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Simulations of a hailstorm and the impact of CCN using an advanced two-moment cloud microphysical scheme

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ABSTRACT

A hailstorm that caused significant damage in South-West Germany was simulated with the numerical weather prediction model COSMO. To cover hail evolution a sophisticated two-moment cloud microphysical scheme was extended by a particle class representing hail and implemented into COSMO. The horizontal resolution was 1 km. For initialization and boundary values COSMO forecasts with a coarser resolution and the standard one-moment microphysical scheme were used. Running this model system several convective cells develop including a severe hailstorm that resembles the observations qualitatively well and produces realistic amounts of precipitation and hail at the ground. Sensitivity studies were conducted varying the concentration of cloud condensation nuclei (CCN) and the shape of the cloud droplet size distribution (CDSD). Results show that both have a significant impact on hail accumulated at the ground and on the size of the hailstones. For two of the three CDSDs assumed the intensity of the severe storm decreases with increasing CCN concentration. However, this is not true for some of the weaker storms that form as well as for the third CDSD. Two model runs are analyzed and compared in more detail revealing the strong coupling between the numerous microphysical processes and between microphysics and dynamics. The sensitivity studies illustrate that the complexity of such storms makes it difficult to foresee, what will happen, when one microphysical parameter is changed. Thus, general conclusions whether an increase or decrease in CCN concentration invigorates a hailstorm cannot be drawn.

1. Introduction

For many centuries hailstorms have been a threat to societies in many regions of the world by causing significant loss to crop yields. Consequently, people have always sought means to suppress hail. Today, the loss caused by damage to cars and buildings is usually higher than that to crops, and there is still a great interest in the prediction and suppression of severe hailstorms (Wieringa and Holleman, 2006). For example, according to the natural hazard statistics in the United States (www.weather.gov/os/hazstats.shtml) the total damage caused by hail in the years 2000 to 2008 amounts to $8.45 billion and crop damage to $1.25 billion (for comparison: the total damage by tornados in the same time period was $8.13 billion).

An additional current issue is the question whether the intensity or frequency of hailstorms will increase or decrease due to anthropogenic emissions leading, e.g., to higher concentration of particulate matter serving as cloud condensation nuclei (CCN) or ice-forming nuclei.

One approach to suppress hail that has been studied during the last decades is seeding the base of the clouds with hygroscopic particles, get some large cloud droplets and thereby initiating the warm rain process in lower levels of the cloud (Cotton and Pielke, 1995; Farley et al., 2004; Caro et al., 2002). The idea is that in this way liquid water is depleted from the cloud and, as a consequence, the growth of hailstones by riming is reduced.

Recent studies of cloud interactions with particulate air pollution, performed mostly on a conceptual level, suggest that

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this inadvertent seeding with many small particles slows down the conversion of cloud droplets into precipitation and in this way may have the opposite effect of hail suppression by hygroscopic seeding finally leading to more severe hailstorms (Rosenfeld, 2007; Rosenfeld and Khain, 2008). If the concentration of aerosols that act as CCN is increased in originally rather clean air this will lead to the nucleation of more cloud droplets with the size of the nucleated droplets depending on the size of the CCN. After nucleation the droplets start to grow by condensation. The more droplets compete for the available water vapor the slower they grow. Therefore, a higher CCN concentration usually leads to smaller droplets. After some time, e.g., further away from cloud base, droplets mainly grow by collision and coalescence. The efficiency of collisional growth depends on droplet size and the shape of the cloud droplet size distribution (CDSD). Droplets of similar size possess similar sedimentation velocities making collisions less likely than for droplets of different size. Hence, a narrow CDSD will lead to less collisions and therefore to a slower formation of raindrops than a broad CDSD. Additionally, due to their low inertia, very small droplets tend to follow the streamlines around the collecting drop which decreases collision efficiency. Besides, CDSD also has an impact on the formation of ice because the freezing rate of small droplets is lower and due to the lower sedimentation velocity smaller droplets are carried faster to higher levels. Hence, one can suggest, that a higher CCN concentration increases the amount of supercooled water in the mature stage of a cloud which in turn leads to enhanced riming.

According to the hypothesis that should be tested within the ANTISTORM (Anthropogenic Aerosols Triggering and Invigorating Severe Storms) project (Rosenfeld and Khain, 2008), the slower rain formation and the increased amount of supercooled water in polluted clouds result in enhanced riming, the production of hail, high precipitation rates and stronger downdrafts. A similar aerosol-cloud dynamics effect was also found by Seifert and Beheng (2006b) who showed that high CCN concentrations can lead to an increased release of latent heat of freezing, and thereby invigorate convective storms, especially at high CAPE and low wind shear conditions. van den Heever et al. (2006) also studied the sensitivity of convective storms to CCN concentration but additionally included the effect of further parameters that depend on aerosol conditions, like the concentration of ice-forming nuclei or giant CCN. They found that enhanced CCN concentration affects a convective storm mainly during its initial stages, leads to stronger updrafts, but reduces surface rainfall. Simulations by Pozo et al. (2008) indicate that the impact of CCN concentration on convective clouds is rather weak.

The ANTISTORM project was initiated in 2005 with the aim to test the hypothesis that increased CCN concentration can invigorate storms, to study the impact of aerosols on convective storms in Europe, and to "develop models that should help to improve forecasting and even suggest strategies for mitigating storms before disaster strikes" (http://antistorm.isac.cnr.it/).

Within ANTISTORM investigations with two different numerical models were performed: (a) the 2-dimensional model HUCM including detailed spectral bin microphysics (Khain et al., 2008), and (b) the 3-dimensional numerical weather prediction model COSMO formerly called LM (Steppeler et al., 2003) combined with the two-moment bulk microphysical scheme by Seifert and Beheng (2006a). In the following only results obtained with COSMO will be presented. In course of the ANTISTORM project some parameters and process descriptions of the two-moment scheme have been extended to better represent "hail" particles (Blahak, 2008).

In our experience, idealized simulations of convective storms, that use artificial soundings to initialize the model and a warm-bubble approach to trigger convection, often show quite different sensitivities than the simulation of real cases. Therefore, the real case described in the following section was used as a basis for our sensitivity studies. The aim was not to forecast the storm, i.e. to get exactly the same storm at the same location and time, but to simulate a storm that is similar enough to the observed one, so that a more detailed analysis of the simulations may give deeper insight into the behavior of real storms.

The representation of hail in the model, the model setup used to conduct the sensitivity studies and the experiment design are described in Section 3. A general description of the model results and a short comparison to the observed storm are presented in Section 4 and the results of the sensitivity tests are discussed in Section 5. Section 6 includes a summary of our findings and the conclusions.

2. The observed hailstorm

On the evening of 28 June 2006 the small town of Villingen-Schwenningen (VS) was hit by a severe hailstorm. VS is situated in South-West Germany at about 700 m AMSL (Fig. 1) between two low mountain ridges, the Black Forest (up to 1500 m AMSL high) and the Swabian Alb (up to 1050 m AMSL). Due to the storm and the associated flooding more than 100 people got injured and one man drowned. Additionally, many crops, cars and buildings were damaged. Fig. 2 gives an idea of the amount of hail and the size of the hailstones. One day later, on 29 June, another but weaker hailstorm occurred in the same area. Both hailstorms together caused overall economic losses of 380 mEUR and insured losses of 230 mEUR (Munich Re Group, 2008).

According to radio soundings (not shown) at Nancy (200 km northwest of VS, see Fig. 1) and Stuttgart (100 km northeast of VS), the situation on 28 June 2009 was characterized by a strong vertical wind shear, with northerly to easterly winds at the bottom and a strong wind from South-West at levels above 3000 m. At 12 UTC lifting condensation level (LCL) was at about 800 m AMSL and temperature at that level about 14 °C. Air temperature near the ground was about 19 °C with a high relative humidity (86 to 89%). Surface measurements near VS indicate that LCL there was at about 800 m AGL during the whole afternoon.

Fig. 3 shows radar reflectivities, *Z*, measured by C-band radar Albis near Zurich in Switzerland (80 km south of VS). In the late afternoon several convective cells were observed in the vicinity of the Black Forest and the adjacent Rhine Valley (not shown). At about 17 UTC one of the cells splits close to the crest of the Black Forest. The right cell moves almost perpendicular to the main wind in easterly direction with a slight component to the south. This right mover intensifies, developing radar reflectivities of more than 65 dBZ, reaches VS at about 17:30 UTC and passes it with the core of the cell situated slightly to the north of the town. At about 18:00 UTC the storm has passed VS and moves further East. After crossing the Swabian Alb it finally weakens about 1 h later (not shown). Although the lifetime of the right mover is rather short, the cell splitting, the deviation of the storm