Precipitation Simulation Associated with Typhoon Sinlaku (2002) in Taiwan Area Using the LAPS Diabatic Initialization for MM5

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1. Introduction

One of the major forecasting technique developments of the Central Weather Bureau (CWB) in Taiwan has been to improve the quantitative precipitation forecasting (QPF) of tropical cyclones. Geographically, Taiwan is one of the regions around the world mostly frequently affected by tropical cyclones. On average, three or four tropical storms (or typhoons) hit Taiwan and one or two of them make landfall annually. Because the enormous damage produced, tropical cyclones are the most serious weather systems in the Taiwan area.

As a tropical cyclone approaches Taiwan, the steep and high altitude topography over the island — Central Mountain Range (hereinafter, CMR) with highest peak close to 4000 m —, is a critical factor for the storm's track deflection, local circulation variations, and many extreme rainfall events (Wu and Kuo 1999). For example, on 31 July and 1 August 1996, Typhoon Herb produced a maximum 24-h rainfall of 1798 mm over the CMR (Wu and Kuo 1999). This extreme rainfall caused 51 fatalities and 22 people missing. Damage from Herb was in excess of $5 billion (NT). Moreover, in July, August, and September 2001, there were four tropical cyclones — Trami, Toraji, Nari, and Lekima making landfall on Taiwan one after another and resulting in a total of 201 fatalities and 121 missing. Therefore, improving accuracy of tropical cyclone precipitation forecasts is very important scientific and forecasting endeavor in Taiwan.

To improve precipitation forecasts, the high-resolution mesoscale model holds some promise. Furthermore, computers have grown greatly in capability recently. Microphysical schemes, those were once only used in research before the 1990's, are being adopted by operational numerical weather prediction models. This will improve the explicit forecasts of clouds and precipitation. However, an accurate quantitative precipitation forecast remains one of the most difficult tasks in meteorology. During the past decades, there was more improvement in numerical forecasts of the mass and wind field than precipitation forecasts (Olson et al. 1995). One reason is attributable to the complicated and ill-understood precipitation physics. Another important reason is that most model initialization routines provide adiabatic initial conditions, leading to the infamous spin-up problem. The associated lack of condensation and latent heat release during the early part of model integration, restricts the short-range (0-12 h) forecasting accuracy of mesoscale models.

To address the spin-up problem, the Forecast Systems Laboratory (FSL) of the National Oceanic and Atmospheric Administration (NOAA) has developed LAPS (Local Analysis and Prediction System; McGinley et al. 1991; Albers et al. 1996), a data assimilation system, that ingests radar, satellite, profiler, aircraft reports, and conventional data. A unique aspect of LAPS is production of a three dimensional cloud field including vapor, water, ice, mixing ratios and vertical motion estimates (Albers et al. 1996). The resulting fields are used to initialize a range of mesoscale models with all microphysical species, which are in mass and momentum balance in model initial conditions. Using LAPS, the FSL began initializing real-time forecast system by Pennsylvania State University and the National Center for Atmospheric Research (PSU-NCAR) Fifth-Generation Mesoscale Model (MM5) since the fall of 2000. Based on experimental runs for the Colorado forecasting domain, the preliminary quantitative evaluation of prediction showed improved skill in forecasting clouds and precipitation in the early part (0-6 h) of the forecasts (Shaw et al. 2001). Due to its unique diabatic initialization technique, it has been dubbed the "hot start" MM5 forecast. This will hereinafter referred to as LAPS/MM5.

Abundant data at the CWB provides an opportunity for data assimilation and short-range quantitative forecasts. Through a collaborative project with NOAA/FSL, the CWB has run LAPS analysis since 1999. Hourly analyses of the atmospheric state variables, clouds, precipitation, and surface variables are produced daily using radar, satellite, soundings, aircraft observations, and surface mesoscale network observational data. Furthermore, to improve the QPF of tropical cyclones and the heavy rainfall events during the warm season in the Taiwan area, development and application of the LAPS/MM5 operational system are part of ongoing efforts at the CWB.

The primary purpose of this paper is to test the effects of LAPS diabatic initialization on the simulated precipitation associated with Typhoon Sinlaku (2002) over the complex topography in Taiwan area since there is evidence for sensitivity of typhoon prediction to data assimilation and diabatic initialization (Shi et al. 1996; Karyampudi et al. 1998). Typhoon Sinlaku was selected because Doppler radar is one of the most important data sources for an accurate analysis of typhoons and Sinlaku was located close to the Wu-Fen-Shan (WSR-88D) Doppler radar station during part of its lifetime on 6-7 September 2002. Therefore, there were radar radial velocities and reflectivity data to enhance the LAPS diabatic initialization. In this study, we will address specific questions, such as 1) whether LAPS diabatic initialization will provide a superior simulated precipitation to the non-LAPS cold start (no hydrometeors in initial fields), and 2) whether the Wu-Fen-Shan Doppler radar data play a key role on the simulated precipitation associated with Sinlaku over Taiwan.

2. Methods and data

LAPS was developed in the early 1990's and has undergone continuous improvements at FSL. It was designed to combine all available meteorological data sources into a single, coherent three-dimensional depiction of the atmosphere. Within the CWB, LAPS is run routinely on a domain covering approximately 1.75 million square kilometers (Fig. 1a) using a 153 by 141 horizontal grid with a 9-km grid spacing. This domain contains 21 pressure levels with a 50 hPa vertical spacing ranging from 1100 hPa through 100 hPa. Over this domain, the atmospheric state variables, clouds, precipitation, and surface variables (which can be used as a nowcasting tool) are produced hourly. The data collected routinely include the following (see Fig. 1 for locations) :

- Surface observations (include synoptic stations, ships, and buoys) and hourly meteorological aviation routine weather report (hereinafter, METAR) data.
- Wu-Fen-Shan (WSR-88D) Doppler radar volumn scans at 6 minute intervals were ingested in this study (Chi-Ku, Ken-Ting, and Hua-Lian Doppler radar data were also available since October 2002).
- Geostationary Meteorological Satellite (GMS-5) infrared 11μm and visible data.
- Rawinsonde sounding data.
- Automated and voice reports from aircraft at random times.

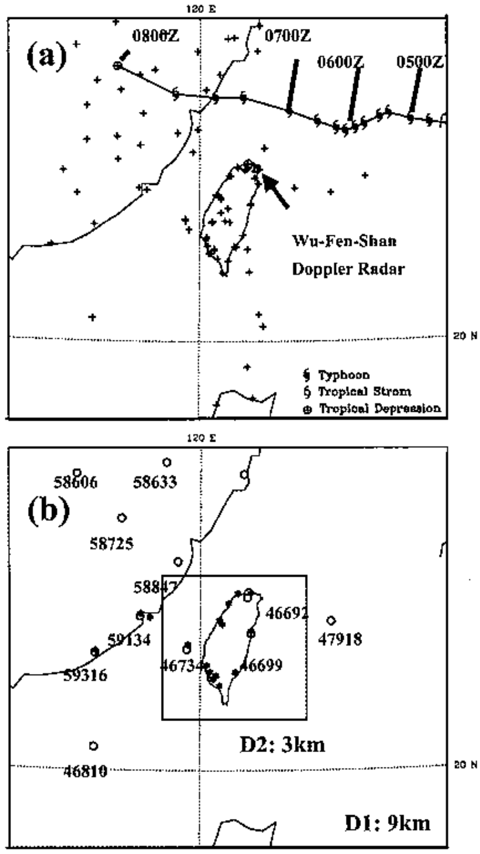


Fig. 1. (a) Domain configuration of LAPS analysis. The plus signs indicate the surface observation stations. The triangle sign shows the location of the Wu-Fen-Shan Doppler radar station. Also shown on the map in the best track of Typhoon Sinlaku from CWB (6-h interval). (b) Domain configuration for MM5 simulation. A stationary 3-km domain (D2) is nested within a 9-km domain (D1) using two-way nesting interfaces. The stars and circles signs indicate the meteorological aviation routine weather report (METAR) and the sounding stations, respectively.

The PSU-NCAR MM5 (version 3.5) is configured in nonhydrostatic mode for short-range forecasting at the CWB. The domains, shown in Fig. 1b, are a stationary 3-km domain of 151 by 151 grid points nested within a 9-km domain using two-way interfaces. The horizontal size and geographic location of the outer domain are the same as the LAPS analysis domain. Both MM5 domains extend in the vertical to 100 hPa and are resolved by 30 unevenly spaced sigma levels, with the finest resolution near the boundary layer. Two-minute-averaged terrain data are analyzed to model grids using a Cressman (1959) analysis scheme and filtered by a two-pass smoother/desmoother. For initializing the various surface categories and coastline, a two-minute-averaged vegetation/land-use and land-water mask dataset from U.S. Geological Survey are used. Initial atmospheric conditions are provided by LAPS, sea surface temperature from the National Centers for Environmental Prediction (NCEP), and lateral boundary conditions of outer domain from the CWB limited-area model. For the nested domain, the initial conditions are generated from its parent mesh.

For the physics options, the explicit moisture scheme of Schultz (1995) is used, which includes prognostic equations for cloud ice and water, snow, rain, and graupel. The surface and PBL are parameterized using the five-layer soil model and medium-range forecasting (MRF) PBL scheme (Hong and Pan 1996). The Rapid Radiative Transfer Model (RRTM) of Mlawer et al. (1997) is applied and no cumulus parameterization is used. In addition, Klemp and Durran's (1983) upper radiative boundary condition is applied to allow wave energy to pass through the model top.

Simulations were conducted with the LAPS/MM5 system to test its effectiveness forecasting the precipitation associated with Typhoon Sinlaku in the Taiwan area. Three simulations are initialized at 0000 UTC 6 September 2002 and integrated for 24-h. The first experiment used both the operational model physics and the LAPS diabatic initialization for initial conditions. This is the control run (referred to as CTRL) for the homogeneous comparison with other experiments. The second one (referred to as CLDS), with the same model configuration as CTRL, but utilized only the CWB limited-area model data as a non-LAPS cold start initialization. The third experiment (referred to as NRAD) excluded the Wu-Fen-Shan Doppler radar data from CTRL to study the impact of Doppler radar data on the precipitation simulation.

3. Results and discussion

On the basis of the reasonable simulation in typhoon track and intensity (figures not shown), the time series of averaged 3-h accumulated rainfall is compared in Fig. 2. The observed precipitation amounts, which are averaged for 391 rain gauge stations, present two rainfall episodes. One was late in the morning on 6 September (0603-0606 UTC) and the other was that midnight (0615-0618 UTC). For each simulation the rainfall was interpolated from the 3-km domain to all rain gauge locations in Taiwan. In CTRL, there was agreement with the observations, except at the 0603-0612 UTC period where forecast rainfall was more than

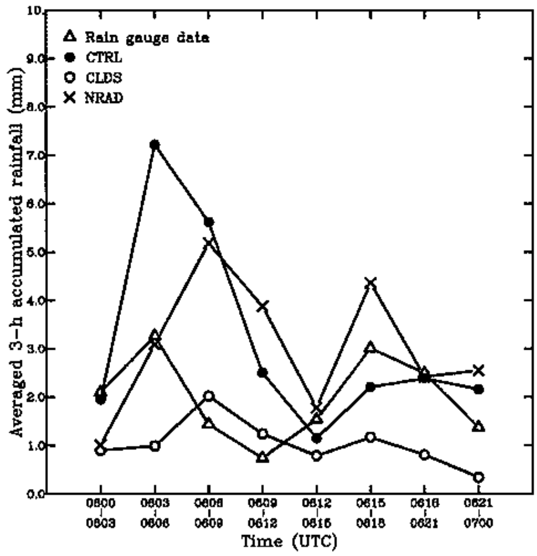


Fig. 2. Time series of 3-h accumulated precipitation averaged for the 391 precipitation verification samples in Taiwan from 0000 UTC 6 to 0000 UTC 7 September 2002.

twice the observed. Moreover, the first episode produced more rain than the second but in the observations the two episodes had similar magnitudes. Such overforecasting during the early period and underforecasting during the late period of a simulation have been reported as a deficiency of rainfall simulations. Furthermore, owing to passage of the rainband, the observations shows rapidly decreasing rainfall during 0606-0612 but in CTRL the rainfall decreased more slowly and resulted in strongly overforecast precipitation. This rapid change in the observed precipitation amounts is still a big challenge for numerical weather prediction. For CLDS, the model precipitation was strongly affected by the spin-up problem during the initial 0-9 h. Furthermore, the timing of the first rainfall peak was delayed about 3-h and the rainfall amounts were strongly underpredicted through the entire 24-h simulation. In NRAD case, which did not include Doppler radar data in the initial conditions, the simulated precipitation also presented two peak rainfall periods similar to CTRL. However, the precipitation was underforecast during the first 3 h simulation. This suggests that NRAD also needed about 3-h to spin-up the model rainfall and resulted in about a 3-h delay for the first simulated rainfall peak. Following the spin-up period, the simulated precipitation in NRAD increased quickly and became an overforecast during the 6-24 h period. Comparing the CTRL and NRAD reveals that the impact of Doppler radar data is evident on the early portion of rainfall simulation in our case study.

To examine the short-range precipitation forecasts of the LAPS/MM5 system, the ETS and bias score were computed at 6-h intervals and shown in Fig. 3. During the first 6-h simulation (0600-0606, Fig. 3a), the bias showed that the CTRL simulated rainfall was overforecast, but had better ETSs than in CLDS for large thresholds (≧ 10-mm). The highest ETS exceeded 0.35 at the 10-mm thresholds in this period. In contrast to CTRL, CLDS showed strong underforecasting. Although the ETSs of CLDS was comparable to CTRL at small thresholds, these ETSs dropped quickly as the underforecast at large thresholds. The ETS scores show that NRAD performed better than CLDS but worse than CTRL at large thresholds (≧ 15mm). For small thresholds, the performance of NRAD was similar to CTRL. These results suggest that improvement in heavy rainfall simulation during 0-6 h was mostly due to including Doppler radar data in CTRL's initial conditions.

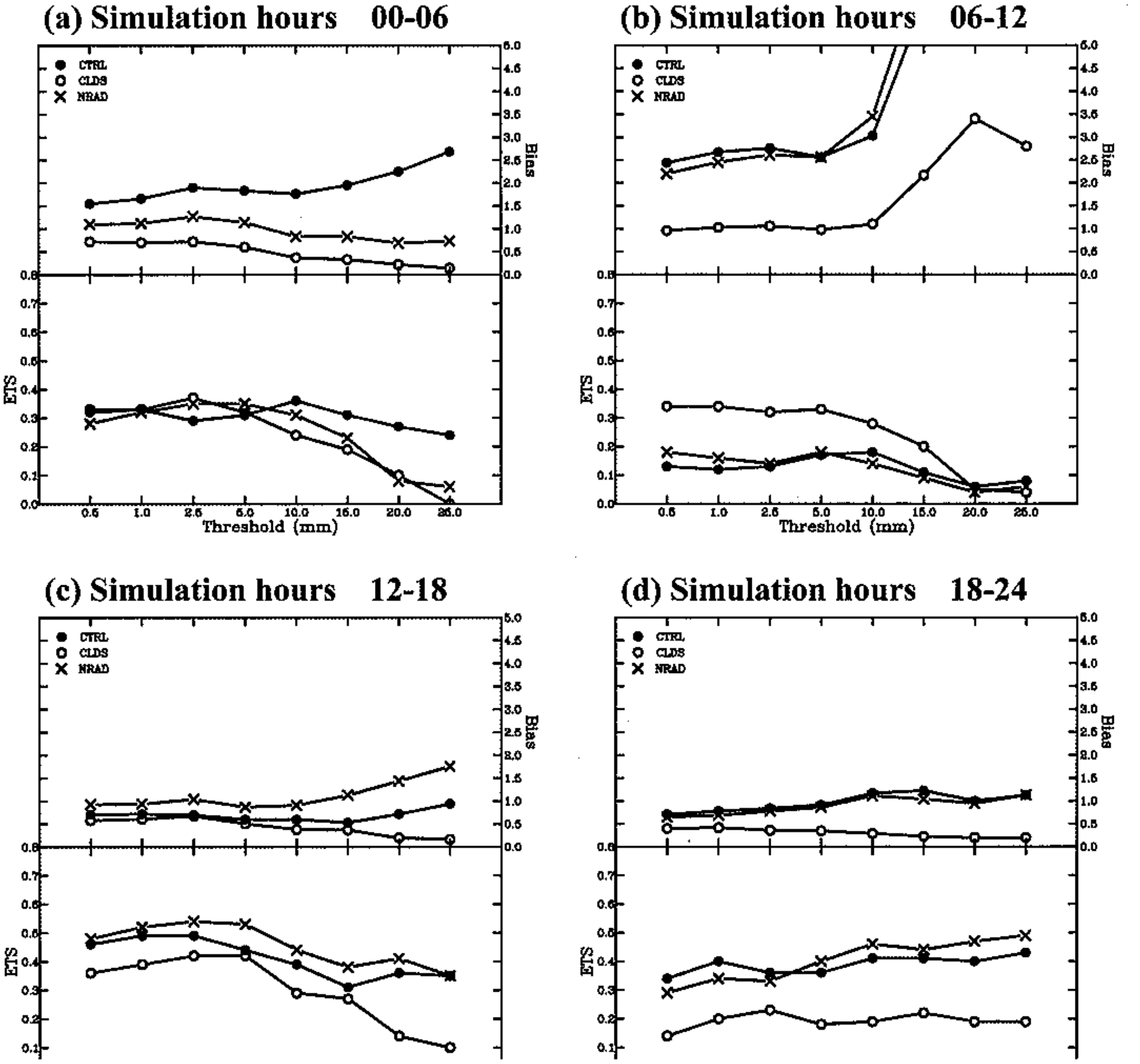


Fig. 3. Bias scores (upper panel) and equitable threat scores (ETS, lower panel) at various thresholds for (a) 0-6 hours, (b) 6-12 hours, (c) 12-18 hours, and (d) 18-24 hours accumulated precipitation simulation for the CTRL (filled circles), CLDS (open circles), and NRAD (cross signs). The bias magnitudes, which out of range for large thresholds in (b) are (6.2, 6.8, 6.6) for CTRL and (6.4, 7.2, 6.9) for NRAD at the (15-mm, 20-mm, 25-mm) precipitation thresholds.

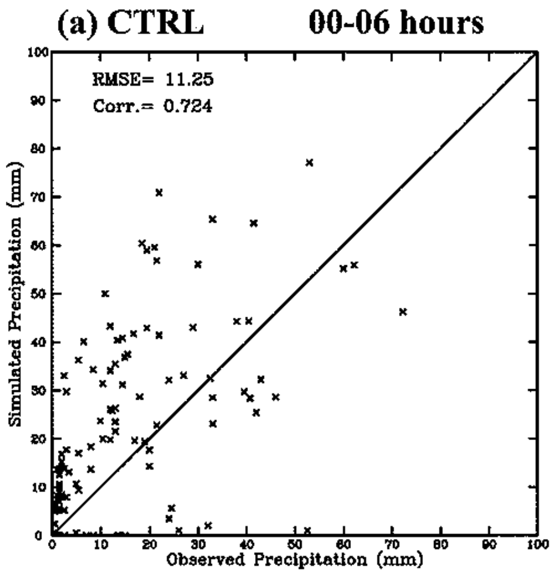
threshold amounts increased. These results demonstrate that the LAPS/MM5 improves the forecasting of heavy rainfall during the early portion of integration. The large biases indicate that spin up is reduced, but the model appears to overshoot based on gauge observations. In NRAD, the precipitation was slightly overforecast at small thresholds and

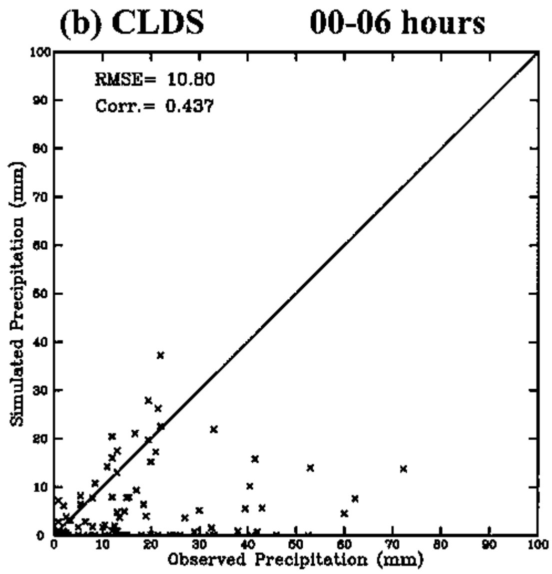
During the next 6-h interval (0606-0612), the observed rainfall amounts decreased rapidly, whereas the CLDS and NRAD produced more rain than the first 6-h period and the CTRL maintained precipitation longer than the observations (see Fig. 2). Therefore, all three experiments performed poorly, although the CLDS gave higher ETSs than the CTRL and

NRAD at small thresholds (Fig. 3b). In this period, both CTRL and NRAD produced too much rain at all thresholds resulting in very high bias scores and low ETSs in Fig. 3b. Moreover, the CLDS also had similar high bias errors at thresholds larger than 15-mm. These results reveal the limitations of a numerical model to capture the exact timing of the observed rainfall variation, especially for the early portion of the simulation. Missing the movement of the rainband was a large liability. During the next two 6-h intervals (0612-0618, Fig. 3c; 0618-0700, Fig. 3d), the CTRL and NRAD tended to underforecast the precipitation at small thresholds and overforecast at large thresholds. However, all precipitation was underforecast in CLDS. For ETSs, the CTRL and NRAD show a similar behavior and yield better scores than the CLDS for all thresholds during 12-24 h simulation.

In summary, comparing the simulated precipitation of CTRL, CLDS, and NRAD shows that the enhanced initial conditions with Doppler radar data yielded a positive impact on the early portion of precipitation simulation. Furthermore for Taiwan, the LAPS/MM5 system provided a better simulation than the non-LAPS cold start experiment for the precipitation associated with Typhoon Sinlaku. We feel these results are related to the LAPS diabatic initial conditions in the mesoscale model, which allows a better representation of the vertical motions, moisture field, and microphysical species, thus producing a better rainfall simulation and reducing the spin-up problem.

The positive impact of the Doppler radar data on the early portion of precipitation simulation can be better discerned by comparing the precipitation distribution from all three experiments. Fig. 4 shows the scatterplots comparing precipitation amounts from the rain gauge stations and the mesoscale model results. Moreover, the root-mean-square errors (RMSE) and correlation coefficients (Corr.) were calculated and are also shown in Fig. 4. In CTRL (Fig. 4a), the rainfall distribution between the observed amounts and the simulation reveals the evident overforecast at precipitation amounts





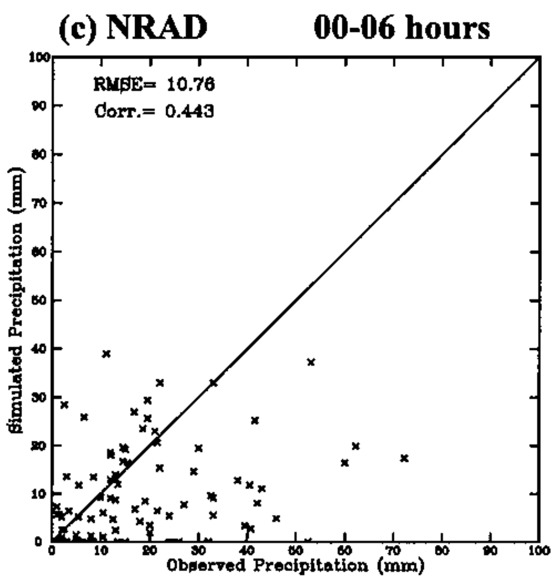


Fig. 4. Scatterplot comparing the 6-h accumulated precipitation between the observations and the (a) CTRL, (b) CLDS, and (c) NRAD simulations from 0000 UTC 6 to 0600 UTC 6 September 2002. The root-mean-square errors and correlation coefficients are also shown.

less than 20-mm. However, the CLDS (Fig. 4b) underforecast especially for precipitation amounts more than 30-mm. The NRAD (Fig. 4c) produced more rainfall than the CLDS but still underforecast at large precipitation amounts. To examine the correlation between the observations and simulations, the correlation coefficients of CTRL, CLDS, and NRAD are 0.724, 0.437, and 0.443, respectively illustrating the significantly better performance of the LAPS/MM5 system with assimilated Doppler radar data in this typhoon case study. Moreover, the similar correlation coefficient between CLDS and NRAD points out the critical role played by Doppler radar in the definition of cloud and estimation of cloud variables. Inclusion of radar in the initial conditions of CTRL allowed improvement in the skill at higher precipitation, where CLDS and NRAD showed deficiencies. As to the RMSE, all three simulations show comparable values with 11.25 mm, 10.80 mm, and 10.76 mm for CTRL, CLDS, and NRAD, respectively. In summary, the simulated precipitation distributions associated with Typhoon Sinlaku suggest that the Wu-Fen-Shan Doppler radar data played a key role in enhancing the heavy rainfall prediction ability for the LAPS/MM5 system during the early portion of the simulation. However, there was no evident improvement for light rain prediction. Overall, the mesoscale model initialized diabatically with LAPS data assimilation shows improved capability on the typhoon short-range quantitative precipitation forecasts, especially when the Doppler radar data is included.

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