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Analysis and numerical simulation of a real cell merger using a three-dimensional cloud resolving model

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ABSTRACT

A three-dimensional cloud resolving model is used to study a real cell merger case that occurred on 10 August, 2008 over north-central Greece, causing heavy rainfall, hailfall and high-frequency lightning. Firstly, the storm is observed, analyzed and recorded using a C-band weather radar. Secondly, three distinct simulations are performed using a cloud resolving model. An unseeded simulation, in order to test the ability of the model to reproduce the structural and evolutionary properties of the storm and two seeded simulations in which seeding occurred before and after cell merging. Reflectivity fields are analyzed, horizontally and vertically, at different simulation times. The 3-D numerical simulations suggest that the merger process occurred by two or three isolated single-cells and formed during their SW–NE motion. The merging process apparently alters dynamical and microphysical properties through low and middle level forcing; increases cloud diameters and cloud depths, producing more graupel and ice particles and increases radar reflectivity values. Processed radar images depict a similar view of the storm structure, evolution and interactions of such merging processes. The model calculated maximum radar reflectivity values coincide with the recorded ones. Results indicate that seeding the cloud before its merging produces more positive effects on hail suppression than seeding after merging. These findings are quite important, in order to document the value of the cloud resolving model and its capability to simulate and reproduce the realistic storm processes and to provide a better understanding of the cloud dynamical and microphysical features related to different seeding approaches.

1. Introduction

Airborne cloud seeding of convective clouds aiming for hail suppression is a big challenge and common practice in many areas over the world for more than 60 years. There is a strong scientific evidence and assessment on the status of weather modification from literature (Rosenfeld and Woodley, 1989, 1993; Silverman, 2001; Pocakal and Stalec, 2003; Cotton and Pielke, 2007; Levin and Cotton, 2008). A number of projects applied, related to hail suppression and rain augmentation, have showed optimistic results over the years, applying static glaciogenic seeding of cumulus convective clouds (Dennis, 1980; Mason, 1980; Isaac et al., 1982; Silverman, 1986; Makitov, 2007; Krauss and Santos, 2004). Nevertheless, further research and improvements are required, since weather modification projects still have associated risks and the results may remain uncertain. Numerical modeling capabilities offer new opportunities and permit a more detailed examination and practice on weather modification activities. Modeling of the seeding procedure is a valuable tool at investigating responses on cloud dynamical and microphysical features. Moreover, hail reduction and precipitation enhancement can be measured and tested against different seeding methods and strategies, seeding rates and seeding locations.

Northern and central Greece is frequently affected by severe storms, accompanied by hail, during the warm period of the year (April to September). For this reason, the Greek National Hail Suppression Program (NHSP) was designed (Karacostas, 1984) and applied in these areas since 1984, with the objective to reduce hail damages on agricultural products. Several studies of convective storm characteristics and hailstorms over northern Greece have been based on the NHSP program (Karacostas, 1989; Karacostas, 1991; Foris et al., 2006; Bampzelis and Karacostas, 2012). A set of sensitivity experiments have been conducted to examine the cloud seeding effects of different convective clouds, under different atmospheric environments (mid-latitude, tropical) using both, single and double-moment microphysics schemes. An important aspect in the study of convective activity is the identification of situations, such as cloud splitting or merging, which lead to intense

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hailfall and rainfall (Curic et al., 2009; Spiridonov et al., 2010). These processes are found to depend on the variation of wind with height, the relative stage of development of the two cloud-cells and their initial separation. Interaction between convective cells may alter cells on longevity, intensity and propagation characteristics. In the present study an intensive storm that took place on August 10th, 2008 is examined, where two initially separate cloud cells interact and merge, causing heavy rainfall, hailfall and high-frequency lightning.

The objective of this study is firstly, to analyze and depict the storm event using the cell tracker TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) (Dixon and Wiener, 1993) and reproduce it using a three-dimensional cloud resolving model. Secondly, using the cloud resolving model, two airborne seeding experiments are performed on the same case, in order to reproduce the operational seeding carried out under NHSP and to evaluate the seeding hypothesis. Further to that, numerical sensitivity tests are performed, in order to identify the optimal results through seeding convective clouds in different phases of their evolution.

2. Data and methodology

Storm characteristics are obtained from weather radar reflectivity measurements taken from the C-band (5-cm) weather radar located at the Fyliro mountainous area (40.672°N, 23.014°E), near Thessaloniki, close to the storm affected area. Radar reflectivity measurements have 750 × 750 m spatial and approximately 3.5 min temporal, resolutions. Storm characteristics are observed, analyzed and extracted using the cell tracker TITAN, which is capable of automatic identification, tracking and forecasting of convective cells, based upon radar reflectivity measurements. The algorithm, at a given reflectivity image, defines a convective cell as a 3D region, in which reflectivity values exceed a given threshold. The threshold reflectivity value used for this analysis is 35 dBZ, since that value correlates well with the development of mature cumulonimbus clouds (Roberts and Rutledge, 2003). Following that, the algorithm matches convective storms between successive radar images. The algorithm can also deal with storms that merge, or split, classifying them as multicell storm or single cell storm. The sequence of radar reflectivity images provides the storm characteristics, necessary for the analysis and gives a realistic view of the storm development and its evolution time.

2.1. Convective cloud model

The convective cloud resolving model is used to simulate the actual storm and its merging process and assess cloud seeding at two different stages of the storm's growth. Only a few basic characteristics of the model are summarized. The 3D cloud model (Spiridonov and Curic, 2003, 2006, 2015) is a three-dimensional, non-hydrostatic, time-dependent, compressible system, which is based on the Klemp and Wilhelmson (1978) dynamics, the bulk cloud microphysics scheme from Lin et al. (1983) that takes into account seven different categories of the three phases of water and Orville and Kopp (1977) thermodynamics.

The numerical experiments have been conducted using the double-moment microphysical scheme based on Kovacevic and Curic (2015). The double-moment microphysical scheme predicts not only the mixing ratio, but also the number of concentrations (Murakami, 1990; Wang and Chang, 1993; Ferrier, 1994; Cohard and Pinty (2000a, 2000b); Morrison and Pinto, 2005; Thompson et al., 2008; Lim and Hong, 2010; Kovacevic and Curic, 2015). Despite the fact that this approach requires more computing power, there are many advantages relative to single-moment approach, that is, more flexibility in size distributions, improvement in the representation of the microphysical processes in convective clouds, simulation of the heavy rainfall and clear boundary between convective and stratiform regions. With respect to cloud seeding, the double-moment scheme has shown higher sensitivity and more realistic cloud seeding effects. Both, bulk mass mixing ratios and concentrations of cloud water, rainwater, cloud ice, snow, graupel and hail, as well as the bulk mixing ratio of water vapor, are also predicted in the model. The number concentration (N) and bulk mixing ratio (Q) are given by the following equations, respectively:

$$\frac{\partial N}{\partial t}+\frac{\partial NU_j}{\partial x_j}-N\frac{\partial U_j}{\partial x_j}-\frac{1}{\rho}\frac{\partial \rho V_t N}{\partial x_3}=S+E_n \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial QU_j}{\partial x_j}-Q\frac{\partial U_j}{\partial x_j}-\frac{1}{\rho}\frac{\partial \rho V_t Q}{\partial x_3}=S+E_q \tag{2}$$

where S is the sink or source term, V_t is the group terminal fall speed of any particular water category, which is equal to zero for cloud water in the model and E_n, or E_q, is the subgrid-scale contribution and ρ is the air density. An additional conservation equation is considered here:

$$\frac{\partial X_s}{\partial t}+\frac{\partial X_s U_j}{\partial x_j}-X_s\frac{\partial U_j}{\partial x_j}=S_{X_s}+E_{X_s} \tag{3}$$

where, X_s is the mixing ratio of AgI particles, S_{Xs} is the sink- or source-term of mixing ratio and E_{Xs} is the subgrid-scale contribution.

The activation of AgI is parameterized by the three nucleation mechanisms, based on Hsie et al. (1980) and Kopp (1988), which are the deposition nucleation (including sorption), contact freezing nucleation-Brownian collection and inertial impact, due to cloud droplets and raindrops. The sink term of X_s can be calculated using the following equations:

(1) for contact freezing nucleation-Brownian collection and inertial impact due to cloud drops:

$$S_{BC}=-4\pi D_s R_C X_s N_C \tag{4}$$

$$S_{IC}=-\pi R_C^2 X_s N_C E_{CS} \tag{5}$$

(2) for contact freezing nucleation-Brownian collection and inertial impact due to raindrops:

$$S_{BR}=-2\pi D_s N_{OR}\lambda_R^{-2} \tag{6}$$

$$S_{IR}=-2.54E_{RS}\rho^{-0.375}X_s q_R^{0.875} \tag{7}$$

(3) for deposition nucleation due to water vapor at ice supersaturation:

$$SDN=\begin{cases} m_s\dfrac{dN_{aD}(\Delta T)}{dt} & \text{when } 5^\circ C \le \Delta T < 20^\circ C \\ m_s\, N_{aD}(\Delta T) & \text{when } \Delta T \ge 20^\circ C \end{cases} \tag{8}$$

where D_s is the diameter of AgI particles, N_C is the cloud droplet concentration, R_C is the cloud droplet radius, N_{OR} is a parameter of raindrop size distribution indicating also the rainwater mixing ratio, λ_R is the slope parameter of rain, E_{cs} and E_{RS} are the collection efficiencies of cloud water and rainwater, respectively, ρ is the air density, m_s is the agent particle mass, ΔT is the supercooling temperature and N_{aD} is the number of AgI particles which act as deposition of nuclei at supercooling temperature ΔT. The initial mixing ratio X_{s0} of agent homogeneously distributed in the seeding zone at the seeding moment is the source term of X_s. Since the seeding agent with respect to the model is released on sub-grid scale, its advection and turbulent diffusion need to be parameterized. This problem, which is related to calculation of trajectories and dispersion of the airborne seeding agent with a double-moment scheme, is solved by approximating the line of the seeding agent with a series of individual spherical small clouds (puffs) with radii of 10 m. The spread of a seeding agent in the cloud is then simulated by advection and spreading of each individual puff. The advection of puffs is calculated based on wind values using bilinear interpolation among the four adjacent grid points. The turbulent