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Improving forecasting of strong convection by assimilating cloud-to-ground lightning data using the physical initialization method

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ABSTRACT

Lightning network data can record lightning information (including location, intensity, and frequency) with high temporal resolution. Such data can provide a useful supplement to radar observations, which are limited in temporal and spatial coverage. It has been previously reported that in convective weather systems, the correlation between cloud-to-ground lightning and radar reflectivity is strong, which suggests the possibility of improving convection forecasting through assimilating lightning data. In this study, the benefits of assimilating lightning data are demonstrated by a series of experiments using data from a strong convection event that occurred in Jiangsu and Anhui provinces, China, on 5 June 2009. Using a simple assumed relationship between flash density and reflectivity in the Gridpoint Statistical Interpolation (GSI) system, the lightning data were first converted into 3D lightning-proxy radar reflectivity, which was subsequently assimilated using the physical initialization method to adjust model variables (i.e., vertical velocity, specific humidity and specific cloud water content). For this case, the results show that convection forecasting is improved by assimilation of the lightning-proxy reflectivity using the physical initialization method. There was a significant improvement in the prediction of reflectivity, and this was maintained for about 3 h. Assimilating multi-time lightning data with assimilation cycles can further improve forecasting accuracy.

1. Introduction

Lightning is a common atmospheric discharge phenomenon, and as such can provide detailed information regarding convective clouds, such as time, location, number, polarity, and strength of discharge events. Furthermore, lightning data are relatively unaffected by geographical constraints, and exhibit higher temporal and spatial resolution than meteorological radar observations do; because of these characteristics lightning data offer notable advantages for convective weather research. Lightning data can be used during the initial process of refining weather forecasting to improve the accuracy of predictions of convective activity in the initial field of models, thus improving the accuracy of short-term forecasts of convective weather processes. The assimilation of lightning network data is a relatively new approach; therefore, research in this field is limited as compared with applications of other meteorological data. The difficulty in assimilating lightning data is that the observational variable is not one of the variables incorporated into the models; thus it must be connected with a model variable or a diagnosed variable before assimilation. Recently, a strong connection was observed between cloud-to-ground lightning in convective weather systems and convective precipitation rates (Benjamin et al., 2007; Chang et al., 2001; Correoso et al., 2006;

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Fierro et al., 2012, 2014; Hodapp et al., 2008; Hu, 2009; Hu et al., 2008; Katsanos et al., 2007; Liu et al., 2009, 2011, 2013; Mazarakis et al., 2009; Qie, 2012; Qie et al., 2002, 2014; Tapia et al., 1998; Weygandt et al., 2007; Zhou et al., 2002), specific ice water content (Gauthier et al., 2006), radar vertically integrated liquid water content (VIL), and radar echo tops (MacGorman et al., 2007; Munsell, 2009). Furthermore, in the Rapid Update Cycle (RUC) cloud analysis and diabatic digital filter initialization (DFI) procedure, lightning data are converted to reflectivity using a simple assumed relationship between flash density and reflectivity, and are then used in the DFI to induce convective-scale features within the model initial fields. This storm-scale initialization capability (using both reflectivity and lightning data) has yielded impressive improvements in RUC model predictions of ongoing convection. In addition, 3 km High Resolution Rapid Refresh (HRRR) forecasts initialized with the RUC radar/lighting DFI procedure have shown a marked improvement over parallel 3 km forecasts without the special assimilation procedure. This same storm-scale initialization capability is being ported to the Rapid Refresh (RR) system, which will then replace the RUC as the source for HRRR initial fields (Benjamin, 2006; Benjamin et al., 2004, 2007; Hu, 2009; Hu et al., 2006a, 2006b, 2008; Weygandt et al., 2007, 2008). Papadopoulos et al. (2009) assimilated ground-strike lightning data to nudge relative humidity through the use of sample profiles of humidity associated with deep convection. They used a version of the Eta model with the Betts–Miller–Janjic (BMJ) scheme. The relative humidity was adjusted in proportion to the ground flash rate reported by the ZEUS long-range detection system in Europe. During the assimilation periods for three cases, the nudging technique generally resulted in improved precipitation rates, especially for higher thresholds. Pessi and Businger (2009) also obtained a quantitative relationship between the lightning rate and the maximum radar reflectivity and its height in summer and winter. Their results have been applied over data-sparse ocean regions by allowing lightning-rate data to be used as a proxy for related storm properties, which can be assimilated into numerical weather prediction (NWP) models. Subsequently, RUC/RR has been assimilating lightning-proxy reflectivity transformed from lightning data, which shows excellent feasibility. Based on this approach, it is possible to assimilate lightning data in the same way as that of radar reflectivity data. Many previous studies have examined methods of assimilating Doppler radar reflectivity data, including the variational method (Gao and Stensrud, 2012; Gao et al., 2004; Pu et al., 2009; Sun and Crook, 1997, 1998; Xiao et al., 2005), the ensemble Kalman filter (Gao and Xue, 2008; Tong and Xue, 2005; Zhang et al., 2004), and experiential methods such as cloud analysis and physical initialization (Haase et al., 2000; Krishnamurti et al., 1991; Milan et al., 2008; Yang et al., 2006).

Physical initialization, proposed by Krishnamurti et al. (1991), is based on a semi-experiential relationship between radar reflectivity and precipitation that focuses on adjusting vertical velocity, specific humidity and specific cloud water content using a physical analysis process. This method can shorten the spin-up time of the initial field of a model, and has a positive effect on precipitation forecasting (Haase et al., 2000; Milan et al., 2008; Yang et al., 2006). To some extent, physical initialization is similar to the method of adjusting vapor and cloud microphysical variables in GSI cloud analysis.

The strong convective event that occurred on 5 June 2009 is the focus of the analysis presented here to examine the effect of assimilating lightning data with the physical initialization method. First, lightning data were transformed into 3D proxy radar reflectivity using a simple assumed relationship between flash density and reflectivity in the GSI system.[1] In this process, a statistical relationship between the number of flashes per grid column and the corresponding column maximum of model grid-box averaged reflectivity is used, and then vertical reflectivity distribution is retrieved using a statistic reflectivity profile based on converted maximum reflectivity with different seasons. Second, lightning-proxy reflectivity was assimilated by physical initialization, and then the analysis field was used as an initial condition for launching a forecast using Weather Research and Forecasting (WRF, Version 3.5.1) to examine the possibilities and limitations when applying physical initialization to lightning data assimilation.

The remainder of this paper is organized as follows. Section 2 describes the physical initialization method, Section 3 presents the experimental design and an analysis of results, and Section 4 provides a summary of the results.

2. Physical initialization

The physical initialization method used here is an improvement of the scheme proposed by Krishnamurti et al. (1991), as described below.

First, the 3D lightning-proxy radar reflectivity was selected in the vertical direction to obtain the composite reflectivity (Z_e in mm^6/m^3). Then, the rain rate (RR'_{obs} in mm/h) was obtained from the Z–R relationship shown in Eq. (1).

$$RR'_{\mathrm{obs}} = \left(\frac{Z_e}{300}\right)^{\frac{1}{1.4}} \quad (1)$$

The rain rate was then converted into the form of precipitation flux (RR_{obs} in $kg/(m^2 \cdot s)$):

$$RR_{\mathrm{obs}} = RR'_{\mathrm{obs}}/3600. \quad (2)$$

Assuming that the echo tops of lightning-proxy reflectivity represent the height of the cloud top, while the height of the cloud base is approximated by the Lifting Condensation Level (LCL) of the background, then:

$$z_{\mathrm{cb}} \approx LCL = 121 \times (T_2 - TD_2) \quad (3)$$

where T_2 and TD_2 are the temperature and dew point at the height of 2 m, respectively. Vertical velocity in clouds can then be expressed as shown in Eq. (4) (Haase et al., 2000).

$$w_k = \left(\rho^*_{v,k}\right)^{-1}\left\{\rho^*_{v,k+1}w_{k+1} - (z_{k+1}-z_k)\frac{RR(z_{\mathrm{cb}})}{z_{\mathrm{ct}}-z_{\mathrm{cb}}}\left[1-\frac{\pi}{2}\left(1+\frac{1}{c}\right)\sin\left(\frac{\pi}{2}\frac{z_{k+1/2}-z_{cb}}{z_{ct}-z_{cb}}\right)\right]\right\}. \quad (4)$$

Here, $c = \frac{RR}{\rho^*_v w}\big|_{z=z_{cb}} \in [0,1]$ and is a tunable parameter (set to 0.4) representing the efficiency of transforming saturated vapor

[1] The code file is gsdcloud/convert_lghtn2ref.f90 and the subroutine convert_lghtn2ref is used.