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A lightning-based nowcast-warning approach for short-duration rainfall events: Development and testing over Beijing during the warm seasons of 2006–2007

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ABSTRACT

Nowcasting short-duration (i.e., < 6 h) rainfall (SDR) events is examined using total [i.e., cloud-to-ground (CG) and intra-cloud (IC)] lightning observations over the Beijing Metropolitan Region (BMR) during the warm seasons of 2006–2007. A total of 928 moderate and 554 intense SDR events, i.e., with the respective hourly rainfall rates (HRR) of 10–20 and ≥20 mm h^{-1}, are utilized to estimate sharp-increasing rates in rainfall and lightning flash, termed as rainfall and lightning jumps, respectively. By optimizing the parameters in a lightning jump and a rainfall jump algorithm, their different jump intensity grades are verified for the above two categories of SDR events. Then, their corresponding graded nowcast-warning models are developed for the moderate and intense SDR events, respectively, with a low-grade warning for hitting more SDR events and a high-grade warning for reducing false alarms. Any issued warning in the nowcast-warning models is designed to last for 2 h after the occurrence of a lightning jump. It is demonstrated that the low-grade warnings can have the probability of detection (POD) of 67.8% (87.0%) and the high-grade warnings have the false alarms ratio (FAR) of 27.0% (22.2%) for the moderate (intense) SDR events, with an averaged lead time of 36.7 (52.0) min. The nowcast-warning models are further validated using three typical heavy-rain-producing storms that are independent from those used to develop the models. Results show that the nowcast-warning models can provide encouraging early warnings for the associated SDR events from the regional to meso-γ scales, indicating that they have a great potential in being applied to the other regions where high-resolution total lightning observations are available.

1. Introduction

The Beijing Metropolitan Region (BMR), which is one of the world's biggest megacities with dense population, has frequently suffered from heavy rainfall events during warm seasons (i.e., May–September), when the southwesterly monsoonal flow interacts with local complex topography and urbanization (Yin et al., 2011; Zhang et al., 2014; Hu, 2015; Li et al., 2017a, 2017b). One of the recent heavy rainfall events occurred on 21 July 2012, when the BMR received the heaviest rainfall in the past 6 decades with hourly rainfall rate (HRR) exceeding 85 mm and a record-breaking amount of 460 mm in 18 h (Zhang et al., 2013; Yin et al., 2014). Numerous studies have been performed to examine the impact of local complex topography and urbanization on the generation of some extreme rainfall events. Hu (2015) indicated increased heavy rainfall events in the BMR following its rapid urbanization since the late 1990s. After examining the relationship between the BMR's urbanization and rainfall variability, based on both observations and numerical simulations, Zhang et al. (2014) found that its central urban area (CUA) has fewer raining days, but with higher rainfall intensity than its surroundings due to the urban heat island effects. From a statistical analysis of the spatiotemporal characteristics of heavy rainfall events, Li et al. (2017a) noted the importance of local topography over the western and northwestern BMR in the generation of heavy rainfall events. The combined effects of topography and urbanization have also been found to influence the diurnal variations of rainfall in the BMR (Yin et al., 2011), with the night (afternoon) rainfall peaks usually occurring over the plain (mountainous) areas. The associated complex surface processes make it difficult to provide accurate rainfall forecasts

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over the BMR by traditional methods.

Previous studies showed that many heavy rainfall events over the BMR lasted for < 6 h, the so-called short-duration rainfall (SDR) events that often caused inundations in the CUA and landslides over the western mountainous regions of the BMR (Li et al., 2008; Zhang et al., 2013; Yuan et al., 2014). Predicting these SDR events presents a special challenge to local operational weather forecasters (Yin et al., 2014; Hu, 2016). Typically, radar-derived rainfall has been used to predict heavy SDR events, but with much less forecast skill over complex terrain and urban area due to the temporal extrapolation methods used (Mecklenburg et al., 2000; Vivoni et al., 2006; Novák et al., 2009; Wilson et al., 2010). Although today's mesoscale numerical weather prediction (NWP) models have advanced considerably in predicting the development of mesoscale weather events, the progress to predict the timing and location of heavy SDR events is far from satisfactory due to the lack of high-resolution observations in the model initial conditions and some weaknesses in parameterized convection and cloud microphysics schemes (Zhang et al., 2013; Cao and Zhang, 2016). Therefore, searching new forecast techniques to improve SDR prediction is of great significance. For this reason, the up-to-date lightning location data by lightning locating systems (LLSs) are examined in this study to see if they can be used to improve the nowcasts of SDR events.

The recent development of LLSs allows us to obtain lightning location, timing, and flash rate, the peak-current polarity of cloud-to-ground lightning (CG) and intra-cloud lightning (IC). In addition, LLS can provide real-time detection, high detection efficiency and broad coverage, and has great potential in providing severe weather prediction and warning (Nag et al., 2015; Wu et al., 2016). Trends in total lightning (CG and IC) have been frequently reported to have robust correlation with severe weather occurrences, so lightning observations have been used to aid in severe weather warnings and thunderstorm nowcasts (Schultz et al., 2011; Chronis et al., 2015; Farnell et al., 2017). Many researchers found that the rapid increase of total lightning flash rates, also termed as *lightning jump*, could be an important predictor for severe weather phenomena (e.g., Williams et al., 1999; Goodman et al., 2005; Schultz et al., 2009; Gatlin and Goodman, 2010; Schultz et al., 2011; Rudlosky and Fuelberg, 2013; Chronis et al., 2015; Farnell et al., 2017), which is closely related to rapid increases in graupel concentration and updraft volumes in the mixed-phase layers (Schultz et al., 2015, 2017). In order to facilitate the application of this predictor in an operational setting, several lightning jump algorithms have so far been developed, based on LLSs (Schultz et al., 2009, 2011; Gatlin and Goodman, 2010). Previous studies showed that the sigma (σ) lightning jump algorithm, which typically uses a jump threshold of several times the standard deviation (i.e., σ) of lightning flash rates during the previous period to represent lightning jump, could perform well in providing warnings of tornados, and storms producing large hails and wind gusts (Schultz et al., 2009, 2011, 2015; Chronis et al., 2015). For example, after applying this algorithm to 711 thunderstorm cases, Schultz et al. (2011) found a probability of detection (POD) of 79% with a false alarm ratio (FAR) of 36%, and an averaged lead time of 20.7 min prior to severe weather occurrences. This lightning jump algorithm and its adaption have also been applied to convective storm detections and severe weather nowcasts elsewhere, showing great promises (Rudlosky and Fuelberg, 2013; Chronis et al., 2015; Farnell et al., 2017). Rudlosky and Fuelberg (2013) showed that lightning data could achieve the radar-derived measures of storm severity with related storm-scale information. Chronis et al. (2015) found that storms with at least one lightning jump could last longer and encompass larger hailstones than those without a lightning jump. Farnell et al. (2017) applied the 2σ lightning jump algorithm to the nowcasts of severe weather events in Catalonia, showing that 39 of the 48 events detected lightning jumps between 90 min before and 30 min after observing the severe weather conditions.

While the lightning jump algorithms have shown successful applications for nowcasting tornados, severe hail, and severe winds, few studies have applied them to SDR events. According to the non-inductive charging mechanism for lightning generation, lightning and precipitation are closely related through cloud microphysical processes (Jayaratne et al., 1983; Williams et al., 1991; Saunders and Brooks, 1992; Saunders and Peck, 1998). In fact, previous studies have shown positive correlations between lightning activity and convective rainfall, with the former often preceding the latter by time lags varying from a few minutes to nearly 1 h (Piepgrass et al., 1982; Tapia et al., 1998; Liu et al., 2011; Koutroulis et al., 2012; Iordanidou et al., 2016; Wu et al., 2017). This indicates that the lightning jump algorithm may also have a great potential in nowcasting SDR events, especially more intense convective rainfall. Thus, the objectives of the present study are to (i) improve the current sigma lightning jump algorithm by optimizing its parameters for its application to nowcasting SDR events; (ii) develop a rainfall jump algorithm with optimized parameters, following the philosophies involved in the sigma lightning jump algorithm, in order to use the rainfall jump as a warning target for SDR events; (iii) construct graded SDR nowcast-warning models using lightning jumps of varying intensities, and then evaluate their performance through historical data; and (iv) validate the graded SDR nowcast-warning models using three heavy-rain-producing storms that are independent of the historical cases used for constructing the models in (iii). These objectives will be achieved with the total lightning data from the Surveillance et Alerte Foudre par Interférometrie Radioélectrique (SAFIR)-3000 lightning detection network and the rainfall data from the intensive automated weather station (AWS) network at 5-min intervals that were taken during the warm seasons (May–September) of 2006–2007. The two warm seasons are selected because of (i) the best performance periods of the SAFIR-3000 system, and (ii) the first-year operation of the AWS network in 2006 with rainfall records at 5-min intervals.

The next section describes the data and methodology used for this study, including the description of a lightning jump and a rainfall jump algorithm, and the graded nowcast-warning models for SDR events of different intensities. Section 3 presents the optimization of the parameters used for the above rainfall and lightning jump algorithms, and the performance of the graded SDR warning models using historical data. Section 4 shows the validations of the graded SDR warning models using three typical heavy rain-producing storms over the BMR that are independent from the historical cases used in Section 3. A summary and concluding remarks are given in the final section.

2. Data and methodology

2.1. Datasets and study area

Both the CG and IC lightning data are obtained from the BMR's SAFIR-3000 lightning detection network, which is a three-dimensional lightning detection system providing the timing and location of CG and IC lightning radiation sources. A very high-frequency (VHF) sensor (110–118 MHz) and a low-frequency (LF) sensor (300 Hz–3 MHz) are both used to locate IC and CG lightning, respectively. The SAFIR-3000 network consists of three substations covering an area of 270–280 km^2 of the BMR and its surroundings (Fig. 1a). This system began its test run in 2003. After one-year updates and maintenance, the network operated smoothly until one of the substations broke down in 2008. Both the LF and VHF sensors of the network have been claimed to have a detection efficiency of up to 90% and a location error of < 2 km (Zheng et al., 2009). Wu et al. (2016) have examined the network's performance carefully using peak currents and the other independent observations. Their results showed that the network had decreasing detection efficiency and location accuracy from the southeastern plains to the northwestern mountains of the BMR, and that the best detection efficiency is within 100 km from the center of the three substations (Fig. 1a). Lightning flashes are calculated using the detected radiation sources with the 1-s and 10-km method as used by Wu et al. (2016). That is, radiation sources detected within 1 s and a distance of < 10 km