS in the summer, its pressure gradient can probably enhance the monsoonal southwesterlies in the region, and the impact of the southwesterlies to Taiwan's topography modifies the original rainfall distribution brought by the TC only. On the other hand, when a TC is in the vicinity of Taiwan in the autumn or early winter, the warm moist air in its main circulation can confront with the cold, dry winter-monsoonal northwesterlies and form a near frontal system that brings even larger amount of rain to certain regions in Taiwan. This TC-monsoon interaction problem is also very important from the disaster mitigation point of view. Although these situations are not frequent climatologically, totally different disaster preparedness plans are needed due to the abrupt change in the rainfall amount and distribution resulted from this kind of interaction.

2. Data

Various data is utilized in this study to diagnose the heavy rainfall event associated with Typhoon Mindulle. These include global analyses from the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) with 1° latitude/longitude resolution and are available six-hourly. TC track data from the Taiwan Central Weather Bureau (CWB) is used since the standard best track from the Joint Typhoon Warning Center is not available yet by the time of the study. Observational data is mainly from the weather maps, local soundings and rain-gauge data of CWB. Currently there are 365 automated weather stations distributed over the Taiwan Island able to record the amount of rainfall. This number is greatly increased from previous studies that used data from the traditional stations only (number around 20–22) (e.g., Chang et al. 1993 and Yeh 2002). Thus the overall rainfall distribution over the Island is well monitored. When the rainfall amount at a location other than the stations is desired, interpolation based on the station data within a certain range is performed. Besides, remote-sensing data are also used to supplement the coarse resolution of usual analyses, and correct their model dependence. These include the Geostationary Operational Environmental Satellite (GOES-9) infrared imageries, QuikSCAT ocean-surface winds, and composite radar reflectivity data from the four Doppler radar stations on the Taiwan Island (Jou 2004). Rain rate can be derived from the radar reflectivity data and counterchecked with the raw rain-gauge data.

3. The flood event during 2–4 July 2004

a. Track of Typhoon Mindulle and synoptic situation

Typhoon Mindulle is one of the eight TCs that affected Taiwan in 2004. It formed in the WNP northwest of Guam on 0600 UTC 23 June (hereafter 062306) and moved westward (Fig. 1). Then it intensified gradually and reached typhoon intensity at 062706. About two days after Mindulle formed, another typhoon Tingting formed at about the same location as of Mindulle, and was about 20° latitude northeast of Mindulle at 063000. At 063006, Mindulle made a sharp northward turn and approached the Taiwan Island. Typhoon Mindulle made landfall at about 070112 on the east coast of Taiwan near the city Hualien (and reduced to tropical storm intensity shortly afterwards). It stayed over land for about 30 h before going out to ocean surface again near the city Tanshui at about 070206 (Fig. 1). Afterwards, it continued its northward motion and made extratropical transition on 4 July.

Another importance synoptic feature is the high pressure system southeast of Mindulle, which persisted for several days (not shown). The associated anticyclone of the system provided a channel for the cross-equatorial southwesterlies. Note also that the subtropical high was much modified by the existence of Typhoon Tingting such that the ridge was retained east of 150°E throughout the period of our interest. At the upper level (200 hPa), strong divergence is found at the outflow structure of Mindulle as in other mature TCs. Following the track of Mindulle, the diffluent region moved from south of Taiwan to the northern part from 070100 to 070200 (not shown). This is also an essential feature of the heavy rainfall event associated with Typhoon Mindulle.

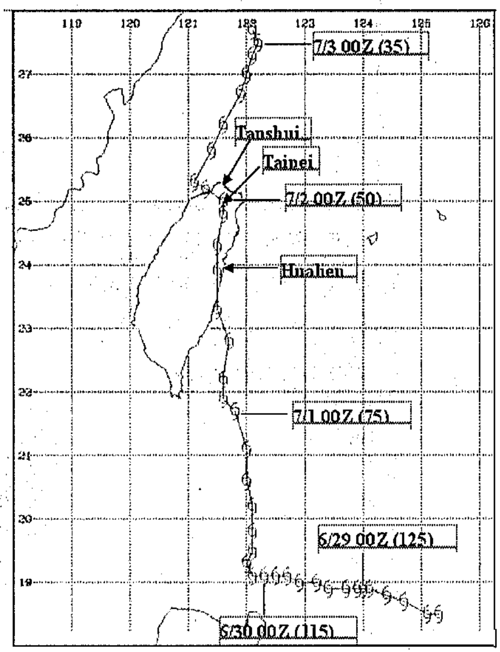

Fig. 1 Strom track of Typhoon Mindulle from the Central Weather Bureau, Taiwan for the period 062900 to 070300. The figures in parentheses are the corresponding intensities (unit: kt), and the time interval between two storm centers is 3 h. The locations of the cities Tanshui, Taipei and Hualien are also marked.

b. Mesoscale features

The GOES-9 satellite imageries are examined to reveal the mesoscale features in the vicinity of Typhoon Mindulle. At 070100 when the center of Mindulle was just south of Taiwan, the spiral-band structure of the typhoon was still clear (Fig. 2a). However, convections are seen to concentrate at the southern part of the TC circulation when the northern part was probably affected by the topography of the Taiwan Island. In addition, the northeasterlies to the north of Mindulle advected the dry air from inland China, thus suppressing the convective activity in that area. From 070112 to 070212, a MCS started to organize southwest of Mindulle's center (Figs. 2b–d). At 070300, the MCS elongated in the east-west direction and evolved into a line structure and covered the southern part of Taiwan (Fig. 2e). From the previous depiction of the synoptic situation, it is known that the MCS is embedded in the monsoonal southwesterlies and in the region where these southwesterlies met the circulation of Mindulle. From the GOES-9 imageries, the MCS was about 500-600 km from the typhoon center and was advected following the typhoon motion. When Mindulle was further away from Taiwan at 070312, only low-level clouds covered the Island (Fig. 2f).

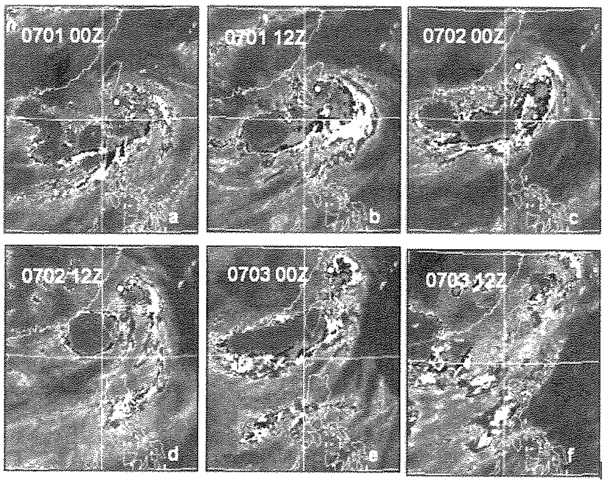

Fig. 2 GOES-9 satellite imageries of Typhoon Mindulle for the period 070100 to 070312. The time interval between successive images is 12 h. The location of typhoon center is marked with a typhoon symbol.

c. Rainfall distribution in Taiwan

During 063000–070600 when Typhoon Mindulle approached Taiwan, made landfall and then extratropical transition, the rainfall distribution in Taiwan had enormous variation. The spatial and temporal distributions of the rainfall associated with Mindulle is examined using the local rain-gauge data of Taiwan. Before its landfall when Mindulle was southeast of Taiwan from 063000 to 070200, rainfall started at the east coast of Taiwan (Figs. 3a, b) that agrees with the TC rainfall climatology (Lee et al. 2005). In the day of 070200–070300 when Mindulle passed through the Taiwan Island, large amount of rainfall occurred in the entire southwest part of Taiwan with some locations receiving over 500 mm of rain (Fig. 3c). This is considered to be unusual when only examining the TC circulation being lifted by the CMR of Taiwan. Actually the largest amount of rainfall happened after 070215 when the land warning of Mindulle had already been cancelled by the CWB as the wind threat weakened a lot. The event was well known as the 7-2 flood event locally. Flooding occurred at a lot of places in Taiwan and even caused a reservoir gate damage. Afterwards during 070300–070500 when Mindulle was further away, the monsoonal southwesterlies persisted in the region and brought rainfall that concentrated around the north-south oriented CMR (Figs. 3d, e).

The rain event associated with Typhoon Mindulle also set some records in the local Taiwan society. For example, one of the stations (Jiu-Fen-Er-Shan, Nantou County) recorded a rainfall rate of 151.5 mm/h while the total accumulated rainfall during the entire period at Xinan, Kaohsiung is a record-high 2005.0 mm. The flood event also caused 1023 landslide and debris flow incidents, and one of the highest amounts of agricultural loss. Therefore, understanding the physical processes behind the heavy rainfall event has become an urgent task of the local meteorologists.

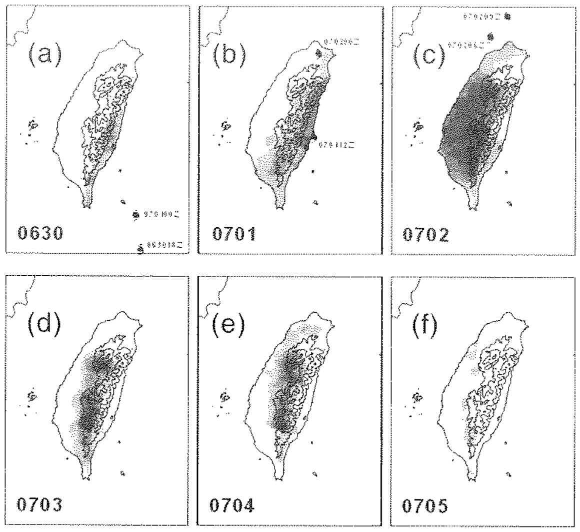

Fig. 3 Accumulated rainfall for the period 063000 to 070600. The time interval between successive images is 24 h. The location of typhoon center is marked with a typhoon symbol.

4. Diagnosis of the heavy rainfall event

Although the spatial and temporal distribution of rainfall associated with Typhoon Mindulle in general agrees with the cloud system development as seen in satellite imageries, the underlying physical processes and the detailed evolution of rainfall are not well explained. Therefore additional observational data is used to diagnose the rainfall event in this section.

Four factors are identified to be essential determining the development of the entire rainfall event. These include the convergence between the southwesterly flow and Typhoon Mindulle's circulation, the warm and moist monsoonal southwesterly flow, the high-pressure system east of the Philippines, and Taiwan's orographic effect. These are discussed in details as follows.

a. Convergence dynamics

At 070212, a MCS is seen on satellite imagery located at the southwestern tip of Taiwan when the center of Typhoon Mindulle was just north of the Island (Fig. 2e and Fig. 4a). The enhanced satellite imagery shows that the MCS was quite symmetric and deep convections were at the center. However, radar reflectivity data reveals rather a convergence line structure at the low level (Fig. 4b). The line extended from the Taiwan Strait into the southern part of the CMR. Thunderstorm convective cells are also identified from the radar data (shown as small boxes in Fig. 4). They are seen distributed along the convergence line, and moving eastward or northeastward, thus bringing large amount of rainfall to the southwest part of Taiwan right after 070212. Note that this is consistent with the observed sequence of rainfall. The heavy rainfall first occurred in the southwestern part of the CMR before moving up to the north when Mindulle also moved northtward. That is, the low-level convergence line resulted when Mindulle's circulation met with the southwesterlies also moved northward during the several hours after 070212.

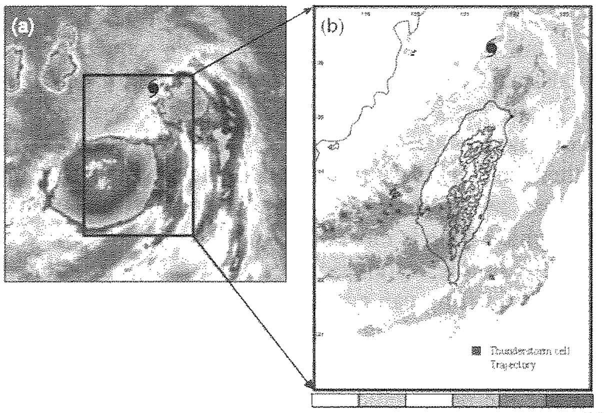

Fig. 4 (a) Satellite imagery of Typhoon Mindulle at 070212, showing a developing MCS located at Taiwan Strait. (b) Composite radar reflectivity image in the square frame of (a), showing many thunderstorm cells growing inside the MCS and moving northeastward into southern Taiwan.

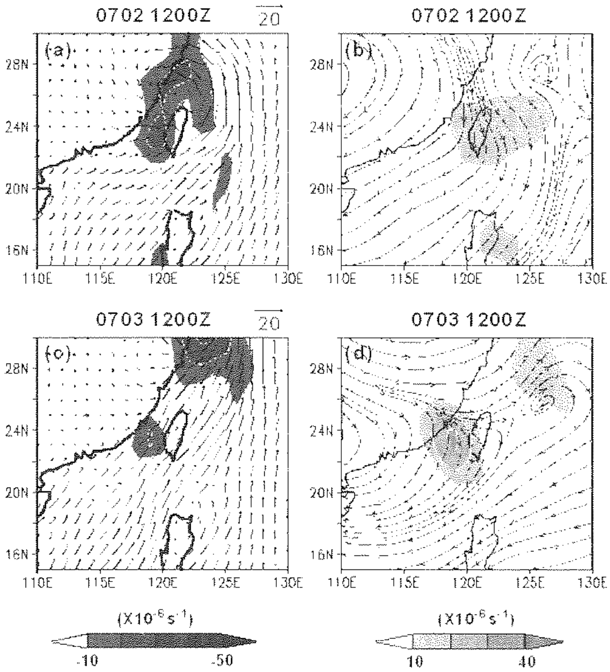

Fig. 5 NOGAPS 10-m wind vector (two upper left panels, unit: m s^{-1}) and 200-hPa streamline (two lower right panels) at (a), (b) 070212 and (c), (d) 070312. Shaded area is divergence (unit: 10^{-6} s^{-1}) less than -10 for the lower level and larger than 10 for the upper level.

Dynamically speaking, the presence of a TC circulation in the Taiwan area brings low-level convergence in the region. The low-level circulation of a TC also enhances cyclonic vorticity to the incoming southwesterlies. Examination of the NOGAPS near-surface (10 m) winds at 070212 reveals that indeed strong convergence existed southwest of the major TC circulation at the west coast of Taiwan (Fig. 5a). One day later when Mindulle moved northward to about 30°N, only a slight convergence area associated with the southwesterlies remained west of Taiwan (Fig. 5c). At the upper level, divergence flow is seen to persist in the vicinity of Taiwan from 070212 to 070312 (Figs. 5b and d). At 070312, a diffluent flow between the high-pressure system in mainland China and a trough to the north was at the Taiwan Strait. A concern here is that synthetic data has been added to the data assimilation cycles of NOGAPS (Goerss and Jeffries 1994) in order to improve TC track forecasts, but may modify the circulation near the locations of the synthetic data. Therefore, local weather maps from the CWB are also examined to verify the NOGAPS flows. The CWB maps indicate that the low-level TC circulation in NOGAPS agrees well with observations (not shown). One slight discrepancy is at the upper level in that the station observations show that the cyclonic circulation associated with Typhoon Mindulle at 070212 was actually quite deep and extended as high as 200 hPa (not shown). Nevertheless, the diffluent flow suggested by NOGAPS is correct to a large extent.

Another source to verify the near-surface winds is the QuikSCAT oceanic winds. Except the rain contamination problem, they provide the ground truth about wind magnitude over the data-sparse ocean surface. There were two swathes of QuikSCAT data passed by the Taiwan Strait at 07021312 and 07031312, respectively (Fig. 6). At 07021312, the convergence between the northerlies from Mindulle's circulation and the southwesterlies at about 24°N is clear. Note that the maximum magnitude of convergence computed from NOGAPS data is about 20–30×10^{-6} s^{-1} (Fig. 5a). Rough estimate using the QuikSCAT raw observations obtains a value that is up to an order of magnitude larger. A day later at 07031312 when the center of Mindulle was further to the north, the QuikSCAT data also shows southwesterlies throughout the Taiwan Strait and the east coast as in the NOGAPS data (Fig. 5c).

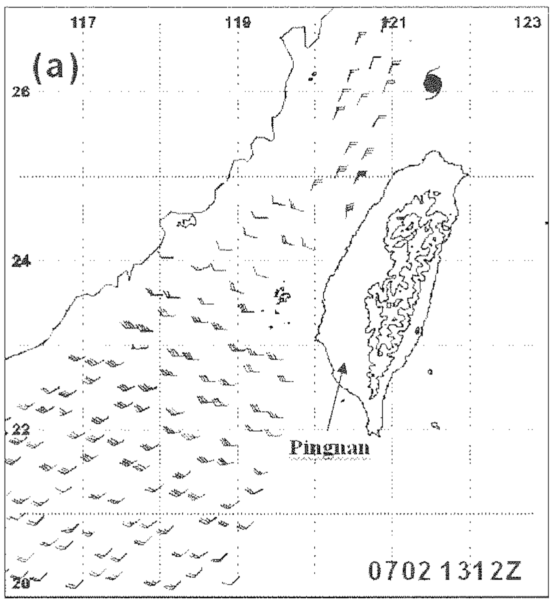

Fig. 6 QuikSCAT ocean winds at (a) 07021312 and (b) 07031312.

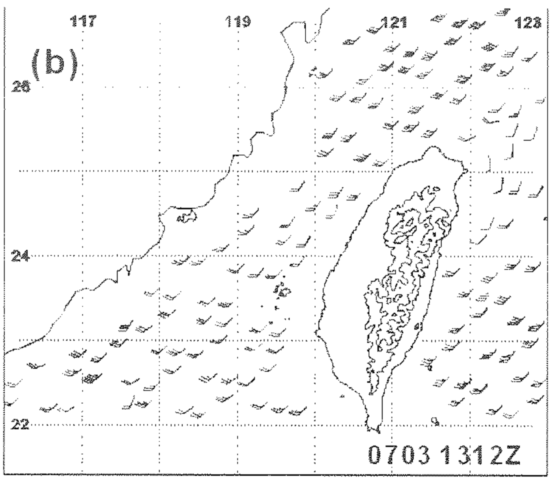

Fig. 6 (continued)

b. Warm and moist southwesterly flow

The second important factor determining the heavy rainfall event is moisture supply, which came mainly from the southwesterlies during early July. The NOGAPS specific humidity fields at 1000-hPa indicate that low-level moisture is abundant in the entire region of southwesterlies from the first day of July till 070300 (not shown). There was diurnal variation as seen in the data, but the SCS remained relatively moist throughout the period. In contrast, the air was relatively dry at the TC circulation with strong winds aloft. Another noteworthy feature is that the air over mainland China was also dry. During the heavy rainfall event between 070212 and 070312, the circulation of Mindulle was just at a position advecting the dry air over land towards the moist southwesterlies. The formation of this near-frontal system resulted in the line structure as seen in the radar reflectivity data (Fig. 4) and hence the localized center of rainfall at the southwestern part of Taiwan during the day.

c. Other factors

Two other factors playing important role in the heavy rainfall event are the high-pressure system east of the Philippines and Taiwan's orographic effect. The former, as mentioned in section 3a, provided an "appropriate" synoptic pattern for the southwesterlies and that their convergence with the TC circulation is right at the Taiwan Strait. If it were a low-pressure system in the area, then either the southwesterlies are reduced in speed or deflected in direction. In either case their interaction with the TC circulation will be quite different. Moreover, this synoptic pattern is highly similar to the two historical cases of Typhoon Ellen (1959) and Typhoon Agnes (1981) depicted in Yu (1982), which shows that this is a typical synoptic situation for heavy rainfall event associated with southwesterlies.

In previous studies (some of them mentioned in the Introduction), the rainfall by orographic lifting effect has been much emphasized. In this heavy rainfall event associated with Typhoon Mindulle, orographic effect only played its determining role after 070312 when Mindulle was further away from the Taiwan Island and the peak rain rate around 070300 due to the convergence of Mindulle's circulation with the southwesterlies ceased. After 070312 when only the southwesterlies were dominating, the orographic lifting effect turned in and brought the rainfall center back to the CMR (Figs. 3d and e). Detailed comparison of the rainfall sequences also reveals that the southwesterlies first brought a peak rain rate to the southern part of the CMR at about 070318. Several hours later large rain rate was also found at the northern part of the CMR because the mountains at that location are facing the southwesterlies and hence orographic lifting is most effective.

A simple estimation of the rain rate due to orographic lifting can confirm the above statements. The sounding data obtained at the city Tainan (23°N, 120.2°E) at 070200 is put into the term $\rho/\rho_w \times E(V_H \cdot \nabla h) \times qL_s/C_s$ to estimate the orographically induced rain rate where ρ is the air density, ρ_w the water density, E the precipitation efficiency (taken to be 1), V_H the low-level horizontal flow velocity, h the mountain geometry, q the water vapor mixing ratio and L_s/C_s the duration of the convective system that is taken to be 3 h (Lin et al. 2002). The contribution from the environmentally forced vertical motion has been neglected in this estimation. Using a typical value of 0.047 for the height gradient of the CMR, the rainfall amount is estimated to be 117 mm within 3 h. As a matter of fact, this rainfall amount is similar to that actually obtained at the southern part of CMR around 070318 when the southwesterlies were flowing towards the CMR, showing the dominating role of the orographic lifting effect at that time.

5. Conceptual model

In summary, the spatial and temporal distribution of rainfall in Taiwan during 2–4 July associated with Typhoon Mindulle and the accompanied southwesterly flow is diagnosed with conventional analyses and remote-sensing data, and all the available data is found to be consistent in explaining the rainfall sequence. Similarity with a few historical cases reported in previous studies allow us to derive a conceptual model of rainfall caused by an interaction of TC circulation north of Taiwan and the monsoonal southwesterlies. In Phase 1 of the conceptual model, a TC is either north of Taiwan or already made landfall over the northern part of Taiwan during the summer monsoon. Its low-level cyclonic circulation west of the TC center brings the dry northerlies from land southward, and these northerlies merge with the warm, moist monsoonal southwesterlies to form a convergence line that is east-west oriented (Fig. 7a). The severe convective activities at the convergence line bring a large amount of rainfall to the southwest plain of Taiwan. Phase 2 of the conceptual model is a continuation of Phase one but the TC circulation is moving northward, and hence a new convergence line between the dry northerlies and moist southwesterlies forms in the Taiwan Strait (Fig. 7b). In addition, if there is confluent flow within the southwesterlies under the influence of the TC circulation, a confluence line might also form south of the convergence line. In Phase 3, the TC is further away from Taiwan, and the effect of the TC circulation to the Island ceases. Strong southwesterlies continue to flow over the entire Taiwan area. Orographic lifting of the southwesterlies takes the place of the convergence line as the primary mode of interaction, and convective rainfall forms in upstream side of the CMR (Fig. 7c).

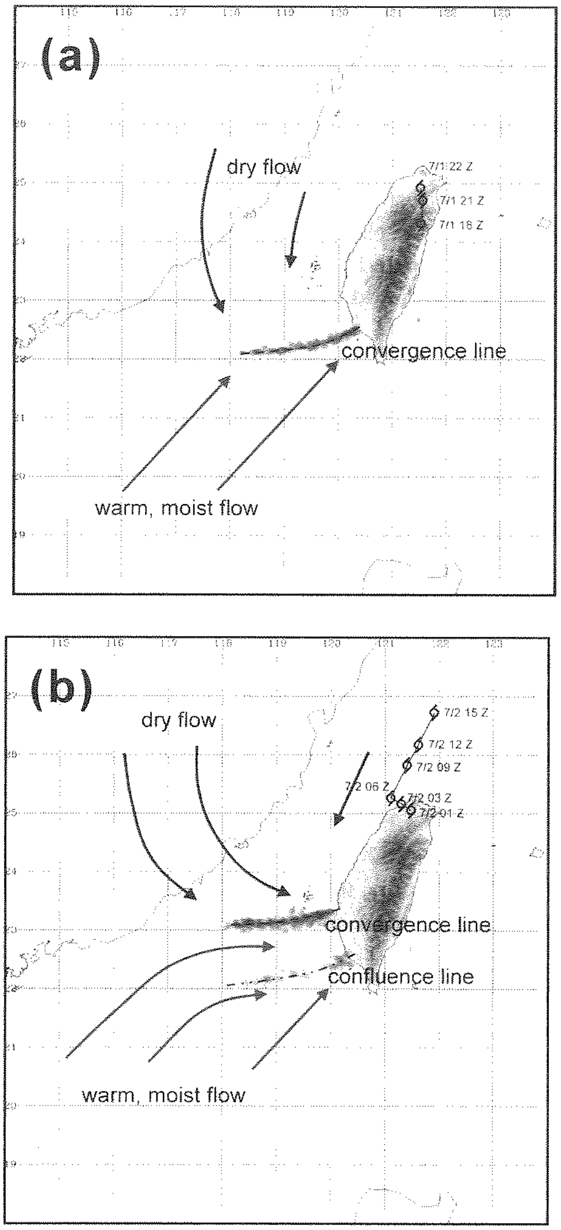

Fig. 7 Schematic diagram of the convections formation during Typhoon Mindulle. (a) Phase 1: Typhoon landfall at northeast Taiwan. Dry northerlies and moist southwesterlies merged and formed a convergence line southwest of Taiwan. (b) Phase 2: Typhoon center moved northeastward away from Taiwan. The typhoon circulation, dry northerlies and moist southwesterlies merged and formed a new convergence line in the Taiwan Strait. A confluence line within the southwesterlies might also form south of the convergence line. (c) Phase 3: Typhoon is away from Taiwan and strong southwesterly flow covered all Taiwan area. Convections formed in upstream side of mountain area.

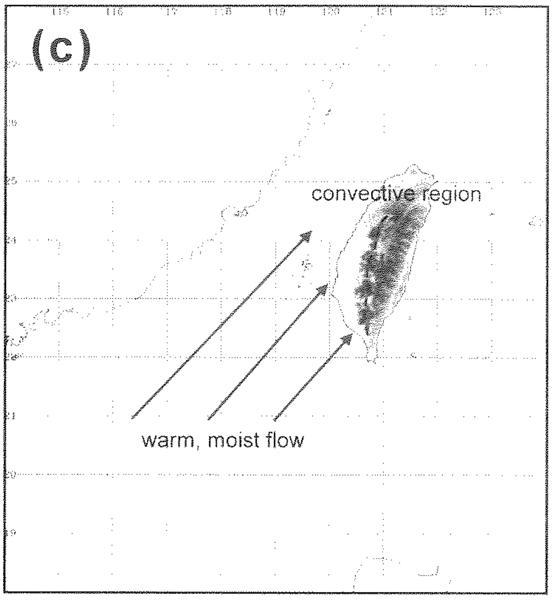

Fig. 7 (continued)

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