

TYPHOON MORAKOT

Key Findings from the Journal *TAO* for Improving Prediction of Extreme Rains at Landfall

BY CHUN-CHIEH WU

Typhoon Morakot (2009) was one of the deadliest typhoons to impact Taiwan in the past 50 years. It brought catastrophic damage to Taiwan, leaving 673 people dead and 26 others missing. This slow-moving storm produced huge amounts of rainfall, peaking at 2,965 mm (116.73 in.) in 4 days (7–10 August 2009), and caused enormous mudslides and severe flooding throughout southern Taiwan. One massive mudslide devastated the entire Shiaolin village, killing approximately 500 people in this village alone. The estimated agricultural losses amounted to roughly NT\$16.4 billion (about US\$550 million). Morakot also caused widespread damage in China and the Philippines. Improving forecasting techniques and early warning systems for landfalling tropical cyclones (TCs) has thus become one of the most important tasks facing scientists and governmental agencies.

Since this extreme rainfall event, there have been extensive studies focusing on its record-breaking amount of rainfall from various scientific and forecast perspectives. Accordingly, a conference named “The International Workshop on Typhoon Morakot (2009),” summarized by C.-S. Lee and colleagues in a 2011 article, was held on 25–26 March 2010 in Taipei, Taiwan, during which various aspects of TCs were communicated and discussed. The conference specifically aimed to identify gaps in our understanding of TCs and to discuss advanced forecast guidance tools required to improve warnings of these extreme precipitation and flooding events. The community went a step further to propose a special issue to the

journal *Terrestrial, Atmospheric and Oceanic Sciences (TAO)* in order to provide a comprehensive summary of Morakot and other extreme rainfall events associated with landfalling TCs. The special issue, “Typhoon Morakot (2009): Observation, Modeling, and Forecasting Applications,” was published in December 2011 and covered observation analyses of circulations and structures, mesoscale model simulations, data assimilation techniques, and practical forecast verification and guidance.

Key findings and consensuses in this special issue are carried out from approaches of statistics, observations, and numerical simulations, and are summarized below.

- 1) Morakot’s notable precipitation is highlighted by statistics on rainfall-return periods.
- 2) The extreme rainfall brought in by Morakot is associated with Taiwan’s topography and the flow interactions of several multiscale weather features (monsoon gyre, moist winds, and a nearby typhoon).
- 3) While the forecast/simulated track errors are small, the deficiencies in the representation of the TC translation speed, the vortex intensity/structure, and its interactions with its ambient systems in the model appear to hinder the forecast/simulation of rainfall associated with Morakot.
- 4) Numerical models with sufficiently fine resolution and sophisticated physical processes are very important and can be combined with initial atmospheric and oceanic conditions for better understanding mechanisms involved in extreme rainfall events.
- 5) Improvements in initial atmospheric and oceanic conditions are required, particularly the observations on critical positions of multiscale flow regimes and the effective vortex initialization in numerical weather prediction schemes.

The key findings and insights on these topics are presented in this short article. It is hoped that this brief

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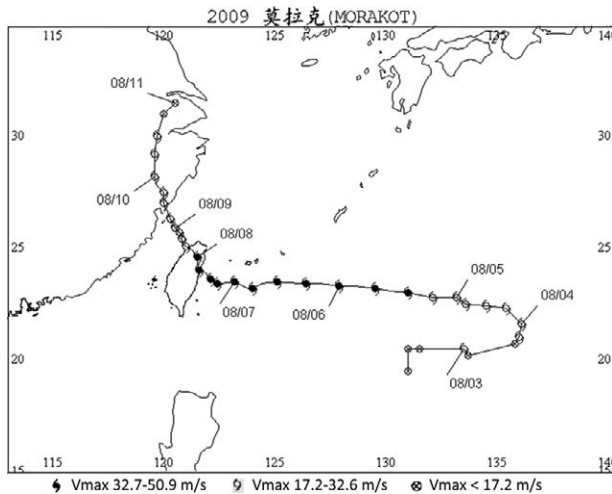


FIG. 1. The best track of Typhoon Morakot. The date labels mark the locations of the typhoon at 0000 UTC on the dates indicated. [SOURCE: Central Weather Bureau (CWB) of Taiwan]

introduction will bring more attention to this very important TC issue and the series of related studies.

OBSERVATIONS. In early August 2009, a large-scale cyclonic circulation identified by C.-C. Hong and colleagues was present over the South China Sea and western North Pacific. Typhoon Morakot, the dominating feature embedded in this circulation, formed to the east of Taiwan at 0000 UTC 3 August 2009 before heading steadily westward and making landfall on the east-central coast of Taiwan at 1600 UTC 7 August. The intensity of Morakot was equivalent to a strong Category 1 and perhaps a low-end Category 2 hurricane on the Saffir-Simpson hurricane wind scale (Fig. 1). I.-I. Lin and colleagues found that the presence of a warm ocean eddy—with its high upper-ocean heat content—located to the east of Taiwan created favorable conditions for Morakot to develop. At the same time, a weaker TC, Goni, formed at 1200 UTC 3 August and hovered cyclonically over the Hainan Island region of southern China. A tropical depression, which is the predecessor vortex of Tropical Storm Etau, was also identified on 8 August. Morakot, Goni, and this tropical depression coexisted within a broad monsoon gyre of cyclonic circulation with a zonal span of more than 4,000 km.

T.-H. Yen and colleagues showed that when Morakot made landfall in Taiwan, its translation speed decreased significantly from more than 20 km h^{-1} to around 10 km h^{-1} . This slow movement resulted in a prolonged influence on Taiwan. Within the southern

periphery of the salient monsoon gyre, the prevailing southwesterly flow affected southwestern Taiwan during and after Morakot's landfall. The convective bands associated with Morakot as well as the environmental configuration (i.e., the monsoon gyre, Goni, and Etau) in which Morakot traveled created conditions for heavy rainfall in southern Taiwan. Heavy rain occurred from 7 to 10 August, mainly falling in the mountains and on the southwestern plains of Taiwan (Fig. 2). The accumulated rainfall within the four days amounted to nearly 3,000 mm on the southwestern slope of the Central Mountain Range (CMR), where the high topography captured more rainfall in the windward slope area. The peak rainfall for a 24-h period reached 1,623.5 mm in the Ali mountains.

The extreme rainfall was well documented by the Doppler radar network in Taiwan (Fig. 3). The integrated reflectivity map around Taiwan illustrated

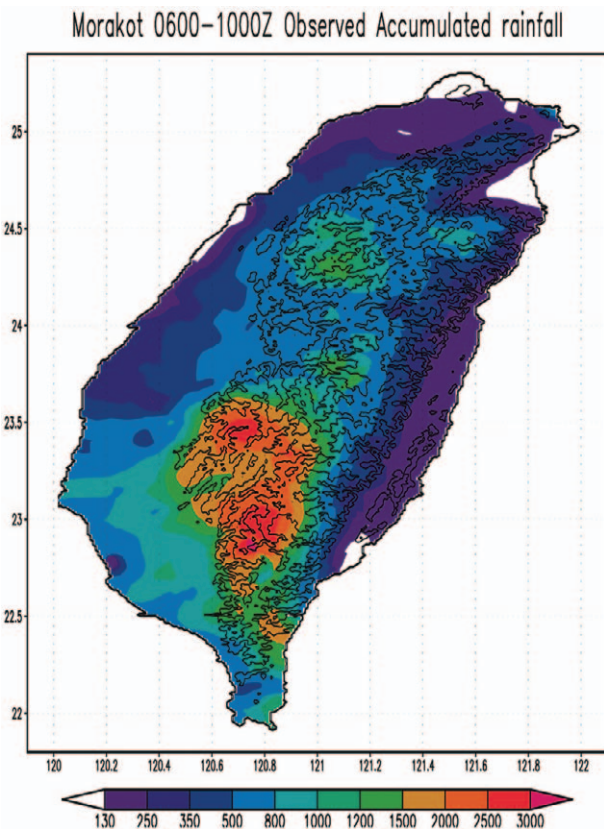


FIG. 2. The terrain of Taiwan (solid contour line) and the accumulated rainfall (mm; shaded) of Typhoon Morakot observed during the four days from 0000 UTC 6 Aug to 0000 UTC 10 Aug 2009. The solid contour line marks the height of 1,000 m of the topography. The x and y axes are the longitude ($^{\circ}\text{E}$) and latitude ($^{\circ}\text{N}$), respectively. (SOURCE: T.-H. Yen and colleagues)

strong, distinct rainbands over the southwestern part of the island, and away from the center of Morakot by about 250 km. T.-C. Wang, B. J.-D. Jou, and their colleagues found that the formation and stagnation of these rainbands can be partly attributed to the convergence of northerly wind associated with Morakot's outer circulation and the southwesterly monsoon flow. These devastating west–east-oriented convective bands oscillated between 22.5° and 23.5°N and poured down huge rainfall in southwest Taiwan. Wang and colleagues showed that strong southwesterly flow with a maximum surface wind speed (at 10-m height) greater than 45 m s^{-1} was found in distant rainbands. These west–east-oriented rainbands over southwestern Taiwan repeatedly formed along the convergence zone of Morakot's swirling circulation and the southwesterly flow.

NUMERICAL STUDIES. Numerical models have played an important role in both operational TC forecasts and scientific research in recent decades. Cloud-resolving mesoscale models are especially useful in addressing the issues with TC intensity evolution, interaction with terrain, and quantitative precipitation forecasts (QPFs). The rainfall pattern over Taiwan can be reasonably simulated in these models, provided that the model and terrain resolution is sufficient and the TC track in the model does not excessively deviate from observations. Several high-resolution regional models run in real time yielded good track forecasts of Morakot and captured the more prominent characteristics of rainfall in Taiwan with a lead time of about two days. C.-C. Wu and colleagues showed that eight ensemble members operated by the Central Weather Bureau (CWB), National Taiwan Normal University (NTNU), and the Taiwan Typhoon and Flood Research Institute (TTFRI) based on the Weather Research and Forecasting Model (WRF) and Cloud-Resolving Storm Simulator (CReSS) models obtained a maximum Equitable Threat Score (ETS) of around 0.3 on average in terms of 6- to 12-h QPF, which is fairly low but still indicates skill despite great uncertainties in the maximum rainfall amount among models with different initialization and physics parameterization schemes. E. A. Hendricks and colleagues evaluated real-time Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) forecast products for Morakot. This forecast system has the capability of ocean coupling; however, for this study, the model was

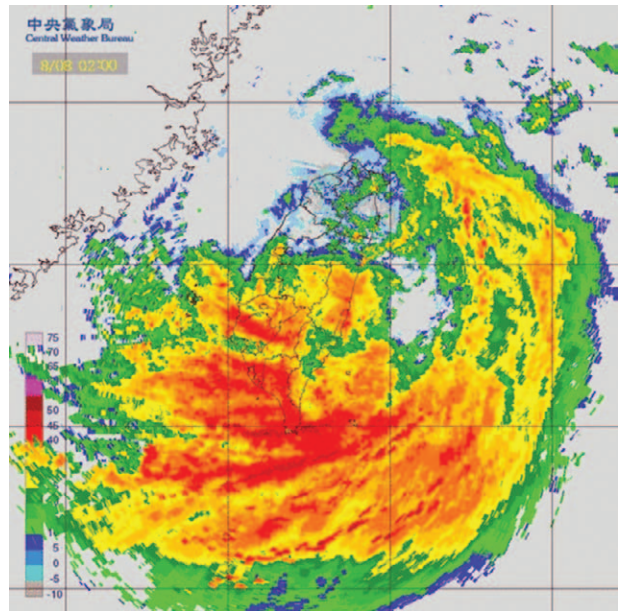


Fig. 3. The Central Weather Bureau (CWB) of Taiwan radar mosaic Column Vector (CV) image of reflectivity (dBZ) at 1800 UTC 7 Aug 2009.

run in standalone atmosphere mode. It was found that average track errors for Morakot were smaller than those of other operational global models, and that the average intensity errors were also small. COAMPS-TC was able to predict the finescale structure of Morakot reasonably well before and after landfall, reproducing a large asymmetric tropical cyclone with the precipitation shield shifted to the south of its center. However, the maximum rainfall amount in southern Taiwan was underestimated by about 50%, which is possibly attributed to the insufficient representation of Tropical Storm Goni, as well as the large-scale southwesterly flow in the South China Sea.

TC initialization has long been an important issue for the improvement of numerical TC simulations. H. V. Nguyen and Y.-L. Chen found that better model forecasts of the track and intensity of Morakot can be obtained with improved TC initialization schemes. Based on Bogus Data Assimilation (BDA), C.-Y. Huang and colleagues showed that a more consolidated TC vortex can be maintained in the MM5 model (the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model), making it more capable of predicting the observed track of Morakot after landfall and producing realistic extreme rainfall amounts in the southern CMR of Taiwan. The BDA technique also helps conduct various sensitivity experiments to

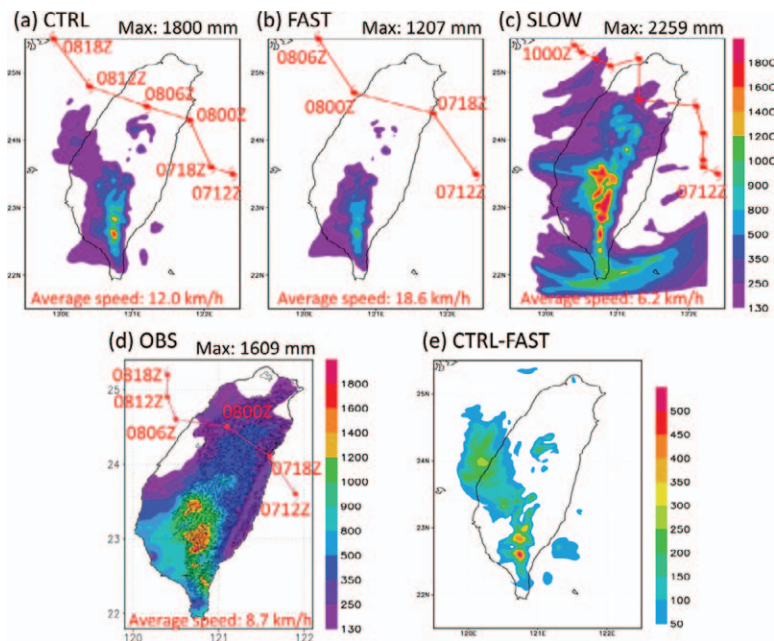


FIG. 4. Accumulated rainfall (mm) from (a) 1200 UTC 7 Aug to 1800 UTC 8 Aug in the control experiment (CTRL); (b) 1200 UTC 7 Aug to 0600 UTC 8 Aug in a simulation with a faster TC translation speed (FAST); (c) 1200 UTC 7 Aug to 0000 UTC 10 Aug in a simulation with a slower TC translation speed (SLOW); and (d) 1200 UTC 7 Aug to 1800 UTC 8 Aug by the rain-gauge network in Taiwan. The corresponding track segments of Typhoon Morakot during these periods are also indicated by the red lines. (e) The difference in accumulated rainfall (mm) between (a) and (b) (CTRL minus FAST). (SOURCE: T.-H. Yen and colleagues)

elucidate the effects of Taiwan's terrain, presence of Goni, and the strength of the monsoon circulation. It was shown that Goni played an important role in enhancing the wind speed of the southwesterly flow as well as in elevating the associated moisture content. The high topography of Taiwan also has significant impact on the rainfall (consistent with the result of X. Ge and colleagues), which is the main reason heavy precipitation occurred in southern Taiwan. Removal of the Taiwan topography reduces the maximum amount of 72-h accumulated rainfall by more than two-thirds.

W.-K. Tao and colleagues examined the sensitivity of physics parameterization schemes in a high-resolution (2 km in the finest nest) simulation of Morakot. The results showed that the improved microphysics scheme simulated a more accurate intensity for Morakot in its early stage, and suggested that ice processes have only limited impacts on surface rainfall. The differences between the planetary boundary layer schemes of Mellor-Yamada-Janjic

and Yonsei University are even less significant than those due to the ice microphysics. Furthermore, considering the essential role of warm-ocean eddies that Morakot passed through, the oceanic part of the numerical model could contribute to the accuracy of the TC intensity simulation.

Ensemble simulations are more ideal than deterministic runs, especially with respect to a probabilistic forecast, which is most valuable to emergency managers as well as the general public. The ensemble Kalman filter (EnKF) is a data assimilation scheme with flow-dependent background error covariances tightly integrated into the ensemble concepts. F. Zhang and colleagues demonstrated the potential application of high-resolution mesoscale ensemble predictions initialized from a real-time global ensemble data assimilation system. Using the WRF-based EnKF data assimilation to adjust the TC translation speed, Yen and colleagues studied the influence of Morakot's translation speed on its associated rainfall over Taiwan. They indicated that a 55% increase (36% decrease) in the translation speed (duration time of landfall) in the Morakot simulation leads to a 33% reduction in the maximum accumulated rainfall over Taiwan (Fig. 4). Quantitatively speaking, this result highlights the important role that Morakot's slow translation speed played in bringing about heavy accumulated rainfall during its landfall in Taiwan.

ADVANCEMENT IN TC PRECIPITATION PREDICTION. Based on the collaborative works following the International Workshop on Typhoon Morakot (2009), it has been shown that a combination of several factors—the prevailing southwesterly flow in the monsoon trough, the steep and high terrain in Taiwan, the slow translation speed of Morakot, the favorable ocean condition, and the presence of Typhoon Goni—created necessary and sufficient conditions for this devastating weather event. As discussed by C.-C. Wu and colleagues, the strong and complicated interaction between typhoon circulation and the Taiwan terrain makes typhoon forecast-

ing in the vicinity of the island a highly challenging task, which is further demonstrated in T.-C. Yeh and colleagues' review of the official forecast of Morakot provided by CWB during the warning period. The 24-h track forecast error of CWB in this case was smaller than the average value among all previous TCs, while the overestimated translation speed near Taiwan resulted in considerable underestimation of rainfall on the island. More refined high-resolution dynamical models are needed to better understand the mesoscale mechanism of extreme rainfall events and to address the issue of TC precipitation prediction. In particular, TC initialization techniques, ensemble data assimilation and forecasts, as well as coupled atmospheric–oceanic models are all vital for improvements of prediction results. Additionally, since quantitative typhoon rainfall forecasts in Taiwan have often been conducted with statistical approaches based on the relation between observed rainfall patterns and typhoon tracks, more advanced statistical models are required to obtain additional information on TC precipitation prediction. For instance, T.-Y. Pan and colleagues used the Artificial Neural Network (ANN)-based forecast model to refine the original statistical rainfall prediction for southwest monsoon-enhanced TC cases, including Morakot. The significant precipitation brought about by Morakot has also been highlighted by statistics on the rainfall-return period. H.-J. Chu and colleagues indicated that the rainfall intensity in Taiwan during Typhoon Morakot was significantly higher than during other TCs.

CONCLUDING REMARKS. The papers published in the special issue on Typhoon Morakot (2009) in *TAO* suggest that the extreme rainfall associated with Morakot is due to the topography of Taiwan (high, steep, and complex) and the multiscale flow interactions in the environment [amid a monsoon gyre, in moist southwesterly winds, with a typhoon (Goni) nearby]. The numerical studies reviewed in this article show that numerical models with sufficiently fine resolution and sophisticated physical processes (e.g., microphysics) in combination with representative initial atmospheric (multiple scales) and oceanic conditions are very important and can be very useful for better understanding mechanisms involved in such extreme rainfall events. To improve initial atmospheric and oceanic conditions, more observations and adequate data assimilation systems are required, particularly observations at critical loca-

tions of multiscale phenomena (such as the monsoon gyre, southwesterly flow, and vortex structure for the case of Morakot) and effective vortex initialization schemes. Further investigation of these issues is indispensable not only for the study of Morakot but also to forecast future TCs.

In all, the special issue on Typhoon Morakot provides a comprehensive summary of this TC and other extreme rainfall events associated with land-falling TCs, containing both scientific knowledge and operational guidance. For more details, please see the independent articles in Volume 22 (2011), No. 6 of *TAO* (available online at <http://tao.cgu.org.tw>), as well as other reviewed papers in *Weather and Forecasting*, *Monthly Weather Review*, and the *Journal of the Atmospheric Sciences*.

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SOLAR SNOW

People in harsh climates might think that solar cells wouldn’t be of much use if they are spending a significant amount of time buried under snow, but according to new research they should think again. While a layer of snow on photovoltaic panels can cause solar-cell blackouts, they typically do not stay covered for long. “Sometimes snow actually helps solar cells,” says Michigan Technological University scientist Joshua Pearce, who studied the effect of snow on the Open Solar Outdoors Test Field in Kingston, Ontario. The researchers created

a computer model to predict how much power generation would decline in various amounts of snow cover and on different solar modules when mounted at different angles. They then validated their data from commercial solar farms and found that power losses were minimal due to the albedo effect, which can generate more electricity when the sunlight reflects off the snow. The group subsequently developed a model to help design the most efficient photovoltaic systems to use in areas that get snow. (SOURCE: Michigan Technological University)