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Lightning forecasting in southeastern Brazil using the WRF model

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ABSTRACT

This paper introduces a lightning forecasting method called Potential Lightning Region (PLR), which is the probability of the occurrence of lightning over a region of interest. The PLR was calculated using a combination of meteorological variables obtained from high-resolution Weather Research and Forecasting (WRF) model simulations during the summer season in southeastern Brazil. The model parameters used in the PLR definition were: surface-based Convective Available Potential Energy (SBCAPE), Lifted Index (LI), K-Index (KI), average vertical velocity between 850 and 700 hPa (w), and integrated ice-mixing ratio from 700 to 500 hPa (QICE). Short-range runs of twelve non-severe thunderstorm cases were performed with the WRF model, using different convective and microphysical schemes. Through statistical evaluations, the WRF cloud parameterizations that best described the convective thunderstorms with lightning in southeastern Brazil were the combination of Grell–Devenyi and Thompson schemes. Two calculation methods were proposed: the Linear PLR and Normalized PLR. The difference between them is basically how they deal with the influence of lightning flashes over the WRF domain's grid points for the twelve thunderstorms analyzed. Three case studies were used to test both methods. A statistical evaluation lowering the spatial resolution of the WRF grid into larger areas was performed to study the behavior and accuracy of the PLR methods. The Normalized PLR presented the most suitable one, predicting flash occurrence appropriately.

1. Introduction

Favorable atmospheric conditions for the occurrence of lightning must be identified reliably in order to provide alerts and to adopt strategies that eliminate, or minimize, injuries and hazardous situations. Different approaches based on empirical and/or statistical methods have been used to forecast lightning (Mazany et al., 2002; Bothwell, 2005; Burrows et al., 2005; Shafer and Fuelberg, 2006, 2008). For event analysis and as a scientific research tool, there are only a few numerical models with an electrification and lightning parameterization attempt to simulate the whole lifecycle of the electric charges in a thunderstorm (Takahashi, 1984; Helsdon and Farley, 1987; Helsdon et al., 1992; MacGorman et al., 2001; Mansell et al., 2002; Barthe and Pinty, 2007). Evidently, because explicit prediction of the electrical activity in storms is computationally expensive, these complex electrical schemes are not assimilated into atmospheric forecasting models. Moreover, the physical processes responsible for accumulating intense and different electrical charges within the cloud are not fully understood. In part this is due to the electrical structure of a thundercloud being quite complex, which depends on the result of microphysical and macrophysical processes that occur simultaneously within the clouds (Saunders, 1995, 2008). Hence, one interesting way to forecast lightning using numerical models is to rely on possible correlations between lightning occurrence and available model parameters.

Current mesoscale numerical models can run with high space and time resolutions and explicitly represent individual convective storms and their microphysical properties. The appropriate choice of parameterizations of convection

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and microphysics plays a significant role in the model's performance in representing the general characteristics of moist atmospheric conditions. Numerous studies have emphasized the impact that different convective and microphysical options have, especially on precipitation estimates from short-range forecasts of interest in numerical weather prediction to climate simulations (e.g., Kuo et al., 1996; Wang and Seaman, 1997; Gallus, 1999; Kotroni and Lagouvardos, 2001; Jankov and Gallus, 2004; Jankov et al., 2005; Ruiz et al., 2010). The Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) includes multiple physics options, which can be combined flexibly. Since there is almost no documentation about WRF parameterization performance over the South American region, some studies (Ruiz and Saulo, 2006; Ruiz et al., 2007, 2010; Blázquez and Nuñez, 2009; Silva Júnior, 2009) have addressed this question from different perspectives. Their results showed that the sensitivity of short-range weather forecasts to different choices in the model's physics is large, but none of the configurations considered had shown any outstandingly superior results over the whole model domain.

Although the WRF model does not explicitly include any electrification algorithms, several model variables can be combined in an attempt to find a suitable representation for the electrification processes. McCaul et al. (2009), using cloud-resolving numerical simulations produced by the WRF model, estimated lightning flash densities by combining and calibrating vertically integrated ice hydrometeors and the graupel flux near −15 °C. Yair et al. (2010) developed a lightning potential index, based on total liquid and an ice condensate mixing ratio and vertical velocity in the 0 °C to −20 °C layer, to provide a method for forecasting lightning flashes. Barthe et al. (2010) investigated the potential of different microphysical and dynamical WRF model parameters to be used as proxies for lightning flash rate. Results showed that, while the maximum updraft velocity predicts the flash rate magnitude fairly well for a severe storm, the ice mass flux product and precipitation ice mass can reproduce the flash rate trend but not the magnitude.

In this study, we introduce the potential lightning region (PLR), which is the probability of lightning occurring over a region of interest. The definition of the PLR was based on a combination of WRF output variables obtained from high-resolution simulations during the summer season in southeastern Brazil. Short-range runs of twelve non-severe thunderstorm cases were performed with the WRF model, using different convective and microphysical schemes. Due to the lack of studies indicating the proper WRF physical parameterizations that describe convective thunderstorms with lightning in Brazil, we did our own evaluation. The analysis associates the number of grid points close to lightning events to all the grid points of the high-resolution WRF domain for each pair of convective/microphysics parameterizations under investigation. Three case studies were selected to test the PLR methodology.

2. Lightning data

Cloud-to-ground (CG) lightning flash data provided by the Brazilian lightning detection network (BrasilDAT) (Pinto et al., 2007; Pinto, 2009) from October 2005 to March 2006 were used in this study. Fig. 1 shows the map of detection efficiency for BrasilDAT for the year 2005. It is observed that in southeastern Brazil the detection efficiency of CG flashes is approximately 90% (Ballarotti et al., 2006; Saraiva et al., 2011). For this reason, in Fig. 2, the red rectangle (DOM3) indicates the region of interest covering the eastern half of São Paulo state, the southern portion of Minas Gerais state, and the western portion of Rio de Janeiro state.

To ensure the homogeneity of the meteorological patterns associated with lightning occurrences, we selected days with continuous lightning activity of at least 4 h, and with more than 400 flashes per hour as a criterion. Twelve days were selected and characterized as isolated and/or multicellular, non-severe thunderstorms. Table 1 shows the time period, total flashes detected, and meteorological conditions responsible for the lightning occurrence in each case.

3. Weather Research and Forecasting (WRF) model

The fully compressible and non-hydrostatic atmospheric WRF model version 2.2, coded with terrain-following hydrostatic-pressure vertical coordinates (Skamarock et al., 2005), was implemented to process the simulations. As illustrated in Fig. 2, the model setup included a coarse 30 km grid (DOM1) (32.946° to 12.265° S and 62.008° to 32.992° W) and two nested domains: 10 km grid resolution (DOM2) (27.98° to 19.219° S and 54.485° to 40.515° W) and 3 km grid resolution (DOM3) (24.327° to 21.841° S and 48.558° to 42.729° W). In the vertical direction, 31 unevenly spaced full sigma levels were established. The 0000 UT Global Forecast System (GFS) gridded analysis fields and 3-hour interval forecasts with 1° latitude × 1° longitude horizontal grid resolution were used to initialize the model and nudge the boundaries of DOM1 during the 24-hour simulation period.

Three different convective parameterizations: the Kain–Fritsch scheme (Kain and Fritsch, 1990, 1993; Kain, 2004), the Betts–Miller–Janjic scheme (Janjic, 1994, 2000) and the Grell–Devenyi ensemble scheme (Grell and Devenyi, 2002), as well as two different microphysical schemes: the WRF Single-Moment 6-Class Microphysics scheme (WSM6) (Lin et al., 1983; Dudhia, 1989; Hong et al., 1998) and the Thompson scheme (Thompson et al., 2004) were tested. In addition, we used the Rapid Radiative Transfer Model (RRTM) Longwave radiation (Mlawer et al., 1997) and the Dudhia Shortwave radiation schemes (Dudhia, 1989). The Similarity Theory scheme was used to simulate the surface layer fluxes, whereas the Yonsei University (YSU) PBL scheme was used to simulate boundary layer fluxes. The land surface fluxes were obtained with the Noah LSM (Chen and Dudhia, 2001). Except for the microphysics and convective parameterizations, the other schemes were left unchanged for all the simulations.

The microphysics explicitly includes the resolved water vapor, cloud, and precipitation processes. As a general rule, for grid sizes finer than 10 km, where updrafts may be resolved, mixed-phase schemes should be used, particularly in convective or icing situations. Remote sensing studies have found positive correlations between the presence of precipitating ice in clouds and the intensity of the lightning activity (Sherwood et al., 2006; Deierling et al., 2008). The strong interplay among the Convective Potential Available Energy (CAPE) (Moncrieff and Green, 1972; Moncrieff and Miller, 1976), the updrafts, the microphysical formation and vertical extent of ice particles,

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