Atmospheric Research 180 (2016) 297–309

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Cloud electrification and lightning activity in a tropical cyclone-like vortex

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 25 May 2016
Accepted 31 May 2016
Available online 2 June 2016

Keywords:
Cloud electrification
Tropical cyclone

ABSTRACT

In this study, a high resolution simulation of an electrified tropical cyclone-like vortex was performed with the French mesoscale model *Meso*-NH coupled to an explicit electrical scheme. The objective was to analyze how graupel characteristics could influence the occurrence of lightning flashes in tropical cyclones. Two simulations were run: a control simulation using a 1-moment mixed phase bulk microphysical scheme, and a second simulation in which the parameters used to describe the graupel mass-diameter and fall speed-diameter relationships were modified to obtain smaller graupel fall speeds. Decreasing the graupel fall speed (v_g) resulted in a weaker storm with a larger radius of maximum winds. For both simulated tropical cyclones, a deep mixed phase layer conducive to cloud electrification was observed. However, in the simulation where v_g was decreased, the flash rate was almost zero throughout the simulation, whereas it reached a few flashes per minute in the control simulation. Several reasons that can explain this difference in the total flash rate are highlighted. Decreasing v_g resulted in graupel being spread horizontally over a broader area by the secondary circulation. The more pronounced tilting observed with slower v_g meant that poles of charges were not vertically aligned and thus the vertical electric field was reduced. In this study, the difference in the total flash rate mainly arose from changes in the mass and charge transfer rates due to changes in the parameters used to define the mass-diameter and particle-diameter relationships. Cloud electrification and lightning flashes being threshold-processes, a small change in the model physics can have a dramatic impact on the total flash rate.

1. Introduction

Over recent decades, the forecasting of tropical storm tracks has been greatly improved, mainly through a general increase in model horizontal resolution. However, forecasting storm intensity remains a key challenge for the scientific community. Factors at different temporal and spatial scales can impact tropical cyclone intensity. In particular, mesoscale and cloud-scale processes play a crucial role in the system dynamics and precipitation. Among the internal factors that may impact the variation of intensity of the tropical cyclone, the role of microphysics has been highlighted.

Willoughby et al. (1984) and Lord et al. (1984) were the first to point out the importance of ice phase microphysics in the structure and evolution of the simulated vortex. Using an axisymmetric non-hydrostatic hurricane model, Lord et al. (1984) showed that melting of ice particles can produce and maintain downdrafts over tens of kilometers in the horizontal plane. Later, some studies showed the key role of condensation for latent heat release (Wu et al., 2009; Li et al., 2013b), the energy source of the tropical cyclone. The microphysical structure, which determines the distribution of such heating, influences the dynamics of the system and its large-scale structure and behavior.

Most studies have pointed out the significant impact of the choice of cloud microphysics scheme on the storm structure and intensity. Using MM5 at 4 km horizontal resolution and varying the cloud microphysical processes in a 3-ice scheme, Zhu and Zhang (2006) found pronounced differences in hurricane intensity and inner core structures. In particular, removing graupel resulted in a weaker hurricane with a wider region of precipitation due to the enhanced horizontal advection of hydrometeors relative to the vertical fallouts. Li and Pu (2008) performed numerical simulations of Hurricane Bonnie (2005) with the WRF-ARW model at 3 km horizontal resolution and with different microphysical schemes. They showed that the difference in the simulated minimum sea level pressure (MSLP) varied by up to 10 hPa for the four most advanced schemes.

The primary effect of graupel on the minimum sea level pressure and maximum surface wind speed, i.e. the indicators of tropical cyclone intensity, has been recognized. Using MM5 to simulate hurricane Bonnie (1998), Zhu and Zhang (2006) stated that, due to its rapid fallout, graupel helps narrow the dimension of the eyewall. McFarquhar et al. (2006) performed numerical experiments on hurricane Erin (2001)

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http://dx.doi.org/10.1016/j.atmosres.2016.05.023
0169-8095/

with the MM5 model at 2 km horizontal resolution. They showed that using higher graupel fall speed produced lower minimum sea level pressure. By increasing the graupel fall speed, Franklin et al. (2005) observed that graupel was mainly confined to the convective regions. Higher rain rates were also produced in the inner core of the storm.

However, the microphysical state of tropical storms is difficult to observe in detail because their tracks mainly pass over uninhabited ocean. Since the electrical state of the storm is deeply linked to its microphysical structure, lightning activity could be used to infer the microphysical state of the storm. Fierro et al. (2007) were the first to attempt simulations of an electrified hurricane-like vortex to investigate the microphysical and electrical structure of the storm. Their simulation of an idealized hurricane was carried out at 2 km horizontal resolution with the model developed by Straka and Mansell (2005), incorporating a cloud electrification and lightning scheme. Then Fierro et al. (2011) performed a simulation of hurricane Rita during its period of rapid intensification. They used the Los Alamos National Laboratory High Gradient model (Reisner and Jeffery, 2009) and included an electrification scheme based on that of Mansell et al. (2005). Given the cost of the calculations, lightning discharge was treated in a simple manner: when the electric field exceeded the breakeven electric field, the space charge density was decreased by a constant value of 10% through the column upon discharge. The fact that the horizontal extension of the lightning flashes was not taken into account could explain why the flash rate was overestimated. More recently, Fierro et al. (2015) produced a 350-m resolution simulation of the electrification within a hurricane embedded in the general environment of hurricane Isaac (2012). The higher hurricane intensity, larger reflectivities and higher echo top than observed made the simulated lightning activity difficult to compare to observations.

In recent years, several studies have attempted to link lightning activity to changes in tropical storm intensity (Squires and Businger, 2008; Price et al., 2009; Abarca et al., 2011; Zhang et al., 2012; DeMaria et al., 2012; Bovalo et al., 2014; Whittaker et al., 2015; Zhang et al., 2015). However, owing to limitations inherent in the lightning observation networks, only cloud-to-ground (CG) flashes are treated in these studies or, if intra-cloud (IC) flashes are included in the analysis, only tropical storms near to the coast are considered due to the limited-area lightning networks used to detect IC (Fierro et al., 2011) or only partial coverage of lightning within tropical storms obtained from satellite observations (Cecil and Zipser, 1999; Cecil et al., 2002; Jiang et al., 2013). As shown by Bovalo et al. (2014), tropical storms have very different behavior according to whether they are in the open ocean or near the coasts.

The purpose of the present study is to analyze the electrical structure in the eyewall of a tropical cyclone-like vortex and the processes that are decisive for lightning flash triggering. For this purpose, a modeling study is conducted using the mesoscale model *Meso*-NH with an explicit electrical scheme. Due to the critical role of graupel in latent heat distribution (e.g. McFarquhar et al., 2006; Gao et al., 2006; Zhu and Zhang, 2006) and cloud electrification (e.g. Takahashi, 1978; Jayaratne et al., 1983; Saunders et al., 1991; Brooks et al., 1997), a sensitivity analysis changing the graupel characteristics is also performed. It underlines the physical processes that are important for cloud electrification and charge distribution in a tropical cyclone. We first present the numerical experiments. Then the dynamics and microphysics of the simulated tropical cyclone-like vortex are analyzed. Finally, the electrical state of the storm is discussed and physical processes responsible for cloud electrification and lightning triggering are explored.

2. Numerical experiments

2.1. Meso-NH and the electrical scheme CELLS

The mesoscale, non-hydrostatic atmospheric model *Meso*-NH used in this study was jointly developed by the Centre National de la Recherche Météorologique (Météo-France and Centre National de la Recherche Scientifique) and the Laboratoire d'Aérologie (Université de Toulouse and Centre National de la Recherche Scientifique). This model is able to simulate both idealized systems at high resolution and real meteorological events over large domains with complex terrain. A full description of the model capabilities is available at http://mesonh.aero.obs-mip.fr/.

The *Meso*-NH model contains the cloud electrification and lightning scheme CELLS (Barthe et al., 2012). This scheme computes the bulk electric charge attached to each microphysical species (cloud droplets, rain, pristine ice crystals, snow/aggregates, graupel and hail) and to positive and negative free ions. Several parameterizations (Takahashi, 1978; Saunders et al., 1991; Saunders and Peck, 1998; Tsenova et al., 2013) of the dominant non-inductive charging process are included, together with an inductive charging process. The electric field is obtained by inverting the Gauss equation with an extension to terrain-following coordinates. A lightning flash is initiated when the electric field exceeds a breakdown field (Marshall et al., 1995). Flashes are composed of a bidirectional leader phase that represents the vertical extension from the triggering point. A phase obeying a fractal law is added to mimic the horizontal extension in electrically charged zones. Then electric charges are neutralized along the flash path. This electrical scheme in *Meso*-NH has successfully reproduced several idealized storms and the 10 July 1996 STERAO storm (Barthe and Pinty, 2007), the 21 July EULINOX storm (Barthe et al., 2012) and some HyMeX convective events (Pinty et al., 2013).

2.2. Model setup and initialization

The model was set up with triple two-way nested domains having horizontal grid spacings of 32 (D1), 8 (D2) and 2 (D3) km and grid sizes of 128×100, 360×240 and 480×240 points, respectively. The innermost domain was moved 3 times to keep the cyclone inner core in the highest resolution domain. In the vertical, 70 levels were used, with highest resolution near the surface. Note that the simulated storm was located in the southern hemisphere.

An analytic model was used to initialize the radial and vertical distribution of the tangential wind over the largest domain. The analytic wind, which varies with altitude and radius from the storm center, was defined through a simplified version of the formulation proposed by Holland (1980) and Nuissier et al. (2005). The initial horizontally homogeneous environment profile was derived from that of McBride and Zehr (1981). The sea surface temperature was set to 28.6°C.

A first segment of the simulation with two nested domains (D1 and D2) was run for 24 h. During this spin-up period, the subgrid-scale convection was parameterized by a mass-flux convection scheme (Bechtold et al., 2001), and microphysics was inactive, as in Fovell et al. (2009). After 24 h, the domain D3 was introduced, encompassing the tropical cyclone inner core, and a bulk mixed phase microphysics scheme (Pinty and Jabouille, 1998) was activated. The microphysics scheme is a single-moment bulk scheme that predicts the mixing ratio of five microphysical species: cloud water (r_c), rain (r_r), cloud ice (r_i), snow (r_s) and graupel (r_g). This scheme was derived from Lin et al. (1983). The convection scheme was still used in the two coarser resolution domains, while the convection was explicitly resolved in the innermost domain. At 48 h of simulation, the electrical scheme was introduced into the innermost domain and the simulation was run for an additional 48 h. For the three domains, the turbulence parameterization was based on a 1.5-order closure (Cuxart et al., 2000) with purely vertical turbulent flux computations using the mixing length of Bougeault and Lacarrère (1989). The radiative scheme was the one used at ECMWF (Gregory et al., 2000) including the Rapid Radiative Transfer Model (RRTM) parameterization (Mlawer et al., 1997).

The explicit electrical scheme (Barthe et al., 2012) treats both cloud electrification and lightning triggering and propagation. Among several parameterizations available in the model (see Barthe and Pinty (2007)