An Investigation of the Sensitivity of Predicting a Severe Rainfall Event in Northern Taiwan to the Upstream Condition with a WRF-based Radar Data Assimilation System

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Abstract

This study investigates the forecast sensitivity of an afternoon thunderstorm in northern Taiwan to the upstream condition associated with the prevailing warm and moist southwesterly winds on 16 June 2008. This event was initiated near noon and lasted for several hours with a maximum hourly precipitation rate of 69 mm hr$^{-1}$ at 14 LST.

Experiments are conducted to assimilate radial velocity only or both radial velocity and reflectivity data from radars at southwestern and southern Taiwan with the WRF-Local Ensemble Transform Kalman Filter Radar assimilation system. Results show that these experiments can predict the rainfall occurrence in northern Taiwan, but the location and rainfall amount is very sensitive to upstream environmental conditions. Assimilating the unfiltered topography-associated reflectivity noise upstream generates unrealistic light rain and cooling, which leads to a great reduction of rainfall in the target area. The precipitation prediction suggests that a careful topography-based quality control performed on the radar data can be essential to restore the necessary environmental conditions for forecasting the afternoon thunderstorm event.

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1. Introduction

The severe convective system during the Mei-Yu season (mid-May to mid-June) is one of the major precipitation systems in Taiwan (Chen et al. 2004; Kerns et al. 2010). Accurate prediction for the initialization, intensity, location and duration of severe thunderstorms is essential for disaster prevention and decision making. It is a challenging task to predict the characteristics of severe thunderstorm triggering by the interaction with the prevailing winds, local convections, and complex terrain in Taiwan. During the Mei-Yu season, northern Taiwan is one of the regions where there is a higher occurrence of severe convective rainfall systems, particularly in the afternoon (Fig. 10 in Kerns et al. 2010). Northern Taiwan is in the lee wake/convergence region when the southwesterly winds flow around the Central Mountain in Taiwan island and converge in northern Taiwan (Crook 2001; Chen and Lin 1997). During the daytime hours with solar heating over land, in the wake zone with weak prevailing winds, the onshore winds initially flow along the coasts, and into Tamsui and Keelung River valleys (red lines in Fig. 2) where they further develop and turn into upslope flows. This sets up a condition of a convectively unstable atmosphere and in the afternoon, after sufficient heating, convective thunderstorm activity could occur.

This study investigates the predictability of an afternoon thunderstorm event in northern Taiwan on 16 June 2008 using the ensemble radar data assimilation system. However, for this case, and probably for most afternoon thunderstorm cases, the radar data in northern Taiwan is not available before the onset of the afternoon convection. On the same day in this case, there is also a long-lived heavy precipitation on the southwestern coast of Taiwan (Davis et al. 2012). The rainfall systems over southwestern Taiwan provide abundant radar data and part of them are upstream of the northern convective systems.

In particular, we investigate remote influences on predicting the short-lived afternoon thunderstorm in northern Taiwan from assimilating radar data over the area upstream, in central Taiwan. Although Cheng et al. (2017) confirms that assimilating the radar data at Chigu and Kenting (Fig. 3a) can improve the quantitative precipitation forecasts in southwestern Taiwan (Fig. 1), the predictability of the afternoon thunderstorm in northern Taiwan, with similar precipitation accumulation as the one in southwestern Taiwan, has not been investigated with regards to the impact of radar data assimilation. The event in the current study has been well simulated by Tu et al. (2014) and Yang et al. (2017), but both numerical simulations do not include the upstream radars. Particularly, we examine the issue associated with quality control (QC) for radar data and how this can affect the prediction of an afternoon thunderstorm in northern Taiwan.

This paper is organized as follows. Section 2 presents an overview of the afternoon thunderstorm event considered in this study. Section 3 introduces the ensemble radar data assimilation system and the quality control procedure for the radar data. The experimental settings are introduced in Section 4 and the results of the analysis and forecast are presented in Section 5. Finally, Section 6 provides a summary and discussion of the results.

2. Overview of the afternoon thunderstorm on 16 June, 2008

On 16 June 2008, two types of precipitation systems occurred in Taiwan: one over southwestern Taiwan which is characterized by its long duration (> 20 h), and the other over northern Taiwan, which is distinguished by its short duration (about 9 h) and strong intensity.

During this heavy rain period, the ocean upstream of southwestern Taiwan is dominated by southwesterly flow accompanied by warm and humid advection (Figs. 4d and 7e in Xu et al. 2012) which reaches the intensity of a low-level jet at 08 LST. At the same time, a shallow cold pool extending from the land induced by precipitation on the previous day has resulted in southeasterly winds near the surface. This sets up significant convergence between the upstream ocean and the southwest coast of Taiwan and allows for a complex mesoscale system to develop offshore from southwestern Taiwan, resulting in a long-lived heavy rain event over the coastal area of southwestern Taiwan (Xu et al. 2012; Tu et al. 2014). In contrast, the atmosphere over northern Taiwan was relatively stable at this time, and was not affected much by synoptic-scale weather systems located hundreds of kilometers away. Unlike the long-lived heavy rainfall in the south, there was a relatively short-term heavy rainfall in the north, and the accumulated rainfall was comparable to that which occurred in...
Given the weak prevailing wind over northern Taiwan at this time, the local circulation, such as land-sea breeze and mountain-valley breeze, can easily take place and dominate the flow. This provides a favorable condition for the development of afternoon thunderstorms in the area (Tu et al. 2014). As shown by the surface wind observation (Fig. 2), the sea breeze flows through the Keelung and Tamsui river valley and then converges in the Taipei Basin. Reflectivity data shows that convective storms are first generated in the Taipei Basin at 10LST (Fig. 2a), then move southward, gradually enhance (Figs. 2b and 2c), and then expand west-southwestward (Fig. 2d). The overall intensity peaks at 14 LST. During the expansion of the convective storms, the coastal area is dominated by onshore flow and also weak southerly flow over the slope area (red boxes in Figs. 2c and 2d). It indicates a condition of low-level convergence supplying moisture. According to the rain gauge data (Figs. 5a1–5a5), the precipitation at Taipei Basin starts at 11 LST and the Da-Xi station has a maximum rain rate of 69 mm hr$^{-1}$ at 14 LST. The 9-h rainfall accumulation reaches the criterion of heavy rainfall defined by Taiwan Central Weather Bureau (CWB).

### 3. Radar data assimilation and observation quality control

The radar data assimilation system has been established based on the Weather Research and Forecasting (WRF) model and the Local Ensemble Transform Kalman Filter method with the purpose to improve the very short-term precipitation prediction (Tsai et al. 2014). The WRF-LETKF Radar Assimilation System (WLRAS) has been applied to heavy precipitation prediction related to Mei-Yu fronts and demonstrated promising forecast skill by assimilating the radial velocity and reflectivity (Tsai et al. 2016; Cheng et al. 2017, 2019; Yang et al. 2019). This system updates all model variables, including wind, geopotential height, potential temperature perturbation, and mixing ratios of hydrometers.

The current study uses the radial velocity and reflectivity from Taiwan CWB radars at Chigu (RCCG) and Kenting (RCKT), which are located at southwestern and southern Taiwan, respectively (Fig. 3a). The radar data is superobbed into a 5 degree azimuthal spacing and 5 km in radial spacing (Lindskog et al. 2004). Figure 3a is an example of the superobs used in WLRAS. The observations from the radar located at northern Taiwan are not adopted since there are no observations available during the assimilation period, before the onset of the afternoon thunderstorm. The observing ranges from both sites can well capture the characteristics of heavy rainfall in southwestern Taiwan. QC must be performed prior to the use of radar data for data assimilation to filter out non-weather information such as ground clutter and sea clutter. In this study, two-step QC is applied to the radar data for assimilation. The first step takes care of the ground clutter, de-aliasing and weather-unrelated noises. The noises associated with terrain are identified with reflectivity higher than 30 dBZ and wind speed lower than 2 ms$^{-1}$. After this QC step, we notice that there are reflectivities near 20 dBZ but under a non-precipitating condition according to the rain gauge data (Fig. 3b vs. Fig. 5a1). These data have low elevation angles and locate over the terrain area. Therefore, the second step QC is applied to remove these noises with the elevation angles lower than 2.4 degrees and an altitude higher than 200 m (Figs. 3b vs. 3c). We note that such reflectivity noises are not fixed over time and have relatively high amplitudes. It is also difficult to identify these noises in the first-step QC with a rigorous threshold, which results in an overreduction in the observation amount instead.

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**Fig. 1.** Nine hours rainfall accumulation from 1000 LST to 1900 LST 16 June 2008 from (a) rain gauge and the (b) CNTL, (c) VR, (d) TQC and (e) noTQC forecasts. The black box indicates the target area. Contours in (a) demote the terrain height of 0, 200, 500, 1000, 2000 and 3000 m. Miaoli County is highlighted by the red contour.
Fig. 2. Composite reflectivity (dBZ) and surface wind (m s$^{-1}$) from CWB at (a) 1000, (b) 1100, (c) 1200, (d) 1300, (e) 1400 and (f) 1500 LST. Contours have the same definitions in Fig. 1a.

Fig. 3. Reflectivity (dBZ) at 1000 LST 16 June 2008: (a) superobservation after the first-step QC, (b) and (c) are the zoom in of (a), (c) superobservation after the two-step QC. Red and blue stars in (a) represent radars at Chigu (RCCG) and Kentin (RCKT), respectively. Contours have the same definition in Fig. 1a. The red contour in (c) is used in the second-step QC as the threshold of terrain height. (d) is the topography of Taiwan.
4. Experimental design

The Advanced Research WRF V3.2.1 (Skamarock et al. 2008) is used in this study with triple-nested domains and two-way interactions between each. The horizontal grid spacing is 27, 9 and 3 km, respectively, for domains 1, 2, and 3. There are 28 vertical levels with the model top of 50 hPa for all domains. Three experiments are conducted using WLRAS applied in the innermost (3 km) domain (Table 1). The predictability of this afternoon thunderstorm event is explored by the assimilating of winds, adding of assimilation reflectivity, and enhanced QC in the upstream region. The VR experiment assimilates radial velocity and the TQC experiment assimilates the radial velocity and reflectivity. The noTQC experiment has the same assimilation strategy as TQC, but the radar data is only processed with the first step QC. All three experiments update the same model prognostic variables. All WLRAS-related experiments are performed with 36-members using the same assimilation parameters in Tsai et al. (2014), including 8% of multiplicative covariance inflation and horizontal and vertical cut-off scales of 12 and 4-km, respectively.

The initial and boundary conditions of the ensemble for the outer domain are the same for all experiments and are taken from the 27-km analysis ensemble at 02 LST 16 June 2008 from Yang et al. (2014). With the triple nested domains, the ensemble is integrated for 6 hours to generate the 3-km ensemble states at 08 LST, and the WLRAS experiments are conducted from 08 to 10 LST 16 June with an analysis interval of 15-min. The differences among the experiments are evaluated based on the deterministic forecast initialized from the analysis mean at 10 LST.

5. Results

5.1 Impact from assimilating radar data

A baseline taken from the deterministic forecast initialized from the ensemble mean at 02 LST 16 June 2008, before performing the radar data assimilation, is used to identify the impact of radar data assimilation on forecast skill. This experiment is referred to as CNTL. According to the virtual potential temperature (T) and wind fields at the model lowest level (Figs. 4a−4d), CNTL exhibits southwesterly flow over the Taiwan Strait west of northern Taiwan and a sea breeze over the coastal region, flowing into the Taipei metropolitan area similar to observations (Fig. 2) from late morning to the early afternoon. At 10 LST, high T (306 K) air is near the northern coast and is favorable for the occurrence of rainfall in the target area (the black box in Fig. 4a) over the following two hours (Figs. 5b1 and 5b2). However, in the upstream region (the dashed rectangle in Fig. 4a), CNTL exhibits southwesterly flow over the Taiwan Strait west of northern Taiwan, while the observation shows northwesterly to northerly flow, perpendicular to the coastline there (Fig. 2a). This indicates that the simulated onshore flow in CNTL is weaker than what was found in the observations. In terms of the temporal variation, the onset of simulated rainfall occurs an hour earlier than observed. The CNTL produces heavy rainfall over the slope situated south of the observed rainfall maximum (Figs. 5a3 vs. 5b3). The 9-h rainfall accumulation from 10 to 19 LST (Fig. 1b) shows that the heavy rainfall over northern Taiwan is more scattered with much weaker intensity than was observed. In terms of the hourly rainfall (Fig. 6), there is a large discrepancy between the observation and CNTL in the target area. In the following, we present how assimilation of radar data can improve the onset and intensity of rainfall in the target area.

After the model wind field is updated by assimilating the radial velocity (the VR and TQC experiments), high T (306 K) of VR and TQC do not extend to the lowlands near the coast as in CNTL at 10 LST (Figs. 4a, 4c, and 4i). No rainfall is simulated over the target area in these two experiments at 11 LST (Figs. 4c1 and 5d1). It is clear that the intensity, location and temporal variation of the heavy rainfall over northern Taiwan are significantly improved (Figs. 1c, 1d, and 6), even though RCCG and RCKT cannot directly observe the convective storms in this area. Compared to CNTL, VR enhances the onshore flow over the upstream area (Fig. 5c1) and T, is also higher there (Figs. 4a vs. 4c). These differences in VR lead to a great contribution to better predicting the formation and development of the afternoon thunderstorm in the downstream and the location of the rainfall maximum in VR is closer to the observation. When assimilating both the reflectivity and radial velocity, the near surface flow in TQC (Fig. 4i) exhibits a similar performance over northern Taiwan as in VR (Fig. 4e), but the heavy rain in TQC lasts longer (Figs. 5d5 vs. 5e5). Given the similar performance of VR and TQC, the main improvement of the precipitation prediction appears due to the upstream wind adjustment from assimilating the radial velocity.

However, the heavy rainfall that was shown over the coastal area of southwestern Taiwan in the observations is located offshore in the VR forecast (Figs. 1a vs. 1c). This indicates that assimilating radial velocity alone is not enough to constrain the heavy rainfall prediction over the coastal area. As shown in Fig. 1d, the location and intensity of heavy rainfall area over southwestern Taiwan is significantly improved in the TQC experiment, in particular that the heavy rainfall is now located over the coastal region. Assimilating reflectivity has a direct effect on correcting the rainfall location by adjusting the hydrometer concentrations in this region.

5.2 Impact from the topography QC

While results from VR and TQC confirm the importance of assimilating both radial velocity and reflectivity on heavy rainfall prediction, the noTQC forecast significantly underestimates the precipitation amount over northern Taiwan (Figs. 1d vs. 1e) and its intensity during 13 to 15 LST is even weaker than that of the CNTL forecast (Fig. 6 and Figs. 5b3 vs. 5e3). In the following sub-section, we will focus on the cause of the prediction degradation in this area in the noTQC experiment.

Different from VR, TQC or CNTL, the noTQC prediction has early precipitation over Miaoli County (red circle in Fig. 5e1) during 10–11 LST. The convective storms steered by the environmental flow move northward and then dissipate. The precipitation intensity peaks during 12–13 LST and then weakens afterwards (Figs. 5e1−5e5), which stands in contrast to the persistent heavy rainfall in the observation and the TQC forecast. This excessively early precipitation in Miaoli County is unrealistic and the associated evaporation causes a weak cold pool to form near the surface (Fig. 4n). This cold pool accompanies the rainfall area and moves northward following the environmental flow. As shown in Fig. 4o, T, in the noTQC simulation is 3 degrees less over the coastal area in northwestern Taiwan at 12 LST than in the other simulations. Located upstream of the afternoon thunderstorm, such a cold pool hinders the high T, air flowing into northern Taiwan, which leads to a less-favorable condition for the development of afternoon convections. It is also observed that the moisture convergence is smaller in the area with lower T, in the noTQC at 13 LST. Therefore, the precipitation relaxes unrealistically, resulting in an intensity that is much weaker than that in the TQC forecasts (and VR and CNTL). The unrealistic early precipitation in noTQC corresponds to the weak reflectivity over the mountainous area over Miaoli County, as shown in Fig. 3b. The difference between the TQC and noTQC forecast suggests that the first-step QC may not be sufficient to properly consider noises associated with the complex terrain in Taiwan.

Comparing to the hourly precipitation in the noTQC forecast, TQC, without assimilating the near-surface reflectivity over the

| Table 1. Experimental setup. |
|-------------------------------|
| Assimilated variable | CNTL | VR | TQC | noTQC |
|--------------------------|------|----|-----|-------|
| Assimilated variable     | N/A  | Radial velocity with complete two step QC | Radial velocity and reflectivity with complete two step QC | Radial velocity and reflectivity with only first step QC |

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mountainous area, does not exhibit the unrealistic early precipitation during 10–11 LST and thus there is no anomalous cold pool formed near surface (Figs. 4i vs. 4m). This allows for warm and moist southwesterly flow into the northern Taiwan sufficient to sustain the development of the convective storms (Fig. 5d3–5d5). Among all experiments using the radar data, TQC is the only experiment that resulted in a very intense precipitation event during 15–17 LST. As shown in Fig. 6, the hourly precipitation rate of TQC is the most intense (>14.5 mm h$^{-1}$) with a longer duration similar to the observations. The maximum area mean precipitation is about 95% of the observed value for TQC.

We note that the results above are less affected by the uncertainty related to the rapidly evolving nature of the mesoscale convective system. Results show that all noTQC members have unrealistic light rain over the mountainous region in Central Taiwan, i.e. the upstream condition is dominated by the impact of assimilating the terrain-related noises in reflectivity data.

6. Summary and conclusions

This study investigates the forecast sensitivity of relatively short-term heavy rainfall prediction to the errors in the upstream conditions based on an afternoon thunderstorm in northern Taiwan on 16 June 2008. Experiments with WLRAS are performed to assimilate the radial velocity and reflectivity from the RCCG and RCKT radars. The radar data is mainly distributed from offshore to coastal area of southwestern Taiwan, i.e. upstream of the afternoon thunderstorm under the condition of prevailing southwesterly winds during the Mei-Yu season. The investigations focus on the impact of the assimilation of radar data and the topography-based QC on predicting the onset and intensity of rainfall in northern Taiwan. Our conclusions are summarized as follows:

- Updating the upstream wind condition rapidly has a great impact on predicting the relatively short-term heavy precipitation in northern Taiwan. But improving the wind field alone is not sufficient to constrain the long-lived system that produces
In addition to the radial wind, the assimilation of the reflectivity data leads to an improved performance of predicting a long-lived heavy rainfall event over southwestern Taiwan by adequately recovering the characteristics of the coastal heavy precipitation.

A topography-based QC involving the removal of the radar data near the surface over the mountains is designed to filter out the reflectivity noise. Assimilating the unfiltered noise over the mountainous region in central Taiwan moistens the air there and results in unrealistic early precipitation over Miaoli County. This further generates a weak cold pool which blocks the warm and moist air flow into northern Taiwan. Consequently, the development of afternoon thunderstorms in northern Taiwan is hindered and the rainfall intensity is severely underestimated in the noTQC forecast. With the topography-based QC, the TQC forecast has a thermodynamic condition that is more favorable to support the development of afternoon thunderstorms in northern Taiwan. The associated heavy rainfall is well predicted in terms of intensity, location and duration.

As a conclusion, the development of the afternoon thunderstorms heavy rainfall over the coastal area of southwestern Taiwan.

Fig. 5. Hourly rainfall from (1) 1000, (2) 1100, (3) 1300, (4) 1400 and (5) 1500 LST 16 June 2008. From top to bottom rows are observations based on the rain gauge data, the CNTL, VR, TQC and noTQC forecasts, respectively. The red cross in (a1) denotes the Da-Xi station and the black box indicates the target area. The red circle in (e1) highlights the light rain over Miaoli County. The wind bar in (c1) is the wind difference between VR and CNTL at the lowest model level.

Fig. 6. Time series of the hourly rainfall (mm h\(^{-1}\)) averaged over the area in northern Taiwan (the black box in Fig. 1a).
over northern Taiwan is very sensitive to upstream conditions during the Mei-Yu season. If there are errors in the upstream condition of wind, moisture and hydrometers fields, these can hinder the triggering, development, and distribution of convective storms. These errors can easily be induced by the fake signals in the radar data. Based on our results, we suggest that improving the radar data quality with carefully-constructed topography-related QC procedures, or installing additional instruments to provide a sufficient description of environmental conditions in the upstream (central Taiwan) can be beneficial to improve the precipitation prediction of afternoon thunderstorms in northern Taiwan.

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