Application of total-lightning data assimilation in a mesoscale convective system based on the WRF model

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Abstract

A total lightning data assimilation method was proposed and applied in a mesoscale convective system (MCS) simulation with the Weather Research and Forecasting (WRF) model. On the bases of analyses of several thunderstorm processes over northern China, empirical formulas between total lightning flash rate and ice-phase particle (graupel, ice, and snow) mixing ratio were constructed based on the well-known relationship between the occurrence of lightning activity and the content of ice-phase particles. The constructed nudging functions were added into the WSM6 microphysical scheme of WRF to adjust the mixing ratio of ice-phase particles within a temperature layer from 0 °C to −20 °C isotherms, and consequently the convective precipitation. The method was examined in a MCS with high lightning flash rate and heavy precipitation occurred over two megacities of Beijing and Tianjin, northern China. The representation of convection was significantly improved 1 h after the lightning data assimilation, and even during the assimilation period. The precipitation center, amount and coverage were all much closer to the observation in the sensitivity run with lightning data assimilation than in the control run without lightning data assimilation. The results showed promising improvements on the convection and precipitation and demonstrated rationality and effectiveness of the proposed assimilation technique. The results also showed that active lightning regions have a strong capability of adjusting convection and precipitation, suggesting that the assimilation method can be used for improving the short-term precipitation forecasting of MCS with high, even moderate lightning flash rate.

Keywords: Lightning, Convection, Data assimilation

1. Introduction

Mesoscale convective systems (MCSs) usually consist of several isolated convective storm cells and produce heavy rainfall, wind, hail, lightning and possibly tornadoes. They are major precipitation processes and often lead to flooding and disastrous consequences in northern China. However the forecast of MCSs is very difficult because of its nonlinear interactions with the environmental dynamic and thermodynamic field in multi-scales (Liu et al., 2010; Yi et al., 2011; Xiao et al., 2013). Consequently, it is of great importance to assimilate more meso- and small-scale observational data into numerical weather prediction (NWP) models in order to improve the forecast skill for storm and MCS processes (Chen et al., 2012).
Lightning can be regarded as an indication of severe convection (e.g., MacGorman et al., 1989; Qie et al., 1993; Schultz et al., 2011). It has a close relationship with convective precipitation (e.g., Goodman et al., 1988; Zhou et al., 2002; Wiens et al., 2005; Gauthier et al., 2006; Liu et al., 2011) and can provide accurate information regarding the location of severe convection. Moreover, lightning detection demonstrates outstanding advantages of high-precision, long-distance coverage, and free from the influence of terrain. With the development of state-of-the-art lightning detection technologies and the accumulation of high-quality lightning location data, lightning assimilation techniques and their application in numerical weather prediction models, aiming to improve the forecasting skill of MCS precipitation, have been a major scientific effort recently (e.g., Papadopoulos et al., 2005, 2009; Mansell et al., 2007; Fierro et al., 2012; Lagouvardos et al., 2013).

Alexander et al. (1999) investigated the lightning data assimilation technique in an earlier time. They established a relationship between lightning and the precipitation ratio through a kind of classic image processing method using microwave sounding data and cloud-to-ground (CG) lightning data, and applied it in the MM5 numerical weather prediction model. The 12–24 hour precipitation forecast of a super-storm process was improved by using the proposed lightning data assimilation technique. Using a similar method, Chang et al. (2001) established a link between lightning observational data and the Tropical Rainfall Measuring Mission (TRMM) satellite-derived precipitation rate, the 9–18 hour short-term forecast was significantly improved after assimilating the lightning data into a rainstorm process simulation. Pessi and Businger (2009) also utilized empirical lightning–rainfall relationship to adjust the vertical latent heating profiles in MM5’s Kain–Fritsch convective parameterization scheme (Kain and Fritsch, 1992) according to rainfall rates estimated from lightning observations, and the pressure and wind forecasts were improved.

The above-mentioned methods have one thing in common, that is, a statistical relationship between lightning and the precipitation rate was built, and the deduced precipitation information was used as input for the model. In addition to such approaches, some other methods for lightning data assimilation have been proposed either. Analyzing multiple convection processes, Papadopoulos et al. (2005) summed up an empirical formula of CG lightning and water vapor profiles. For areas with lightning occurrence, the greater water vapor out of the modeled and empirical results was taken into the calculation of the cumulus convection parameter. They found that this method improved the accuracy of convective precipitation forecasts for three simulated thunderstorms in the Mediterranean region. Dietrich et al. (2011) developed a method inferring the development (movement, morphology and intensity) of convective rain cells from lightning distribution. They showed that the rain field demonstrated an overall agreement with the satellite-based rainfall estimates. Mansell et al. (2007) modified the Kain–Fritsch (KF) convection parameterization scheme in the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model by taking in the detected CG lightning as an index of convection. The KF scheme was forced to produce convection where lightning indicated storms and, conversely, was optionally prevented from producing spurious convection where no lightning was observed. In an experiment of convective precipitation, it was shown that short-term forecasts of convective precipitation were improved significantly. Lagouvardos et al. (2013) also used lightning data as a proxy for the presence of convection to control the activation of the convective parameterization scheme in MM5. The assimilation of lightning, applied to a heavy precipitation event over southern France, also provided more realistic positioning of the precipitation maxima.

Integrating the methods of Papadopoulos et al. (2005) and Mansell et al. (2007), Ran and Zhou (2011) conducted a nudging assimilation of water vapor and cloud hydrometeors using TRMM satellite lightning observation data. They also adjusted, at the same time, the KF cumulus convective parameterization scheme using lightning data. The technique was applied to simulation of three short-term precipitation events, and improvements in short-term rainfall forecasts were achieved. Fierro et al. (2012) first used the lightning data assimilation method in cloud-resolving scales based on Weather Research and Forecasting (WRF) model. They established an empirical formula for the water vapor mixing ratio, total flash rate and graupel mixing ratio. They found that the assimilation of the total lightning data for only a few hours prior to the analysis time significantly improved the representation of the convection at the analysis time and at the 1-hour forecast time within the convective-resolving grids. Fierro et al. (2014) recently compared this lightning assimilation technique with those obtained using a cloud scale 3DVAR technique that assimilates radar reflectivity and radial velocity data, and found that lightning assimilation was better able to capture the placement and intensity of the derecho event up to 6 h of the forecast.

The non-inductive electrification mechanism involving re-bounding collision between ice-phase particles is well known as the main electrification mechanism inside thunderstorms (Takahashi, 1978; Saunders et al., 1991). Recent space-borne and ground-based observations have also confirmed the close relationship between lightning activity and content of ice-phase particles at various scales (Petersen et al., 2005; Gauthier et al., 2006; Yuan and Qie, 2008). Ice-phase particles are main sources of hydrometeor particles which produce convective precipitation through cloud microphysical processes either. Consequently, it is rational to establish relationship between lightning and ice-phase content, as well as convective precipitation. In the present study, we took ice-phase particles as an assimilation interface, and built a finer and reasonable empirical formula based on the existing well-known relationship between the occurrence of total-lightning activity and the content of ice-phase particles. As we show in the following results, an improvement in short-term forecasting of convective precipitation was achieved when applying the nudging function in a MCS case that took place over northern China around two megacities of Beijing and Tianjin.

2. Model and data description

The numerical model of three dimensional WRF model with the Advanced Research (ARW) dynamic solver (WRF-ARW, version 3.4.1) was used in this study. With a perfect dynamic framework, and comprehensive physical parameterization and assimilation schemes, WRF has been a very useful tool to
simulate the mesoscale weather systems. The WSM6 micro-
physical parameterization scheme (Hong and Lim, 2006) was
chosen in this study. This scheme contains 6-class bulk
microphysics processes, including water vapor, cloud water,
rain, ice, snow crystals and graupels, and is suitable for
high-resolution numerical simulation. In addition, the Rapid
Radiative Transfer Model (RRTM) long wave radiation scheme,
Monin–Obukhov land-surface layer flux scheme, and Yonsei
University (YSU) scheme planetary boundary layer scheme were
used in the simulation. The NCEP/NCAR reanalysis data are used
as the background and the model lateral boundary conditions.

The double-nesting was used for the simulation. The
central point of the double-nesting of the model was set at
(39.8°N, 116.5°E). The outer domain was configured to run
on a larger but coarser resolution of 6 km covering 250 × 250
grid points and nested by a smaller but higher resolution of
2-km for inner domain covering 298 × 298 grid points. The
convection is simulated explicitly with this grid spacing in
model, and no cumulus parameterization is needed. Fig. 1
shows the study region and the configuration of the two
simulated domains. Twenty seven layers were considered in
the vertical direction with the top at 50 hPa for both
domains. The time step was 30 s and the simulation result
was output every 1 h for the outer coarse domain (D01),
while the time step and output were 10 s and every 30 min
respectively for the inner fine domain (D02).

The lightning data used in the present study were from the
SAFIR 3000 lightning detection system, composed of three
sensors at about 120 km apart and covering an area of about
270–280 km². SAFIR 3000 uses interferometry to measure
lightning-generated radiation signals in the very high frequen-
cy (VHF) band from 110 to 118 MHz and low frequency (LF)
band from 300 to 3 MHz. It effectively locates lightning
radiation sources in three dimensions, and presents the spatial
distribution of both CG and intracloud (IC) lightning locations
very well. Liu et al. (2010) and Zheng et al. (2010) suggested
that the efficiency of the Beijing SAFIR 3000 lightning detection
network reaches 90% in the center, with the horizontal location
error being 2 km and the vertical error less than 2 km. Other
studies have also reported positive features of the system,
indicating that it provides lightning information with applica-
tion value and high detection efficiency, accuracy, and
reliability (e.g., Liu et al., 2011, 2013). Compared with the
Lightning Detection and Ranging (LDAR II) or Lightning
Mapping Array (LMA) the accuracy of the SAFIR 3000 lightning
detection network might be relatively low, but nevertheless
provides valuable information on the evolution of lightning,
and reveals characteristics of the total lightning activities of
thunderstorms.

Lightning flash data used in this study were filtered for
the total lightning data, as described by Liu et al. (2013).
Meanwhile, the lightning position was considered as the

Fig. 1. The WRF simulation 6-km parent domain (D01) and the nested 2-km domain (D02). The black dots denote the SAFIR 3000 lightning detection station.
horizontal location of the first lightning radiation source, regardless of its spatial propagation. The radar echo data were from an S-band Doppler radar located at (39.814°N, 116.472°E). It covers a 230-km-radius range and routinely operates a volume scan every 6 min.

3. Methodology

3.1. Establishment of nudging functions

The non-inductive electrification mechanism indicates a direct relationship between lightning and ice-phase particle content in the thundercloud. Although several quantitative formulas between them have been established in previous studies (e.g., Petersen et al., 2005; Yuan and Qie, 2008), the model calculation could not directly adopt these existing formulas in which ice mass is used as a variable; however, ice-phase particle mixing ratios are usually used as variables in most models’ calculations. To assimilate the lightning observation data, a quantitative relationship between flash rate and ice-phase particle mixing ratios was established as the first step.

Owing to the lack of quantitative observations of the microphysics inside thunderstorms in the case of observation area, we incorporated observations and simulated results to establish the relationship between flash rate and the ice-phase particle mixing ratio. Even though, it is still difficult to establish an accurate and quantitative formula between lightning and ice-phase constituents of clouds in the model grid because of the instant and random nature of lightning occurrence, and the microphysical environment at the exact lightning location is difficult to know even with a high-resolution mesoscale numerical model. In this study, we referred to the radar echo characteristics to choose the best moments in which the simulated results best match the observations. The simulated strong radar echo areas that were close in location and form to the observed strong echo areas were chosen as the most probable lightning-producing cells (Zipser and Lutz, 1994; Rutledge and Petersen, 1994; Toracinta et al., 2002). The ice-particle content in the simulated area and observed lightning flashes in the same area were used to construct the empirical formula between them. Following the works of Fierro et al. (2012) and Reisner and Jeffery (2009), initial formulas between flash rate and ice-particle content for the same moment and the same area of the observed and simulated cells were established in the following form:

\[ Q_{\text{sig}} = Q_0 + \beta \cdot \tanh(\alpha \cdot F) \]  
\[ Q_{\text{ass}} = \max(Q_{\text{mod}}, Q_{\text{sig}}) \]  

where \( Q_{\text{sig}} \) represents the snow, ice crystal or graupel mixing ratios after lightning data assimilation; \( Q_0 \) represents the average benchmark concentration of ice-phase particles when lightning occurred; \( F \) is the flash rate in the model time-step grid; \( Q_{\text{mod}} \) represents the ice-phase particle mixing ratio obtained by simulation (i.e., the ice-phase particle mixing ratio without lightning data correction); and \( Q_{\text{ass}} \) is the final mixing ratio used in the model. \( \alpha \) reflects the sensitivity of the ice-phase particle content changing with flash rate, and the content increases rapidly with the enhancement of the flash rate for a large \( \alpha \). \( \beta \) reflects the adjustment level of ice-phase particles, and the particle content will increase at a higher level when the flash rate increases for a large \( \beta \). Besides, another parameter, \( \gamma \), is set in the assimilation, which is used to reflect the impact on ice-phase particle content in the nearby grids without lightning occurrence, so as to eliminate, to some degree, the spatial discontinuity caused by artificially adding the ice phase in the lightning-producing grids, while the temporal discontinuity is eliminated through the model adjustments themselves. During the assimilation, adjustments were only made within the level between 0 °C to −20 °C, which represents the ice-particle-rich region within convection and hence is most likely associated with electrification and lightning activity according to the non-inductive charging mechanism.

The coefficients in Formulas (1) and (2) were determined based on the statistics and analysis of three thunderstorm systems over northern China on 31 July 2007, 14 August 2011, and 26 August 2011, for which integrated data of lightning location and radar observations, as well as favorable simulation results (i.e., matched well observations) were achieved. Several tests were conducted referring to echo intensity and precipitation so that the coefficients could represent all kinds of ice-phase particle content variation when lightning occurred. Table 1 shows the coefficients for three kinds of ice-phase particle content, including the snow, ice crystal or graupel mixing ratios.

The philosophy behind Formulas (1) and (2) is as follows. The ice-phase particle content has a basic value when lightning occurs. If the flash rate is low, the ice-phase particle content increases monotonically with the increase in the flash rate. When the flash rate reaches higher value, the ice-phase particle content will remain stable. Fig. 2 shows the variations of ice crystal, snow and graupel content based on the coefficient in Table 1. This approach not only constrains unreasonable enhancement of ice-phase particles, but also eliminates the effect of error in the detection of flash rate, and maintains stability of the simulation.

3.2. The process of assimilation

Both CG lightning and IC lightning were taken into account in the assimilation. The retained lightning information includes flash time, location and rate. Latitude and longitude coordinates of lightning data were parsed into 10-s intervals of accumulated lightning flash data and gridded onto the local WRF Cartesian grid coordinates. These parsed lightning data were assimilated into WSM6 using the following procedure (Fig. 3). Whenever a flash occurred in a given grid column, the ice-phase particle mixing ratio was calculated via the nudging function, as stated above. Extra ice-phase particle content,

<table>
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<th>Table 1 Coefficient values in the nudging function.</th>
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<tr>
<td>Ice crystal</td>
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<tr>
<td>Snow</td>
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<tr>
<td>Graupel</td>
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determined by $\gamma$, was added in the adjacent grids without lightning occurrence for the continuity. For moments without lightning occurrence, the calculations were processed normally, without lightning assimilation.

At each computational time step, the WRF model initially called the WSM6 microphysical scheme without using lightning assimilation, and WSM6 would output a result for each grid point at that time. A new result would then be attained using the empirical formulas of the gridded flash rate and the simulated ice-particle mixing ratio in each grid with lightning occurrence and its adjacent grids. By comparing the two results, the larger value was chosen to return to the former level of the WRF computation.

In order to examine the improvement of the proposed lightning data assimilation method, two simulations for each case were performed. In the first simulation (the control test), the convection was allowed to develop unforced, without any lightning data assimilation. The second simulation was the sensitivity test, which was the same as the control test except that SAFIR 3000 total-lightning data were assimilated into the model run.

4. Results

The lightning assimilation method developed in the present study was tested for a MCS event featuring short-term heavy precipitation and frequent lightning activity over northern China occurred on 13–14 June 2010. The event spanned more than a period of 12 h, initially developing over northwestern Beijing, moving southeastward over Beijing to Tianjin, then on to Bohai Bay, before dissipating over the sea.
Fig. 4 shows the radar composite reflectivity factor at four moments representing the whole life cycle of the MCS’s evolution. Thunderstorm cells with a central reflectivity of greater than 30 dBZ initiated over northwest Beijing at 14:00 (Beijing time). Multiple cells with reflectivity higher than 50 dBZ developed and aligned more or less linearly with large cloud coverage at 18:00 (refer to Fig. 4a). The squall-line-featured radar echo formed in its mature stage at about 20:00 (Fig. 4b) and produced frequent lightning activity with a flash rate more than 20 fl/min. The thunderstorm was still in its mature stage at 22:00 and the squall line structure can be seen as several cells aligned linearly at the front of the thunderstorm (Fig. 4c). The radar echo broke into several parts and started to dissipate at 24:00 (Fig. 4d).

The simulation period was 12 h from 14:00 on 13 June to 02:00 the following day. Lightning data were not assimilated for the control test, but the lightning data were assimilated between 20:00 and 22:00 after 6 h of the model run for the sensitivity tests. Fig. 5 shows the spatial distribution of lightning location during the period of data assimilation from 20:00 to 22:00. The most intense lightning occurred over the north of Tianjin or the east of Beijing, while comparatively fewer lighting episodes occurred over western Tianjin or southern Beijing. The lightning activity was distributed extensively with a large region of high flash rate.

4.1. Comparison of radar reflectivity between the control and sensitivity tests

Fig. 6 shows a comparison of the radar composite reflectivity factor with and without lightning assimilation. Although the simulation spanned a 12-h period, the following analysis focuses firstly on the forecast period after the lightning data assimilation. The times of interest are 22:30 and 23:00, half an hour and one hour after the lightning assimilation, respectively. From the observed radar echoes shown in Fig. 6a and b, it can be seen that the MCS was composed of two parts from 22:30 to 23:00. The main body
of the system was stretched in the southwest–northeast direction. The maximum reflectivity, i.e., the region with the strongest convection, was located at the front of the MCS.

Fig. 6c shows the results without lightning assimilation at 22:30. Compared with the observation shown in Fig. 6a, although the obvious linear features of the MCS’s main body were represented, the strong reflectivity at the front failed to be reproduced. In contrast, the forecast simulation based on lightning assimilation (Fig. 6e) produced a more accurate pattern of the convection than the control forecast at the same time, both for the main body and the strong reflectivity at the front region of the MCS. It was generally in good agreement with observed radar reflectivity, particularly at the front of the MCS, where the control test did not forecast any convection. Similarly, at 23:00, the simulated radar reflectivity in the sensitivity run with lightning data assimilation matched the observation much better than the control test, both for the main body and the strong radar echo at the front.

Half an hour or one hour after the lightning data assimilation, the sensitivity test demonstrated the convection region very well, and the simulated strong convection region improved greatly. Compared with the lighting distribution in Fig. 5, it can be seen that in the active lightning region, the capability of the model simulation in terms of the convection, particularly the severe convection, was much more enhanced with lightning data assimilation. The region with intense lightning activity corresponded with higher radar reflectivity, while less lightning activity corresponded with weaker radar reflectivity in the sensitivity test with lightning data assimilation.

To show the model respond time after the start of lightning data assimilation, Fig. 7 shows the radar composite reflectivity factors at two moments during the lightning assimilation. The times of interest are 21:30 (1 h into the assimilation period) and 22:00 (one and a half hours into the assimilation period). Comparing the simulation results with the observation, some of the strong echo area, which was not shown in the control run, was found at 21:30 after lightning assimilation, and much clearer at 22:00. Assimilating the lightning data has notable effects on the radar echo coverage one and a half hours into the assimilation period, and the corresponding severe convection was also improved significantly. In particular, the shape of the ring echo was represented at 22:00. It can be concluded that the lightning assimilation method proposed here improves the simulation results quickly, and the effects of lightning data on the radar echo shape and intensity are evident even during the assimilation period, and may be also useful in severe nowcasting either.

4.2. Six-hour accumulative rainfall

The location and amount of precipitation were substantially improved by assimilating the total-lightning data. Observed and forecast rainfall accumulations for 6-hour forecast period in the control and sensitivity tests are shown in Fig. 8. The observed precipitation from rain gauge data was distributed over a large spatial area, and the maximum was located over the northeast of Tianjin with a central rainfall of 25 mm; another sub-maximum occurred over the south of Beijing with a central rainfall of 21 mm. The precipitation center and maximum lightning density (shown in Fig. 5a) were spatially congruent with each other.

Compared with the observed precipitation, the location was biased toward the north and the intensity was weak for the simulated precipitation without lightning assimilation (Fig. 8a). The simulated precipitation center was a little too far from the observed precipitation center. In the sensitivity test, the location of precipitation simulated with lightning assimilation was improved significantly (Fig. 8b), and was in very good agreement with the observation. Furthermore, the precipitation intensity was also much closer to that observed, and the coverage of the precipitation was much improved compared to the control test. Over northeast Tianjin, where there was intense lightning activity, the sensitivity test
Fig. 6. Radar composite reflectivity factor (in dBZ) of the MCS occurred on 13 June 2010: (a) observation at 22:30; (b) observation at 23:00; (c) control test at 22:30; (d) control test at 23:00; (e) sensitivity test at 22:30 (half-hour forecast); and (f) sensitivity test at 23:00 (one-hour forecast). The observed reflectivity was partly shielded by the high structures of the city.
Fig. 7. Radar composite reflectivity factor (in dBZ) of the MCS: (a) observation at 21:30; (b) observation at 22:00; (c) control test at 21:30; (d) control test at 22:00; (e) sensitivity test at 21:30 (1 h into the assimilation period); and (f) sensitivity test at 22:00 (one and a half hours into the assimilation period).
simulated the precipitation center successfully, and the maximum rainfall was in good agreement with the observation as well. Over the west of Tianjin, where there was sparse lightning activity, the simulated precipitation coverage and intensity were much improved by the use of lightning data assimilation, as compared to the control test without lightning assimilation. In particular, the sub-maximum of precipitation was represented well in the sensitivity test with lightning assimilation.

For a quantitative assessment of the proposed lightning data assimilation technique, the mean absolute error of the 6-hour accumulated rainfall has been calculated. Table 2 shows the mean absolute error of the 6-hour accumulated rainfall calculated for 4 observed precipitation ranges. The precipitation simulated by both experiments was compared with the observed precipitation provided by 17 rain gauges deployed in the research area. The mean absolute error for the assimilation run in each range is lower than that of the control run, especially for the higher rainfall. For example, for the rainfall range of 20–50 mm, the mean absolute error of the 6-hour accumulated rainfall is 39.8 mm for the control run, and 13.9 mm for the sensitivity run, 3 times lower than the control run. For the rainfall range of 11–20 mm, the mean absolute error is 53.3 mm and 26.8 mm for control run and sensitivity run, respectively. Even for the small rainfall of 5 mm, the mean absolute error is lower for the sensitivity run with lightning data assimilation than the control run.

Based on the above comparisons between the control and sensitivity tests, it can be concluded that the precipitation was well adjusted for the regions with intense lightning activity. These regions corresponded with high precipitation regions, and widespread lightning with the large coverage of precipitation, in the lightning assimilation result. The adjustment of precipitation in the regions with less lightning was not as good as in the region with intense lightning, but still gave significant improvement in terms of the precipitation.

5. Discussion and conclusions

Ice-phase particles are an essential source of convective precipitation, and are also the main charge carrier of electrification. Based on the close relationship between lightning and electrification in clouds, we analyzed several thunderstorm processes over northern China to summarize an empirical formula between lightning and ice-phase particles. A nudging function was constructed so as to locally adjust the ice-phase particle (graupel, ice, and snow) mixing ratio via a simple smooth continuous function between total-lightning flash rate and ice-phase particle mixing ratio.

The constructed nudging function was used in one mesoscale convective system with high precipitation and high lightning flash rate occurred over northern China. The results showed that the assimilation of total-lightning data for only 2 h significantly improved the representation of the convection. The precipitation center, amount and coverage were much closer to the observation in the sensitivity test.

**Table 2**

<table>
<thead>
<tr>
<th>Range (mm)</th>
<th>Stations</th>
<th>Mean absolute error (mm)</th>
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<tbody>
<tr>
<td>21–50</td>
<td>2</td>
<td>39.8</td>
</tr>
<tr>
<td>11–20</td>
<td>4</td>
<td>52.3</td>
</tr>
<tr>
<td>6–10</td>
<td>4</td>
<td>31.5</td>
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<tr>
<td>&lt;5</td>
<td>7</td>
<td>16.0</td>
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Fig. 8. Observed and forecasted total 6-hour precipitation (mm) from 20:00 on 13 June 2010: (a) control test without lightning assimilation; (b) sensitivity test with total-lightning assimilation. The black contours represent the observed precipitation from rain gauge data. The shaded areas indicate the simulated precipitation.
with lightning data assimilation than in the control test without lightning data assimilation. In the sensitivity test, the strong echo areas of the MCSs were better adjusted an hour or half an hour after the end of the assimilation period, even during the lightning assimilation. The results also suggested that assimilating total-lightning data can have notable desired effects on isolated severe convective cells, indicating that such a nudging technique is effective in short-term forecast of MCS with high flash rate because of the direct relationship between lightning activity and ice-phase particles. The precipitation region with active lightning can be improved significantly, and the distribution of severe convection with high reflectivity was similar to the active lightning region in the present study. Regions with less lightning also showed an adjustment of the coverage and location of convection and precipitation, suggesting that this simple assimilation method could be applied to severe thunderstorm events characterized by moderate to intense lightning activity, as suggested by Mansell et al. (2007) and Fierro et al. (2012).

Although the empirical formulas being based on both lightning observations and simulated in-cloud microphysical parameters will certainly have limited the assimilation results, the constructed relationship between lightning and ice-phase particles is reasonable (Deierling et al., 2008). For the case studies, the lightning assimilation showed promising results and was successful in representing the precipitation centers and coverage as well as the convective cores. The method could therefore easily be used for real-time assimilation of any source of lightning observations. With the development of state-of-the-art lightning detection technologies, high-quality lightning location data are becoming more readily available across the globe. The lightning data assimilation method and its application in numerical weather prediction models are capable of marked adjustments to the position and intensity of convection, thus enhancing the skill of precipitation forecasts.

The lightning data assimilation period was 2 h in this study just to show the effectiveness of the proposed technique. Despite the obvious improvements identified in the present work, there are shortcomings to this lightning assimilation method that should also be noted. First, when lightning occurs, the convection might have already been well developed. So like all the other lightning assimilation methods, the assimilation technique has its own shortcomings in stimulating initially convections, but serves to adjust the convection. Second, some spurious convection produced by the unconstrained model was not corrected in the study. This problem could be improved by using lightning as a proxy for the presence or absence of deep convection, as proposed by Mansell et al. (2007). Third, the assimilation does not efficiently capture the convection where little flash occurred in the assimilation time considered. This could be improved by involving observed radar reflectivity during the lightning assimilation period. Of course, the applicability of the empirical formulas constructed over northern China should be examined for other areas, or other small-scale thunderstorms. All of these issues will be further considered in the future researches. Another goal for future research will be to reduce the operation time of the model simulation in order that the method can be applied in nowcasting. A continuous assimilation method with updated lightning observation should be also tested for the operational forecasting of severe storms.

Acknowledgments

The research was supported by the Key Project of the National Natural Science Foundation of China (Grant no. 40930949) and National Key Basic Research Program of China (Grant no. 2014CB441401). The authors would like to thank the Beijing Meteorological Administration for providing the lightning detection and radar data. They also thank the two anonymous reviewers for their valuable suggestions which improved the quality of this paper.

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