Asia-Pacific J. Atmos. Sci., 47(3), 213-222, 2011
DOI:10.1007/s13143-011-0010-2

Advances in Understanding the "Perfect Monsoon-influenced Typhoon": Summary from International Conference on Typhoon Morakot (2009)

Cheng-Shang Lee[1,2], Chun-Chieh Wu[1], Tai-Chi Chen Wang[3] and Russell L. Elsberry[4]

[1]*National Taiwan University, Taipei, Taiwan*
[2]*Taiwan Typhoon and Flood Research Institute, Taipei, Taiwan*
[3]*National Central University, Taichung, Taiwan*
[4]*Naval Postgraduate School, Monterey, California, U. S. A.*

(Manuscript received 25 August 2010; revised 9 November 2010; accepted 14 December 2010)

Abstract: Typhoon Morakot (2009) produced 2855 mm of rain and was the deadliest typhoon to impact Taiwan with 619 deaths and 76 missing persons, including a landslide that wiped out an entire village. While Morakot did not exceed the heaviest 24-h rain record, the combination of heavy rain and long duration that led to the record accumulation is attributed to the southwest summer monsoon influence on the typhoon. Thus, a special combination of factors was involved in the Morakot disaster: (i) Strong southwesterly monsoon winds; (ii) Convergence between the typhoon circulation and monsoon flow to form an east-west oriented convective band over the Taiwan Strait that was quasi-stationary and long-lasting; (iii) A typhoon in a specific location relative to the Central Mountain Range and moving slowly; and (iv) Steep topography that provided rapid lifting of the moist air stream. The contributions of each of these four factors in leading to the Morakot disaster are reviewed primarily based on new research presented at the International Conference on Typhoon Morakot (2009). Historical data sets, new Doppler radar observations, and numerical modeling have advanced the understanding of the special conditions of monsoon-influenced typhoons such as Morakot. This research is also leading to modifications of existing and development of new forecasting tools. Gaps in scientific understanding, limits to the predictability, and requirements for advanced forecast guidance tools are described that are challenges to improved warnings of these extreme precipitation and flooding events in monsoon-influenced typhoons.

Key words: Typhoon Morakot rainfall, monsoon-influenced tropical cyclones, tropical cyclone rainfall prediction, tropical cyclone track prediction, tropical cyclone flooding

1. Introduction

In the book and movie ≪The Perfect Storm≫, a special set of circumstances (including a human element) led to a disaster because a ship encountered extreme winds and waves. By analogy, the disaster in which at least 500 people in the mountain village of Shiao Lin (23.3°N, 120.6°E) died when a landslide was triggered by extreme precipitation in Typhoon Morakot may justify it to be labeled as "The Perfect Monsoon-influenced Typhoon". Typhoon Morakot was the deadliest typhoon to impact Taiwan in recorded history with 619 confirmed deaths, 76 missing persons, and roughly NT $16.4 billion (USD 547 million) agricultural losses. This typhoon produced 2855 mm of rain (Fig. 1), which greatly surpassed the previous record of 1994 mm set in Typhoon Herb (1996). This slow moving storm also caused widespread damage in China with nearly 6000 homes destroyed and 136,000 homes that were damaged at a cost of USD 1.3 billion.

The largest economic damage in mainland China occurred after Typhoon Bilis was inland and began to move slowly, but the southwesterly monsoon provided a large water vapor flux that sustained the heavy precipitation and led to severe flooding. By contrast, the largest rainfall and damage associated with Morakot was far removed from the center of the typhoon, and was along the steep slopes of the Taiwan Central Mountain Range (CMR). Other tropical cyclone basins such as the North and South Indian Ocean and the eastern North Pacific have a monsoon influence. Another disaster during 2009 in which a landslide along the slopes of a volcano in El Salvador killed more than 200 people was also a remote rainfall event (Lorena Soriano de Cruz, private conversation, March 2010). Whereas the associated hurricane was in the Caribbean, the westerly flow from the eastern North Pacific monsoon was pulled across El Salvador and the moisture flux was rapidly lifted along the volcano slope.

In the case of Morakot and other extreme rain events over Taiwan, the monsoon influence that led to the long duration and intense rainfall (Fig. 1) then triggered the landslide that wiped out the entire village. In these cases, the southwest monsoon flow provides water vapor flux to a heavy rain area well to the south of the center (Fig. 2a). Large moisture convergence between the monsoon flow and the equatorward moisture flux on the west side of the typhoon then leads to an east-west oriented rainband over the Taiwan Strait to the west of the CMR (Fig. 2b). However, this rainband only occurs when the typhoon is in a limited range of positions relative to the CMR. Furthermore, a long duration of the heavy rain in a concentrated region of the CMR will only occur if the typhoon is slowly moving. If the typhoon is moving at typical translation speeds,

Corresponding Author: Professor R. L. Elsberry, Department of Meteorology, Naval Postgraduate School, 589 Dyer Road, Room 254, Monterey, California 93943-51143, U. S. A.
E-mail: Elsberry@nps.edu

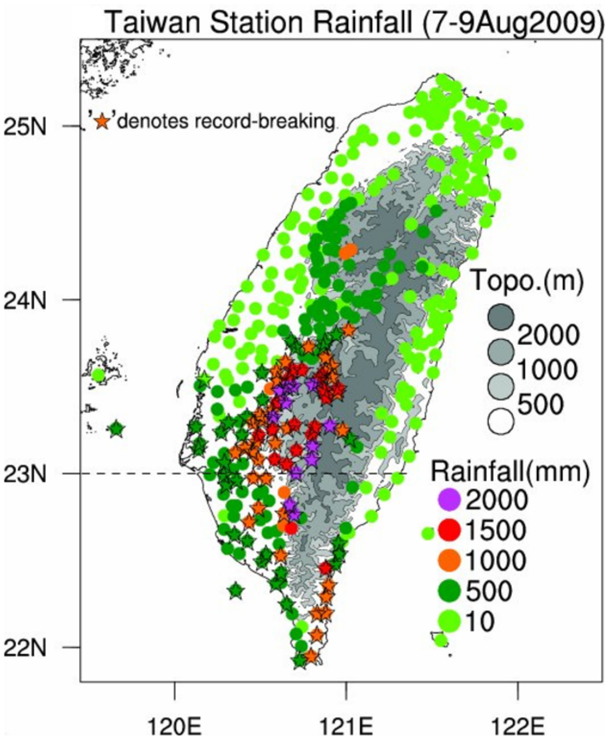

Fig. 1. Taiwan station rainfall during 7-9 August 2009 associated with the monsoon-influenced Typhoon Morakot. Rainfall amounts (mm) are indicated by the colored dots, with a star indicating record amounts for the station. The topography (m, see inset) of the Central Mountain Range is indicated (Hsu *et al.*, 2010). The location of the disastrous landslide at Shiao Lin is near 23.3°N, 120.6°E.

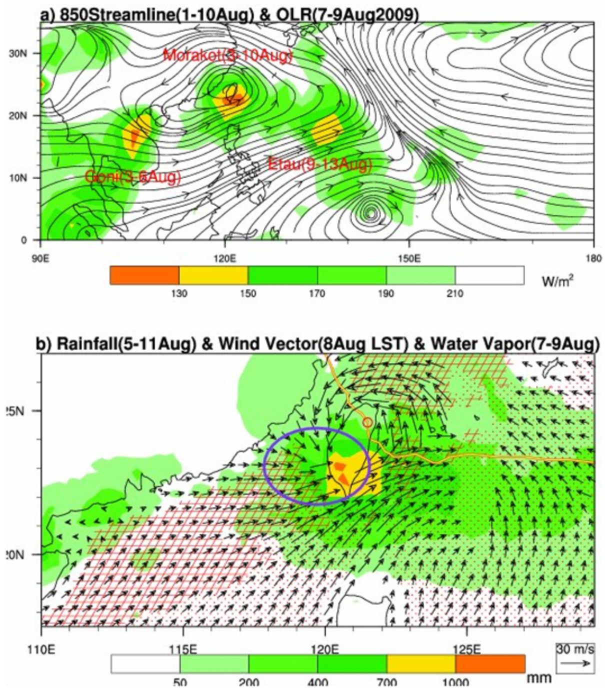

Fig. 2. (a) Streamlines at 850 mb averaged over 1-10 August 2009 and Outgoing Long-wave Radiation (OLR) averaged over 7-9 August (when the heavy rains in Fig. 1 were occurring) with the relative locations of Typhoon Morakot that occurred between 3-10 August, Tropical Storm Goni that occurred between 3-6 August, and Tropical Storm Etau that occurred between 9-13 August. (b) Wind vectors on 9 August 2009 and water vapor transport averaged over 7-9 August with arrows indicating the convergence between the southwesterly monsoon flow and the outer circulation of Typhoon Morakot (Hong *et al.*, 2010).

the heavy rain at a point will be relatively transient.

A very special condition for the extreme precipitation in Morakot is of course the steep topography and high elevation of the CMR of Taiwan (Fig. 1). The CMR is roughly 3 km in elevation with a major southern peak near 23°30'N, 121°00'E. The disastrous and slide occurred in a narrow valley on the slopes of the southern peak when the soil became unstable under the long and heavy rainfall that was occurring on the slopes.

In summary, the perfect monsoon-influenced typhoon that leads to extreme precipitation and associated flooding and potential landslides such as in Morakot requires a special combination of factors: (i) Strong southwesterly monsoon winds; (ii) convergence between the typhoon circulation and monsoon flow to form an east-west oriented convective band over the Taiwan Strait that is quasi-stationary and long-lasting; (iii) typhoon in specific locations relative to the CMR and moving slowly; and (iv) steep topography that provides rapid lifting of the moist air stream over a limited horizontal area such that the heavy precipitation is highly concentrated.

The first objective of this review is to use presentations at the International Workshop on Typhoon Morakot (2009) in Taipei, Taiwan during 25-26 March 2009 to describe extensive research with historical data sets, new radar observations, and numerical modeling that have advanced understanding, and that this research is then leading to modifications of existing, and development of new, forecasting tools to improve forecast guidance. The second objective is to describe gaps in understanding and the advanced forecast guidance tools that are considered to be required to improve warnings of these extreme precipitation and flooding events in monsoon-influenced typhoons.

2. Contributions of the monsoon flow

The Asian-Pacific monsoon circulation is a major factor throughout the life cycle of many western North Pacific typhoons. In the typical northwest-southeast orientation of the monsoon trough over the western North Pacific, all of the favorable environmental factors for tropical cyclone formation are present with high sea-surface temperatures, convectively unstable air with a moist mid-troposphere, cyclonic vorticity in the lower troposphere, and minimum vertical wind shear over the trough axis. Many tropical cyclones form at the eastern end of the monsoon trough in conjunction with wave disturbances approaching from the east, and then the typhoon moves northwestward. However, the formation of Morakot occurred at a more northern location (near 20°N, 131°E) and first moved eastward before sharply turning westward to move along 23°N toward Taiwan (Fig. 3).

An important characteristic of Morakot was the highly

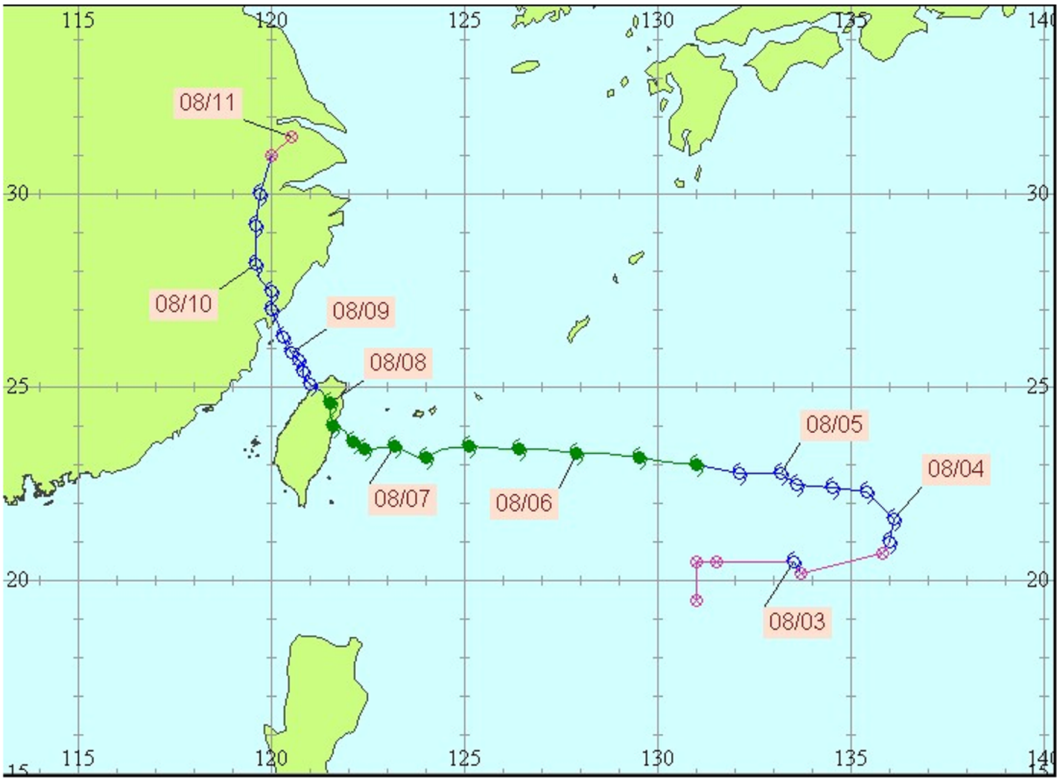

Fig. 3. Best track of Typhoon Morakot in 6-h intervals from Taiwan Central Weather Bureau. Notice the slow motion between 7-9 August when the rainfall accumulations in Fig. 1 were occurring (Hsu *et al.,* 2010).

asymmetric convection pattern as the typhoon approached Taiwan (Fig. 4). That is, an extensive region of convection was found in the south and southwest regions of the system compared to the northeast and north regions. Taiwan and the extreme western North Pacific region were experiencing drought conditions (Hsu *et al.*, 2010) due to subsidence and drying in the descent branch associated with the moderate El Niño occurring during 2009. Such subsidence in the subtropical anticyclone may have contributed to drier air on the easterly tradewind side of the monsoon trough that was not as conducive for deep convection in comparison with the warm, moist equatorial westerlies (Fig. 2a).

An alternate interpretation of the large-scale circulation during the Morakot event as a monsoon gyre has been suggested by Hong *et al.* (2010). The monsoon gyre circulation as defined by Lander (1994) has an outer closed isobar diameter of about 2500 km with an extensive band of deep convection in the equatorial westerlies that then curves cyclonically around the eastern end of the circulation in an "inverted fish hook configuration. Since this cloud band has an associated lower-tropospheric wind maximum, the tropical cyclones associated with the monsoon gyre (it is extremely rare that the gyre circulation becomes a typhoon due to the inner region being relatively dry and the maximum winds are at large radii) tend to be small as they form along the inner-region of cyclonic shear. By contrast, Typhoon Morakot was a relatively large (top 3% of 30 kt wind radii according to Lee *et al.*, (2010)) typhoon as it approached Taiwan (Fig. 4), and may be considered to have originated from a monsoon depression versus from a monsoon gyre (Lander 1994).

Huang *et al.* (2010) note that Tropical Storm Goni was to the southwest of Morakot and Tropical Storm Etau was to the east-southeast of Morakot (Fig. 2a), which is somewhat consistent with the monsoon gyre conceptual model of Lander (1994). However, Tropical Storm Goni was embedded in the southwesterly monsoon flow that extended to Taiwan. Indeed, Huang *et al.* (2010) suggest that the presence of Goni was contributing to the southwesterly water vapor flux toward Morakot. In the Huang *et al.* (2010) numerical sensitivity test in which they "deactivated" the Goni vortex by using their Bogus Data Vortex technique, the southwesterly flow was weakened and the total accumulated rainfall in the southern CMR was reduced by about one third. Elsberry (2010) presented two Chinese studies that also attributed an important role to Tropical Storm Goni in the rainfall accumulation during Morakot. In the numerical sensitivity test by Qian (2010), elimination of the southwesterly water vapor flux reduced the rainfall accumulation more substantially than elimination of the vapor flux from other quadrants.

Lee *et al.* (2010) stated that another consideration with monsoon gyres is that they always have a Mesoscale Convective Complex (MCC; as defined by Maddox, 1980) in the outer region. In the 31% of all western North Pacific tropical cyclones in their study that had an embedded MCC, the MCC was to the southwest of the cyclone center at 200-300 km from the center.

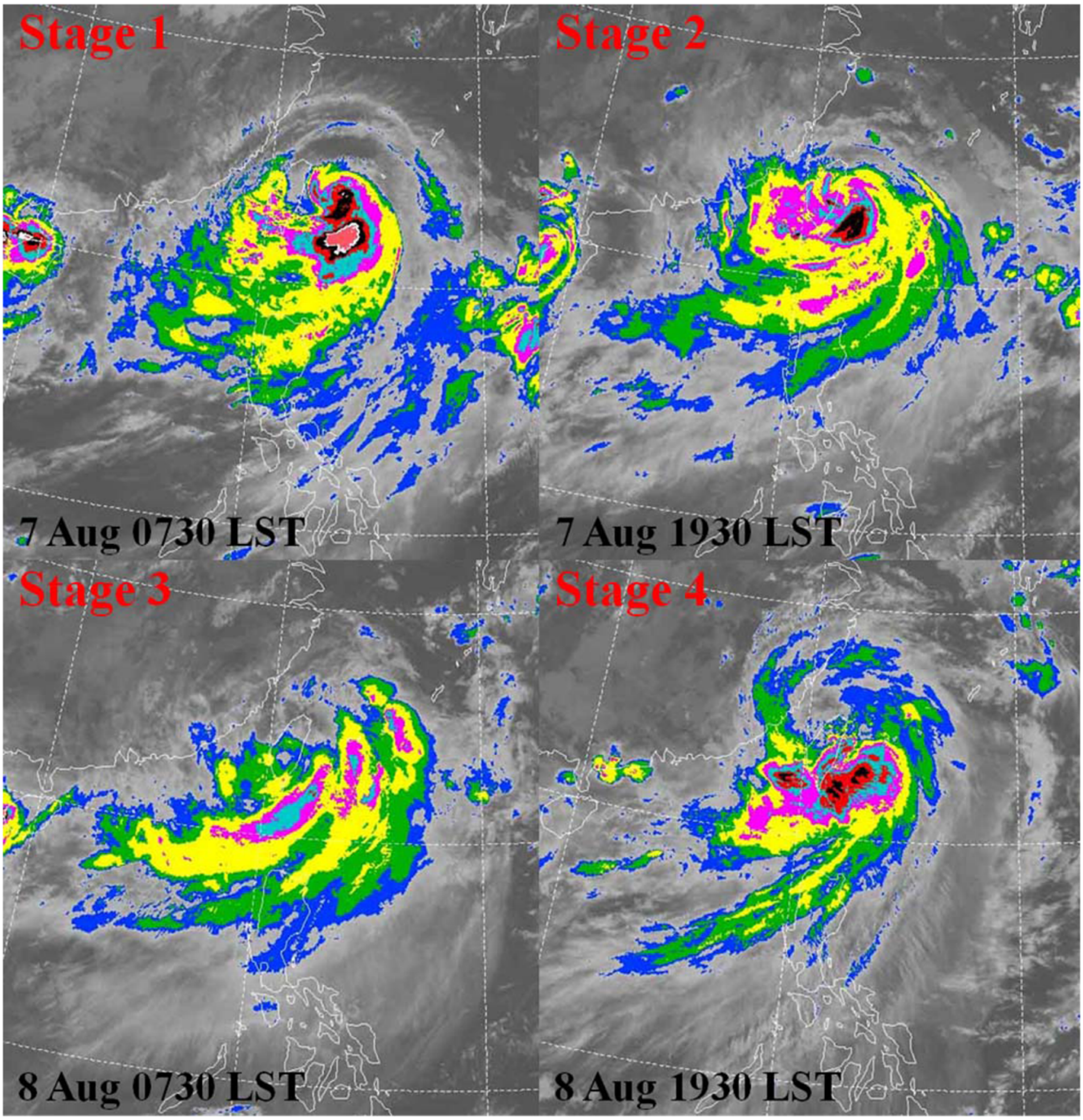

Fig. 4. Satellite imagery at 0730 LST 7 August (upper-left), 1930 LST 7 August (upper-right), 0730 LST 8 August (lower-left), and 1930 LST 8 August (lower-right) illustrating the large size but highly asymmetric convection associated with Typhoon Morakot as the center passed northern Taiwan (Wang *et al*., 2010, imagery provided by CWB Satellite Center).

These characteristics suggest the importance of the southwesterly monsoon that can sustain these large, long-lasting convective systems in the outer region of a typhoon. It will be demonstrated in section 3 that persistent MCC-type deep convection where the outer circulation of Typhoon Morakot interacted with the monsoon flow was an important contribution to the heavy rainfall.

Regardless of whether Morakot originated from a monsoon gyre or a monsoon depression, the southwesterly monsoon flow and the associated southwesterly water vapor flux played a key role in the extreme precipitation over southern Taiwan. Chien *et al.* (2006) had previously studied the heavy rain over southern and central Taiwan associated with northward-moving Typhoon Mindulle (2004) that also featured a convergence line between the typhoon circulation and the southwesterly flow of the monsoon. They examined 56 y of the Joint Typhoon Warning Center northward-moving tracks near Taiwan and found that 33 of the 59 cases were associated with a southwesterly monsoon flow. However, the remaining 26 cases did not have southwesterlies, so a sizeable fraction of these cases did not interact with the monsoon flow.

Another complex remote rainfall event over the Taiwan terrain in conjunction with the outer typhoon circulation interacting with the northeasterly monsoon flow has recently been studied by Wu *et al.* (2009). Even though Typhoon Babs (1998) was well to the south of Taiwan as it moved westward across Luzon, Philippines and into the South China Sea, the convergent flow between the outer typhoon circulation and the northeasterly monsoon led to heavy rainfall in eastern and northeastern regions of Taiwan. Numerical sensitivity tests demonstrated the critical role of the terrain, the outer typhoon circulation strength, and the strength of the northeasterly monsoon flow. Similar sensitivity studies would be useful to explore the role of these factors in the Typhoon Morakot heavy rainfall event.

3. Contributions of the east-west oriented convective band

In the Qian (2010) numerical simulation described by Elsberry (2010), the rainfall amount was under-estimated because the monsoon flow was oriented such that the maximum convergence of moisture flux at 700 hPa was on the eastern side of the southern CMR rather than the western side. Chuang and Wei (2010) used the C-band dual-polarization radar in Makung, Taiwan (23.6°N, 119.6°E) and the S-band Doppler weather radar in Qigu (23.1°N, 120.1°E) to analyze the kinematic structure of the convective cells in Typhoon Morakot during 2200 UTC 8 August to 0600 UTC 9 August. A linear rainband oriented east-west existed in the vicinity of the Taiwan west coast with a significant confluence between the westerly flow associated with the typhoon and the southwesterly monsoon flow. The dual-Doppler radar wind analysis documented a jet-like westerly flow between 2 km and 5 km with a maximum exceeding 24 m s^{-1} that was associated with the east-west rainband. New cells developed upstream of the confluence line and propagated eastward inland toward the CMR.

Wang *et al.* (2010) utilized the entire Taiwan weather radar network of six Doppler radars and four dual polarization radars during five stages of the Morakot passage: (1) Approach to Taiwan; (2) Slow movement; (3) Landfall; (4) Typhoon center in Taiwan Strait; and (5) Approach to Fujian Province. From the radar analyses during stage (4) by Tang (2010), strong east-west oriented rainbands repeatedly formed near southwestern Taiwan along the convergence zone between the typhoon circulation and the southwesterly monsoon flow (Fig. 5). Notice the east-west band designated D3 in Fig. 5a that extends from over the Taiwan Strait at the edge of the radar coverage to the region of the southern CMR where the landslide occurred. Individual convective cells in the bands are shown in the horizontal radar reflectivity depiction at 4 km at 1600 LST 8 August 2009 (Fig.

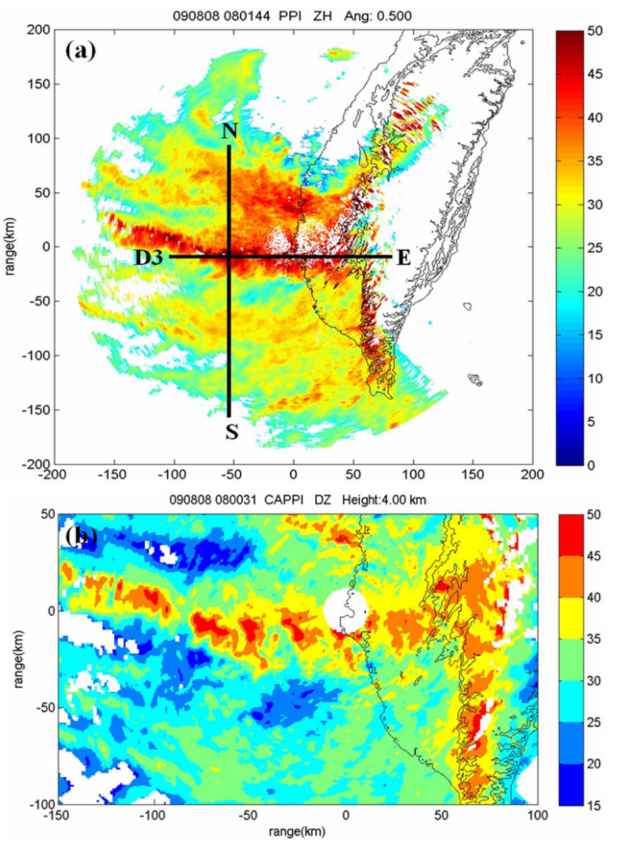

Fig. 5. (a) Plan-position indicator of the radar reflectivity (dBZ, scale on right) at 1601 LST 8 August 2009 as the major devastating rainband designated D3 extended from over the Taiwan Strait to the CMR. (b) Radar reflectivity at 4 km at 1600 LST 8 August indicating individual convective cells along the rainbands (Tang, 2010).

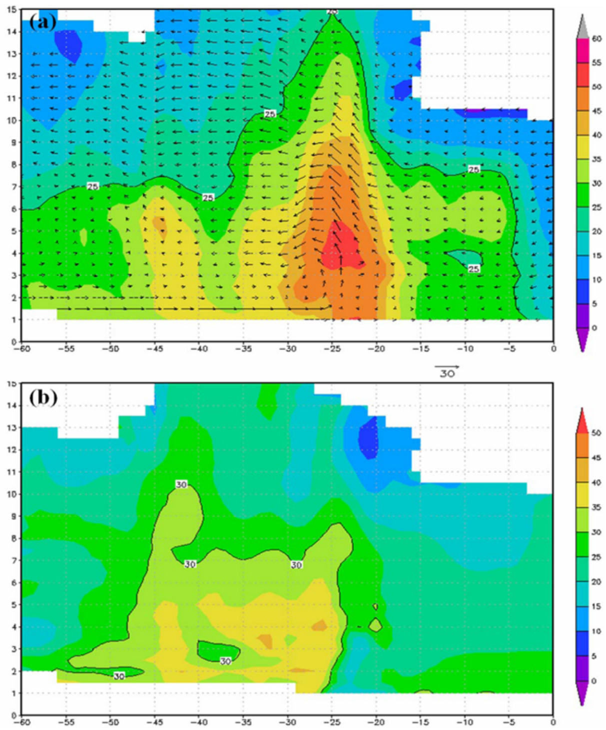

Fig. 6. Vertical cross-sections through a deep convective cell along the North-South line in Fig. 5a of the (a) radar reflectivity (dBZ, scale on right) and vertical and horizontal cell-relative wind vectors, and (b) isotachs of the total wind (m s^{-1}, scale on right). Distances (km) along the abscissa are from the southern end of the line, and the elevations on the ordinate are in kilometers (Tang, 2010).

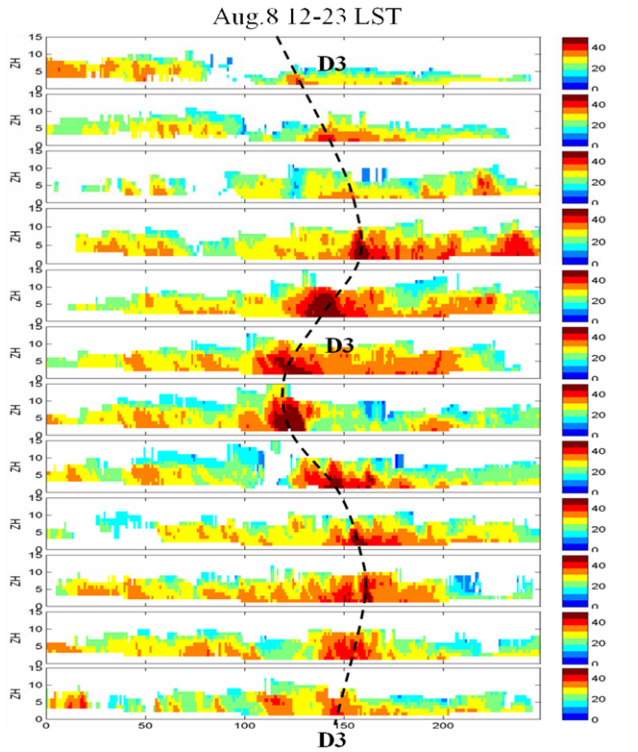

Fig. 7. Hovmoller diagram of the radar reflectivity associated with rainband D3 in Fig. 5a as a function of distance from the radar during 12-23 LST 8 August 2009. The dashed line indicates the presence of very deep convective towers in rainband D3 while the rainband oscillates between 22.5°N and 23.5°N (Wang *et al.,* 2010).

5b). The curvature of the rainband suggests it is related to the outer circulation of Typhoon Morakot and that deep convective cells are beginning at the western end and grow as they propagate along the band toward the coast. These deep convective towers persisted for about two hours and moved rapidly toward the island.

A north-south cross-section through one of the convective cells (Fig. 6a) indicates a strong updraft on the north side (side toward typhoon center) with a strong downdraft in the mid-troposphere on the south side. At this time, the strongest low-level relative inflow to the band was from the south. The corresponding vertical cross-section of the wind speeds (Fig. 6b) indicates the deep convective cell was on the southern boundary of a low-level jet with speeds of 35-45 m s^{-1}. Clearly, this low-level jet was transporting large amounts of water vapor toward the west coast of Taiwan and the southern CMR, and this was contributing to the extreme precipitation.

Although these rainbands generally propagated southward, the major devastating rainband oscillated between 22.5°N and 23.5°N, as indicated in the Hovmoller diagram in Fig. 7. This oscillatory motion of the rainband appeared to be related to a reversal in the relative strength of the low-level inflow from the south and then from the north. These radar studies provide conclusive evidence of the convective cells that build in the convergence line between the typhoon circulation and the southwesterly monsoon winds, and that the east-west orientation of this rainband directed the convective cells toward the CMR.

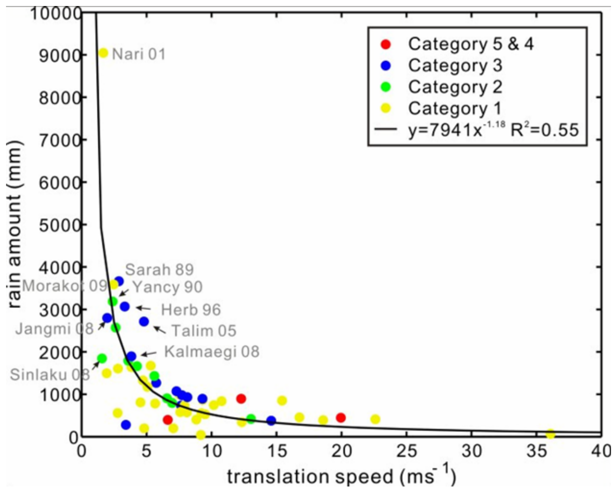

Fig. 8. Translation speed (m s^{-1}) of various typhoons with intensities of greater or less than 40 m s^{-1} while approaching Taiwan and the accumulative rain (mm) at 35 CWB stations. Notice that Typhoon Morakot had one of the slowest crossing speeds and one of the highest rain accumulations (Kuo *et al.,* 2010).

4. Contributions due to typhoon location and slow translation

Yeh and Chang (2009) updated a previous climatological study of the average rainfall amounts when a typhoon existed within various 1° latitude by 1° longitude boxes around Taiwan. This new study utilizing the 400 automated surface observation sites did not fundamentally change the distribution in various regions of Taiwan. However, this study re-affirms that large rain accumulations are to be expected in the southern CMR region where the disastrous landslide occurred during Morakot when the typhoon is near the northern tip of Taiwan. However, these are average rainfall amounts, and do not take into account topographic irregularities. Furthermore, the climatological study does not take into account the typhoon translation speed (or direction).

Kuo *et al*. (2010) demonstrated that large variability exists in translation speed of typhoons near Taiwan. They defined the translation speed of a typhoon crossing Taiwan as the distance between the landfall and departure points divided by the crossing time. Many of the largest rainfall events associated with tropical cyclones have occurred when this storm translation speed was small (Fig. 8). Indeed, Typhoon Morakot had one of the slowest translation speeds while it was in the Taiwan Strait and this is clearly an important factor in the duration of the heavy rainfall amounts both in Taiwan and in mainland China region.

Chien (2010) examined the translation speed of Morakot right before, during, and after the typhoon made landfall. The translation speed of 7.7 km h^{-1} after landfall was uniquely slow, which Chien attributed in part to the presence of Tropical Storm Etau to the east (Fig. 2) having weakened the influence of the subtropical anticyclone on the northward-moving Morakot. In addition, the presence of two midlatitude troughs to the north and northeast of Morakot was also considered to contribute to a weak steering flow over Morakot. Presumably the passage of the eastern midlatitude trough lead to an equatorward flow that also impeded the northward-directed steering flow associated with the subtropical anticyclone to the east.

Yeh *et al.* (2010) indicate that the Taiwan Central Weather Bureau (CWB) 24-h track forecast errors for Morakot were about 87 km, which is smaller than the CWB average track errors in the recent past. However, the translation speed was over-estimated, so that a 24-h early passage of Morakot by northern Taiwan led to an underestimate of the influence of the typhoon on the island rainfall. Yeh *et al.* (2010) also noted that use of a climatological or analog symmetric rainfall distribution would have over-estimated the rainfall to the north of the path because the convection in Morakot was highly asymmetric (Fig. 4).

5. Contributions due to steep CMR topography

The first contribution of the CMR topography may have been via interaction with the circulation of Typhoon Morakot to cause track deflections and the translation speed changes. Many studies have been made of the track modifications as a typhoon circulation interacts with topography. This interaction is a multi-scale, complex process that depends on many factors (e.g., typhoon characteristics, translation speed and direction, environmental steering flow and thermal/moisture structure, etc.).

For the more direct extreme precipitation effect of the CMR topography, Yu and Cheng (2010) utilized dual-Doppler radar observations over a 80 km square domain to document various aspects of the intense orographic precipitation associated with Typhoon Morakot. Even over this primarily land region, > 40 m s^{-1} winds were observed at low levels at 2200 UTC 7 August. Careful processing of the radar observations was necessary to deal with beam blockage, ground clutter, etc., to obtain the lowest-level reflectivity values over the terrain. Animation of the high resolution radar reflectivity images revealed rapidly-propagating gravity wave-like features.

Two patterns of orographically-enhanced precipitation were studied in detail. In the northern region of radar coverage, the enhanced precipitation was closely related to local terrain features, with maximum precipitation at the valley exits of the lower foothills, especially when the low-level flow was west-southwesterly and thus more parallel to the orientation of the foothill ridges. Thus, convergence of the wind flow into the valleys appears to contribute to these precipitation maxima. In contrast, the heaviest precipitation in the southern region was along the windward slopes near and upstream of the mountain crest, especially when the upstream winds were westerlies that were thus more perpendicular to the primary axis of the southern CMR. Although rapid upslope lifting over narrow mountain slopes that may be only 10 km wide is obviously an important factor, strong flow over relatively small terrain features can also contribute significant precipitation.

Jou *et al.* (2010) composited the rain rate observations from four radars during Morakot. On 8 August, the largest rain rate was over the plain as a cell moved inland from the Taiwan Strait. Although the cell originated in the confluent flow over the Taiwan Strait, the speed confluence between the sea and the land was considered to be an additional contributor to the large rain rate over the plain.

6. Advancement in monsoon-influenced typhoon precipitation prediction

As indicated in section 4, the climatological distribution (Cli-Rain from Yeh and Chang (2009)) of average rainfall in various regions of Taiwan as a function of the typhoon position within 1^o latitude by 1^o longitude regions can provide a first-order precipitation forecast given the track forecast. This forecast would not take into account the monsoon influence (recall that Chien (2010) found only 33 of 59 cases had an influence) leading to an east-west oriented rainband or the storm translation speed leading to prolonged interaction with the CMR topography (valleys and ridges). However, such a synoptic climatology technique might be useful as a metric for evaluating the skill of more complex techniques.

Lee *et al*. (2006) have developed a forecast technique that provides hourly and cumulative rainfall amounts that considers the effects of the track, intensity, and size of the typhoon. Cheung *et al*. (2008) did an extensive verification of this climatology-persistence rainfall technique and discussed scenarios of rainfall when typhoons interact with the southwesterly or the north-easterly monsoon flows. Real-time verifications of the technique were provided during the 2008 season by Lee *et al.* (2010). In general, the rain accumulation forecasts are more skillful than the hourly rain forecasts and the rain amounts in Central Taiwan are more skillful than in the Taipei area. An enhancement of the technique to consider the SSM/I satellite-derived rain estimates within 500 km of the typhoon center is being tested.

Jou *et al.* (2010) propose using the differences in precipitation structure revealed from real-time radar composites to improve the Cli-Rain forecasts. Preliminary results do indicate some skill relative to the Cli-Rain technique. Future research will test whether real-time Doppler wind analyses could be used to improve the rainfall prediction in mountainous areas.

Hong *et al.* (2010) reviewed the operational Quantitative Precipitation Forecasting (QPF) procedure at the Taiwan Central Weather Bureau (CWB). This procedure includes the climatological technique and an analog technique as interpreted by an experienced forecaster who also considers a number of track forecasts to arrive at an official track forecast. One issue is how to separate track error contributions from QPF error contributions, since if the track forecast is accurate, the rain forecast guidance is useful. Since no forecast guidance technique is always the best, another issue is how the forecaster can determine which is the most accurate model or technique in each situation.

Hong *et al.* (2010) also compared eight numerical model QPFs during the landfall of Morakot. Three CWB models and three Taiwan Typhoon and Flood Research Institute (TTFRI) models with different initial conditions and model physics were part of the study. No skill was found for rain rates of less than 50 mm $6h^{-1}$. The best equitable threat score was found in the range of 50-100 mm $6h^{-1}$, and the skill decreased rapidly at larger rain rates. A common characteristic of the models was to over-predict the rain rate for amounts greater than 150 mm $6h^{-1}$, and those models initiated from "cold-start conditions" had a precipitation spinup problem. An "ensemble typhoon QPF" technique is being tested in which the ensemble member track that is most similar to the official track forecast will be selected to produce a composite rain map and probability of rain category product.

7. Gaps in understanding and forecast guidance products

A number of scientific, predictability, and forecast guidance product deficiencies became evident at the International Conference on Typhoon Morakot (2009). These deficiencies will be discussed in the same order as the four contributions to monsoon-influenced typhoon extreme precipitation events described in the previous sections.

a. Monsoon influence

Whereas it is generally accepted that typhoon prediction is a multi-scale problem with scales ranging from synoptic scale to the convective scales, the monsoon-influenced typhoon introduces a need for observing and predicting on a still larger scale. One positive factor is that these typhoons occur at the downstream portion of the Asian summer monsoon, and the Asian observational network provides reasonably accurate initial conditions. However, important Asian summer monsoon variability on intraseasonal time scales is not always well predicted. Such variability includes the 10-15 day monsoon trough variability that in turn affects the formation and initial structure of the pre-typhoon seedlings. The variable that is least well observed and predicted is the moisture field, which affects the convective heating distribution that then feeds back to the circulation changes.

The particular challenge for the monsoon-influenced typhoon prediction is to predict the horizontal and vertical structure of the water vapor flux toward the typhoon. More accurate observations of the moisture distribution and representation of the moist processes in the numerical weather prediction models are required. However, it is considered that the monsoon-influence contribution is the most predictable of the factors affecting the monsoon-influenced typhoon extreme precipitation events.

b. East-west oriented convective band

The east-west oriented convective band over the Taiwan Strait and its associated low-level jet have an essential contribution in initiating, growing, and propagating deep convective cells with heavy rain toward the CMR. As indicated by Kuo *et al.* (2010), analyses of past events indicate such a mesoscale convective band is a common feature of the ten most damaging monsoon-influenced typhoon precipitation events in Taiwan. This convective band forms in a confluence zone between the southwesterly monsoon flow and the outer circulation of the typhoon. Depending on the relative strength of these two circulations, the confluence zone will occur at several different latitudes over the Taiwan Strait. Thus, the outer wind structure of the typhoon must be known accurately in addition to the southwesterly monsoon flow structure.

This mesoscale region of confluence, deep convective cell growth and propagation, and the dynamical processes associated with the low-level jet, are the most interesting and challenging of the multi-scale interactions leading to the heavy precipitation and flooding in a Morakot-type scenario. A key issue is why and how the mesoscale convective band remains quasi-stationary so that deep convective cells move onshore and are focused in the same region of the CMR, and thus a heavy rain occurs for a longer period of time than if the band was moving. The dynamical and thermodynamical processes leading to such intense (> 40 m s^{-1}) low-level jets in association with the convective band are not understood or well predicted, and yet this low-level jet is a major contributor to the horizontal vapor flux across the west coast of Taiwan and toward the CMR.

Even if the outer wind structure and the southwesterly monsoon flow were known perfectly, it seems likely that the mesoscale and convective scale processes must have a significant role in maintaining a quasi-stationary east-west convective band. Thus, the predictability of such an event is likely to be considerably shorter than if it was only controlled by the typhoon circulation and the monsoon flow. In addition to a requirement for high horizontal resolution in the numerical weather prediction model, advances in the representation of mesoscale, convective scale, and boundary layer processes will be required to predict the initiation and evolution of the east-west convective band over the Taiwan Strait that then contributes to the extreme precipitation events on the slopes of the CMR.

c. Typhoon location and slow movement

Although dramatic progress has been made during the last decade in tropical cyclone track forecasting, special aspects of track prediction exist when a typhoon is interacting with the CMR. As indicated in section 4, the modifications of the typhoon outer wind structure, as well as changes in the convective heating distribution, may lead to track deflections from the environmental steering. If this environmental steering is relatively weak (e.g., near the subtropical ridge line, a midlatitude trough passage imposing an equatorward steering component, etc.), the typhoon-topography interaction effect will be more significant. In some cases, the low-level circulation is so modified by the interaction with the orography that it is difficult to determine where the center is. Indeed, a new low-level center may form over the Taiwan Strait so that the movement appears discontinuous.

When a typhoon is approaching northern Taiwan, the movement may be slow because the steering flow is being affected by the subtropical anticyclone, a midlatitude trough, the self-propagation associated with the beta gyres, and the typhoon-topography interaction described above. If a slow movement is anticipated, the forecast errors may be quite small, but the situation may have low predictability because of these four influences on the steering flow. Depending on which of the four influences becomes the dominant factor, the direction and speed of the typhoon motion may be quite different. Few conventional observations are available to the east of Taiwan in the subtropical anticyclone, which may not be well predicted due to the physical process representations in the model. Since large typhoons may also modify the subtropical anticyclone and thus "break through the ridge", the outer wind structure of the typhoon must be observed and forecast. While the midlatitude trough influence on tropical cyclone recurvature is well understood in principle, the amplitude and translation of the trough must be predicted as it interacts with the typhoon circulation.

When the typhoon circulation is also interacting with the CMR orography, the prediction of the location and movement of the typhoon near northern Taiwan is not a well-defined forecast problem. Huang *et al.* (2010) indicate great sensitivity to the typhoon track prediction in their numerical prediction where a relatively small northward deflection reduced the maximum accumulated rainfall by several hundred millimeters.

d. Taiwan topography

Some early numerical model simulations of typhoons interacting with the Taiwan topography utilized highly smoothed representations of the CMR. The high resolution radar studies of Morakot have indicated that the detailed topographical features of ridges and valleys in the foothills and canyons in the CMR affect the rain distribution. For example, Yu and Cheng (2010) documented that the local terrain features in the foothills must be considered to explain the precipitation maximum near the valley exit. They also emphasized that the low-level jet associated with the convergence zone can lead to flash flooding in the CMR canyons when the orientation is "optimum". This sensitivity to the detailed features of the Taiwan topography suggest a limited predictability of the rainfall at specific sites in the CMR.

e. Focus of the TTFRI

The specific foci of the Taiwan Typhoon and Flood Research Institute are: (i) Dual-polarized radar observations for the mountain areas that are vulnerable to debris flows, which will improve the quantitative precipitation estimates and the 0-3 h nowcasting; (ii) Advanced data assimilation techniques that will include the Doppler radar observations and thus improve the 3-6 h forecasts; and (iii) Development of a combined dynamical-statistical approach to quantitative precipitation forecasting on 24 h timescales, which recognizes that a strictly deterministic model may have limited validity for the extreme precipitation amounts in a Morakot-type event.

The TTFRI short-term objective is to forecast the 24-h rainfall in specific watersheds over Taiwan that are susceptible to flooding events with severe economic impacts. Their goal is to achieve within three years an equitable threat score of 0.3-0.4 for 24-h rainfall in each watershed. Clearly, achieving this goal will be a great challenge considering the complex topography of Taiwan. The presentations at the International Workshop on Typhoon Morakot (2009) will hopefully provide a basis for meeting this challenge.

Acknowledgments. This workshop was hosted by TTRFI and sponsored by the Taiwan National Science Council and National Applied Research Laboratories. Additional support was provided by the Central Weather Bureau, Institut Francias de Taipei, and the National Center for High-Performance Computing. The permission of various people for permission to publish their research and for providing figures is gratefully acknowledged. The participation of Russell Elsberry is funded by the U.S. Office of Naval Research Marine Meteorology section. Mrs. Penny Jones skillfully prepared the manuscript. Presentation powerpoints from International Conference on Typhoon Morakot (2009) are available at the website www.ttfri.narl.org.tw/workshop/morakot/index.php.

REFERENCES

Chien, F.-C., 2010: On the interaction between typhoons and southwesterly flow in the Taiwan area. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Cheung, K. K.W., L.-R. Huang, and C. S. Lee, 2008: Characteristics of rainfall during tropical cyclone periods in Taiwan. *Nat. Hazards Earth Syst. Sci.*, **8**, 1463-1474.

Chuang, Y.-C., and H.-C. Wei, 2010: Preliminary analysis on the kinematic structure of a convective rainband during the impact of Typhoon Morakot. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Elsberry, R. L., 2010: Tropical cyclone-related precipitation and flooding as a high priority WMO research objective. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, 25-26 March.

Hong, J.-S., C.-Y. Huang, F.-C. Chien, C.-C. Wang, M.-Y. Chang, and Y.-C. Yu, 2010a: Inter-comparison of the model QPF in Typhoon Morakot (2009). *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Hong, C.-C., M.-Y. Lee, H.-H. Hsu, and J.-L. Kuo, 2010: Role of submonthly disturbance and 40-50 day ISO on the extreme rainfall event associated with Typhoon Morakot (2009) in Southern Taiwan. *Geophys. Res. Lett.,* **37**, L08805, doi:10.1029/2010GL042761.

Hsu, H.-H., H.-C. Kuo, F.-C. Chien, C. Chou, J.-S. Hong, C.-Y. Huang, B. Jou, C.-S. Lee, P.-L. Lin, P.-H. Lin, C.-Y. Tu, T.-C. Wang, C.-C. Wu, M.-J. Yang, T.-C. Yeh, and Y.-C. Yu, 2010: Typhoon Morakot-A devastating category-2 typhoon. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Huang, C.-Y., C.-S. Wong, and T.-C. Yeh, 2010: The catastrophic Typhoon Morakot (2009): Mechanisms of the extreme rainfall in Taiwan. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Jou, B. J.-D., P.-L. Chang, L. Feng, and Y.-C. Kao, 2010: Precipitation and kinematic structure changes of Typhoon Morakot (2009) during the landfalling period. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Kuo, H.-C., T.-T. Yang, and C.-P. Chang, 2010: Typhoon Morakot (2009): Interplay of southwest monsoon, terrain, and mesoscale convection. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Lander, M. A., 1994: Description of a monsoon gyre and its effects on the cyclones in the western North Pacific during August 1991. *Wea. Forecasting*., **9**, 640-654.

Lee, C.-S., L.-R. Huang, H.-S. Shen, and S.-T. Wang, 2006: A climatology model for forecasting typhoon rainfall in Taiwan. *Natural Hazards*, **37**, 87-105.

______, Y.-H. Hsieh, and B.-F. Chen, 2010: An analysis of typhoons with active outer-region convections in the western North Pacific. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Maddox, R. A. 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc*., **61**, 1374-1387.

Qian, C.-H., 2010 : Analysis and numerical simulation of Morakot rainfall. Special lecture, *42nd Typhoon Committee meeting*, Singapore, 25-29 January.

Tang, Y.-S., 2010: The mesoscale characteristics of rainband from radar analyses: Typhoon Morakot (2009). M.S. thesis, Department of Atmospheric Sciences, National Central University, 82 pp (In Chinese).

Wang, T.- C., Y.-S. Tang, C.-H. Wei, P.-L. Lin, Y.-C. Liou, W.-Y. Chang, C. B. Chou, B.-T. Ji, and C.-Y. Lin, 2010: Precipitation characteristics of Typhoon Morakot (2009) from radar analyses. Science report of Typhoon Morakot, National Science Council, Taipei, Taiwan, 192 pp (In Chinese).

Wu, C.-C., K. K. W. Cheung, and Y.-Y. Lo, 2009: A numerical study of the heavy rainfall event due to the interaction of Typhoon Babs (1998) and the northeasterly monsoon. *Mon. Wea. Rev*., **137**, 2049-2064.

Yeh, T.-C., and C.-P. Chang, 2009: Terrain effects on the tropical cyclone rainfall over Taiwan. Presentation, *Second Int. Workshop on Tropical Cyclone Landfall Processes*, Shanghai, China, 19-23 October.

______, H.-C. Kuo, K.-C. Lu, S.-C. Wang, and Y.-L. Chen, 2010: Verification of the CWB Typhoon Morakot rainfall forecast and the opportunity of improving typhoon rainfall forecast. *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.

Yu, C.-K, and L.-W. Cheung, 2010: Some unique aspects of orographic precipitation associated with Typhoon Morakot (2009). *Int. Conf. on Typhoon Morakot (2009)*, Taipei, Taiwan, 25-26 March.