1. Introduction

This research proposes an efficient approach by which one can use Doppler radar data to improve the short term rainfall forecast over mountainous areas. Through Observation System Simulation Experiments (OSSE) tests the importance of vapor is identified. Thus, a procedure for adjusting vapor is designed. By assimilating three-dimensional meteorological fields obtained from multiple-Doppler radar wind synthesis, thermodynamic retrieval, as well as vapor adjustment into WRF, we investigate its impact on rainfall forecast for a real case, which is an afternoon thunderstorm event occurred on 19 August, 2014 in northern Taiwan.

The forecast results of the real case demonstrate that the extreme rainfall in Taipei City is well captured. The advantage of the methods developed in this research is that they can be applied directly over terrain. In addition, radar data from only two volume scans are sufficient and can be efficiently used to improve the model short-term rainfall forecast.

2. Methodology

2.1 Wind Synthesis System using Doppler Measurement (WISSDOM)

We employ a 3DVar-based multiple-Doppler three-dimensional wind synthesis method developed by Liou and Chang (2009), Liou et al. (2012) and Liou et al. (2014), which can recover wind field along the radar baseline and over complex terrain. The latter is accomplished by adopting the Immersed Boundary Method (IBM) to handle the bottom boundary condition.

The wind fields are obtained by variationally minimize a cost function to satisfy a series of weak constraints, which include the relationship between Cartesian winds and radial winds, anelastic continuity equation, vertical vorticity equation, and spatial smoothing term. Surface station wind data are also assimilated to improve the low level wind structure (Liou et al. 2019). This method can merge data from any number of radars.

2.2 A Terrain-Permitting Thermodynamic Retrieval Scheme (TPTRS)

In this study we utilize a newly-developed scheme (TPTRS) to conduct the thermodynamic retrieval using the wind data generated by WISSDOM. This new method allows us to obtain the three-dimensional perturbations of the thermodynamic fields over complex terrain, rather than the deviation of the perturbation from its horizontal average as proposed in Gal-Chen (1978).

The algorithm of this method uses the following equations:

\[ \frac{1}{\theta_0} \frac{\partial \theta'}{\partial t} - f \frac{\partial v}{\partial x} + \frac{\partial b}{\partial x} = -F \]  

\[ \frac{1}{\theta_0} \frac{\partial \theta'}{\partial y} = -G \]  

\[ \frac{1}{\theta_0} \frac{\partial w}{\partial t} + \frac{\partial b}{\partial y} + g(q_i + q_0) = -\frac{\partial \theta'}{\partial x} + \frac{\partial q'_i}{\partial x} \equiv -H \]  

\[ \pi = C_p \left( \frac{P}{\rho_0} \right) \frac{\partial q}{\partial t} \]  

\[ \theta_v \equiv \theta (1 + 0.61 q_v) \]  

\[ \theta'_v = \theta' + (0.61 q_v - q_v) \theta_0 \]  

\[ \frac{\partial \theta'_v}{\partial x} + v \frac{\partial \theta'_v}{\partial y} + w \frac{\partial \theta'_v}{\partial z} + S = 0 \]  

\[ S = \frac{\partial q'_i}{\partial t} + \frac{\partial b}{\partial t} (\theta'_v) - \frac{\partial q}{\partial t} \]

Equations (1)-(3) are the momentum equations. The left hand side of the equations can be computed once the three-dimensional wind field \((u, v, w)\) and the horizontally homogeneous basic state (the subscript “0”) are available.

\( \pi \) is the normalized pressure defined in (4), \( P \) stands for pressure, \( P_0 = 1000 \text{ hPa} \), \( R \) is the gas constant, \( C_p \) is the specific heat capacity at a constant pressure. In (5)-(6), the virtual potential temperature and virtual cloud potential temperature perturbation are defined as \( \theta_v \) and \( \theta'_v \). \( \theta \) is potential temperature, \( q_i \) refers to water vapor mixing ratio, \( q'_i \) means the perturbation of water vapor mixing ratio, and \( q_c \) is the cloud water mixing ratio.

Equation (7) is a simplified thermodynamic equation, with \( S \) representing the source and sink term as defined in (8), which includes the \( \theta'_v \), tendency, diffusion and the mixed phase tendency term of each water particle in different phase. A set of three-dimensional \( \theta' \) and \( \theta'_v \) fields which makes equations (1)-(3) and (7) satisfied in a least-square sense can be obtained through variational minimization. However, in order to handle the terrain,
and radar reflectivity is expressed by the following in northern Taiwan.

Based on a 11-year sounding and radar observation, humidity is estimated by using radar reflectivity, according to Liou et al. (2014) is modified in which the relative humidity once the reflectivity reaches a threshold value of -10 dBZ. The complete procedure is described as follows:

(i) Set $q'_{v} = 0$ in (6).

(ii) Uses retrieved $\theta_{e}$ from section 2.2 and the $q_{l}$ from model forecast, one can compute $\theta^*_{e}$ from (6) and convert it to temperature $T'$. 

(iii) Saturation is assumed to take place when the radar reflectivity is greater than -10 dBZ, the saturated water vapor mixing ratio is computed, and the new $q'_{v}$ defined by

$$q'_{v} = q_{sat} \times RH / 100$$

(iv) If the difference between the old and updated $q'_{v}$ and $\theta^*_{e}$ are both smaller than $5 \times 10^{-5} \text{ kg kg}^{-1}$ and $5 \times 10^{-2} \text{ K}$, stop the iteration.

By using WISSDOM, TPTRS, and the modified vapor adjustment, one can obtain a set of three-dimensional meteorological fields which contains wind, pressure, temperature, rainwater mixing ratio and water vapor over complex terrain.

### 2.3 Qvapor Adjustment

The moisture/temperature adjustment scheme of Liou et al. (2014) is modified in which the relative humidity is estimated by using radar reflectivity based on a 11-year sounding and radar observation in northern Taiwan.

The relationship between the relative humidity and radar reflectivity is expressed by the following 4th-order polynomial

$$RH = 0.000124(\eta)^4 - 0.006841(\eta)^3 + 0.054437(\eta)^2 + 2.348806(\eta) + 52.28733$$

where $RH$ means relative humidity (%), $\eta$ refers to reflectivity (dBZ). Equation (9) is utilized to estimate the relative humidity once the reflectivity reaches a threshold value of -10 dBZ. The complete procedure for vapor adjustment is described as follows:

(i) Set $q'_{v} = 0$ in (6).

(ii) Uses retrieved $\theta_{e}$ from section 2.2 and the $q_{l}$ from model forecast, one can compute $\theta^*_{e}$ from (6) and convert it to temperature $T'$. 

(iii) Saturation is assumed to take place when the radar reflectivity is greater than -10 dBZ, the saturated water vapor mixing ratio is computed, and the new $q'_{v}$ defined by

$$q'_{v} = q_{sat} \times RH / 100$$

(iv) If the difference between the old and updated $q'_{v}$ and $\theta^*_{e}$ are both smaller than $5 \times 10^{-5} \text{ kg kg}^{-1}$ and $5 \times 10^{-2} \text{ K}$, stop the iteration.

### 3. Results of OSSE Experiments

An OSSE experiment is first conducted to explore the importance of some selected meteorological parameters in terms of affecting the model rainfall forecast. The main steps are as follows:

(i) A weather phenomenon is simulated by WRF first, to be considered as the true atmosphere (Truth).

(ii) Output some selected variables from (i), to be considered as “true” observations.

(iii) Systematically apply those observed variables to initialize WRF, and conduct forecast.

(iv) Compare the model forecasted results against the truth in (i), identify the role played by each parameter.

#### 3.1 Design of the Experiments

This study uses the Weather Research and Forecasting Model (WRF) version 3.8.1. The model domain contains 61 × 61 grid points along the horizontal, and 100 $\sigma$ layers along the vertical direction. The horizontal resolution is 1 km, time step is 5 seconds, and the model top is 18 km. Warm rain microphysical process uses in all experiments. We put an idealized bell-shaped mountain and a thermal bubble whose maximum temperature perturbation reaches 3.0 K into domain. This is called the True experiment. TABLE 1 gives a description of the design of each experiment.

#### 3.2 Results of the Experiments

The model forecasts of three-hour accumulated rainfall show that if the water vapor is not correct (RxQv) and the storm fails to develop, resulting in inaccurate rainfall forecast (FIG. 2). This leads to the necessity of performing vapor adjustment. In experiment Qvadj2, the vapor adjustment is conducted twice at the initial time and after 30 min. After adjustment, the storm splitting phenomenon

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
<th>Initial Temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>A splitting storm; the true atmosphere. (T' = 3.0 K)</td>
<td></td>
</tr>
<tr>
<td>Ctrl</td>
<td>A weaker and drier storm; an unsuccessful model forecast. (T' = 0.5 K)</td>
<td></td>
</tr>
<tr>
<td>R_all</td>
<td>Replace {U,V,W,P,T,Qv,Qr} in Ctrl by True ones and forecast.</td>
<td></td>
</tr>
<tr>
<td>RxT</td>
<td>Same as R_all, but without replacing {T}.</td>
<td></td>
</tr>
<tr>
<td>RxW</td>
<td>Same as R_all, but without replacing {W}.</td>
<td></td>
</tr>
<tr>
<td>RxQv</td>
<td>Same as R_all, but without replacing {Qv}.</td>
<td></td>
</tr>
<tr>
<td>RxQr</td>
<td>Same as R_all, but without replacing {Qr}.</td>
<td></td>
</tr>
<tr>
<td>Qvadj2</td>
<td>Same as RxQv, but Ctrl {Qv} is adjusted 2 times. The adjustment method according to Liou et al. (2014).</td>
<td></td>
</tr>
</tbody>
</table>
can be successfully re-produced at t = 70 min, as depicted in FIG. 3.

4. Results of a Real Case Study—An afternoon Thunderstorm on 19 Aug., 2014

This real case took place at 0639 UTC (1439 LST) on August 19, 2014 in northern Taiwan. Two isolated convective cells grow in a weak synoptic forcing environment, and induce heavy precipitation in the Taipei.

4.1 Design of the Experiments

The model adopts two-way nesting. D01 includes 100×74 grid points in the horizontal, while D02 contains 150×100 grid points in the horizontal. Both D01 and D02 include 69 \( \sigma \) layers in the vertical. The grid spaces are 5 and 1 km for D01 and D02, respectively. The pressure at the model top is 10 hPa.

(i) **noDA**: The model was directly simulated for 3 hours, and no data assimilation was performed. It can be used as a control run.

(ii) **DA**: The retrieved variables \{U, V, W, P, T, Qv, Qr\} are used to replace their simulated counterparts in the model, followed by a model integration for 3 hours.

4.2 Results of the Experiments

The reflectivity observed by radar and forecasted by model after 1.5 h of integration with and without data assimilation are shown in FIG. 4. The reflectivity results of noDA are obviously different from the observations. By contrast, the reflectivity from experiment DA has better spatial distribution and intensity than that from noDA.

The rainfall forecast results are shown in FIG. 5. From the observation, it can be seen that the rainfall distribution concentrates at two locations, which are associated with two isolated convection cells as shown by the reflectivity data in FIG. 4. The rainfall results of noDA are very different from observations, with missing rainfall extremes and many false alarms. However, from the results of DA, the rainfall extremes in the Taipei are well simulated, and the rainfall distribution is in good agreement with the observations.

As illustrated by the ETS scores of DA experiment in FIG. 6, almost all ETSs of different thresholds are greater equal than 0.3 for the entire forecast period.

Overall, the model forecast skill of the precipitation can be significantly improved by assimilating observed and retrieved variables from radar observations.

5. Summary

In this study two retrieval algorithms called WISSDOM and TPTRS are developed by which on can recover the three-dimensional meteorological
fields, including wind, pressure, and temperature, rainwater mixing ratio over complex terrain. A new scheme is also designed to adjust the water vapor. By assimilating these retrieved fields into a numerical model, it is demonstrated that the model’s short-term rainfall forecast skill can be significantly improved for the case selected in this research, which is an afternoon thunderstorm occurred in northern Taiwan. It should be pointed out our method is particularly suitable for rainfall forecast in mountainous areas. In addition, data from only two radar volume scans are sufficient to perform the retrieval and data assimilation, which makes our approach a very efficient one.

Acknowledgments. This research is supported by the Ministry of Science and Technology of Taiwan under MOST107-2111-M-008-040, MOST107-2625-M-008-008, and by the Central Weather Bureau (CWB) under MOTC-CWB-107-M-02. The authors are grateful for the radar and sounding data provided by CWB.

References


