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Incorporating geostationary lightning data into a radar reflectivity based hydrometeor retrieval method: An observing system simulation experiment

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ABSTRACT

A retrieval method for deriving the hydrometeor mixing ratio within mesoscale convective system (MCS) is presented in this study. The hydrometeor retrieval method was designed to incorporate the flash extent densities (FED) data from the Feng-Yun-4 geostationary satellite into the S-band radar reflectivity (Z_h) and ambient temperature (T) data-based hydrometeor retrieval method. Total lightning data are utilized to better discern regions containing graupel in clouds. In the quantitative estimation of rain mixing ratio, different intercept parameters are used for different ranges of Z_h and different estimated precursors of raindrop in cold-cloud microphysical processes (i.e., graupel and snow aggregate). The hydrometeor retrieval method was evaluated through an observing system simulation experiment (OSSE) in which the pseudo-input-data for the hydrometeor retrieval (i.e., the FED, Z_h and T data) were obtained from the cloud-scale (1-km) simulation of an MCS using explicit electrification implemented within the Weather Research and Forecasting model. By incorporating the FED data as an additional input data source into the Z_h and T-based hydrometeor retrieval method, the hydrometeor retrieval accuracy was improved. The hydrometeor retrievals were then assimilated into the model using the Real-Time Four-Dimensional Data Assimilation (RTFDDA) system. Assimilating more accurate hydrometeor fields slightly improved the analyses and forecasts of convective precipitation in the test MCS case. The improvement could be due to the more accurate hydrometeor analysis, which further affected the strength of the cold pool and gust front.

1. Introduction

The retrieval of hydrometeor within convective clouds is useful to provide a more accurate estimate of latent heat release and to improve hydrometeor analyses for the initialization of convection-allowing numerical weather prediction (NWP) models, among other applications. These applications motivated several studies aimed at developing and testing hydrometeor retrieval methods (e.g., Dawson and Xue, 2006; Hu and Xue, 2007; Kain et al., 2010; Ziegler, 2013; Xue et al., 2014).

Owing to its high spatial and temporal resolution, weather radar remains the primary data source for hydrometeor retrieval. Previous studies have shown that polarimetric radars, which provide a variety of variables (e.g. reflectivity Z_h, differential reflectivity Z_{DR}, specific differential phase K_{DP}, and correlation coefficient ρ_{HV}), has the ability to identify bulk hydrometeor types of convective clouds and improve the quantitative estimate of liquid water content (LWC) and ice water content (IWC; e.g. Vivekanandan et al., 1999; Straka et al., 2000; Zrnić et al., 2001).

For areas solely within the range of non-polarimetric radars, reflectivity (Z_h) and temperature (T) based hydrometeor retrieval methods have been developed by several investigators (e.g., May and Keenan, 2005; Hu et al., 2006; Lerach et al., 2010). The single Z_h threshold (e.g., 32 dBZ c.f. Lerach et al., 2010; Pan et al., 2016) is often used to classify the graupel-dominated regions and snow aggregates-dominated regions above the freezing level. Because the possible ranges of Z_h for graupel and snow aggregates partially overlap (i.e., the Z_h range of graupel and snow aggregates are typically 25–50 dBZ and 0–35 dBZ, respectively; Straka et al., 2000), single Z_h threshold could introduce uncertainty in distinguishing the graupel-dominated versus snow aggregates-dominated regions. Cazenave et al. (2016) tested the

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sensitivity of the polarimetric radar-based classification of graupel and snow aggregates to the bias in Z_h, and found that a positive bias in Z_h of 3 dBZ changed the respective percentages of graupel-dominated regions and snow aggregates-dominated regions from 8% and 32.9% to 13.1% and 28.4% in the classification results of a squall line case, respectively. It can be inferred that the sensitivity of the classification of graupel-dominated regions and snow aggregates-dominated regions to the Z_h bias would be even larger without the additional information supplied by polarimetric radar variables (e.g., K_{DP} and Z_{DR}) in the simple Z_h and T-based hydrometeor retrieval method. Additionally, the classification of graupel-dominated and snow aggregates-dominated regions were found to be highly sensitive to the selected Z_h threshold in the Z_h and T-based hydrometeor retrieval method (include reference here).

It is generally accepted that the primary charge separation mechanism in thunderstorms arises from elastic collisions between graupel and ice crystals in the presence of supercooled water, known as riming electrification. This charging mechanism has been long supported by research based on laboratory experiments (e.g. Reynolds et al., 1957; Takahashi, 1978; Saunders et al., 1991;) and field observations (e.g., Dye et al., 1986; Lang et al., 2004; Qie et al., 2005a, 2005b, 2009; MacGorman et al., 2005, 2008). Lightning discharge, which is a by-product of electrification and charge, is thus closely related to graupel content (e.g., Goodman et al., 1988; Carey and Rutledge, 1996; Fierro et al., 2006). Based on field observations, researchers found that the majority of lightning initiation occurs within or close to regions containing graupel (e.g. Bruning et al., 2007; Lund et al., 2009; Ribaud et al., 2016). Additionally, studies found that the regions without graupel (e.g., pure snow aggregates regions) are characterized by weak electric fields and lightning activity (Ribaud et al., 2016; Takahashi et al., 2017). These findings highlight the promising aspect of lightning data for indicating regions containing graupel.

Owing to recent developments of lightning detection technique, lightning data have been used as a proxy for rainfall (e.g., Alexander et al., 1999; Chang et al., 2001; Pessi and Businger, 2009), water vapor content (e.g., Fierro et al., 2012, 2014, 2015, 2016) and hydrometeor mixing ratio (e.g., Qie et al., 2014; Wang et al., 2017). China recently launched the Feng-Yun-4 (FY-4) geostationary satellite (Yang et al., 2016). One of the instruments aboard FY-4 is the Lightning Mapping Imager (LMI), which is able to detect total lightning (i.e., in-cloud plus cloud-to-ground flashes) over China and its adjacent regions with a spatial resolution of about 8-km at nadir with a detection efficiency nearing 90-% in real time (Yang et al., 2016). Most operational weather radars in China, however, are non-polarimetric, which imposes a stringent limitation for identifying graupel and snow aggregates. In this work, we demonstrate that the lightning data provided by the FY-4 geostationary satellite may, in some circumstances, help to improve the accuracy of the non-polarimetric radar based hydrometeor retrieval within mesoscale convective systems (MCSs).

This study presents a hydrometeor retrieval method, which incorporates the lightning data from the FY-4 geostationary satellite as an additional input data source into the Z_h and T based hydrometeor retrieval method. The hydrometeor retrieval method was evaluated via an observing system simulation experiment (OSSE). The impacts of the hydrometeor retrieval method on the short-term forecasts of an MCS at convection-resolving scale (1 km × 1 km) were evaluated through the use of the National Center for Atmospheric Research (NCAR) Real-Time Four-Dimensional Data Assimilation (RTFDDA) system.

2. Case description and model setup

2.1. Brief description of the severe convective event

An MCS, which took place in the North China Plain on 13 June 2010 was selected as the OSSE case. The MCS initially developed over the northwestern Hebei province around 0500 UTC and gradually moved southeastward toward Beijing around 1200 UTC. The MCS dissipated shortly before moving over the Bo Sea by 1800 UTC. The severe convective event lasted for > 15 h. It was influenced by a deep low (996 hPa) situated over eastern Inner Mongolia. Convective available potential energy (CAPE) exceeded 2200 J/kg throughout much of Hebei, Beijing and Tianjin during this time, while convective inhibition (CIN) was overall weak (approximately −30 to −200 J/kg), indicating an environment favorable for severe convection.

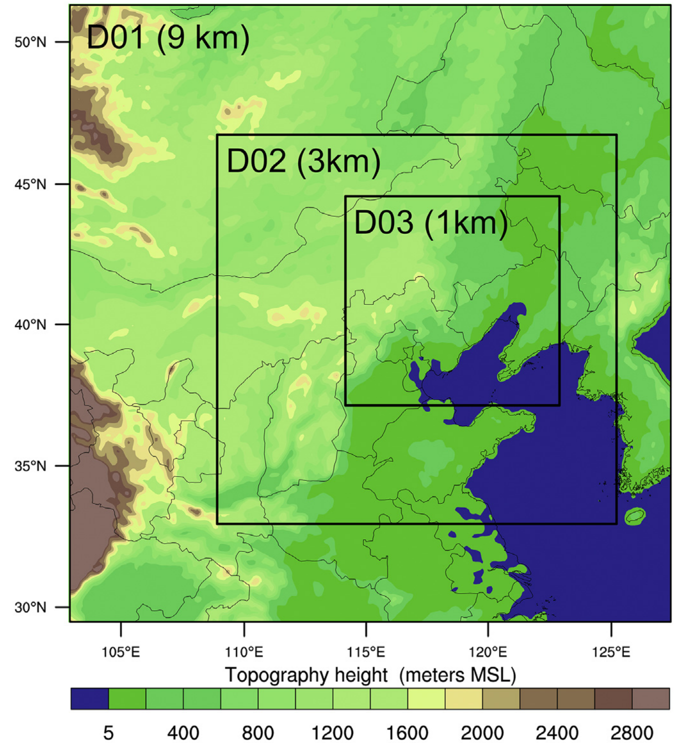

Fig. 1. Configuration of the WRF parent domain (D01: 9-km) and the two nested domains (D02: 3-km and D03: 1-km) for the OSSE case study. Terrain heights are shown in colored shades.

2.2. Model setup

The numerical model used for this work is the Weather Research and Forecasting - Electrification (referred to as E-WRF; Mansell et al., 2005; Fierro et al., 2013) model. The simulation domains included two nested grids (Fig. 1). The horizontal grid spacings were 9 km, 3 km (i.e., convection-allowing scale) and 1 km (i.e., cloud-resolving scale) for each of the three domains, respectively. Hydrometeor retrieval and data assimilation were only performed in the innermost, cloud-resolving domain. Two-way nesting between parent and inner nests were activated, so the impact of data assimilation can feedback from the innermost cloud-resolving domain to its parent domains. Each domain features 43 vertical eta levels with a model top set at around 50 hPa. The "true simulation" used the ERA-Interim reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF; Dee et al., 2011) as initial and lateral boundary conditions. The simulations were initialized at 0600 UTC, 0700 UTC, 0900 UTC for the D01, D02 and D03, respectively, and were ended at 0000 UTC, 14 June 2010. The initial fields for the nested domain were interpolated from their parent domain. The MCS was well captured by the innermost cloud-resolving domain (i.e., D03) during the entirety of the simulation (i.e., 15 h).

The physical schemes employed in this study included the NSSL double-moments bulk microphysics (Ziegler, 1985; Mansell et al., 2010a,b), the Noah land surface model (Chen and Dudhia, 2001), the Mellor–Yamada–Janjic turbulence kinetic energy (TKE) scheme for the planetary boundary layer (Janjić, 1994), and the Rapid Radiative