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Evaluation of moist processes during intense precipitation in km-scale NWP models using remote sensing and in-situ data: Impact of microphysics size distribution assumptions

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ABSTRACT

This study investigates the sensitivity of moist processes and surface precipitation during three extreme precipitation events over Belgium to the representation of rain, snow and hail size distributions in a bulk one-moment microphysics parameterisation scheme. Sensitivities included the use of empirically derived relations to calculate the slope parameter and diagnose the intercept parameter of the exponential snow and rain size distributions and sensitivities to the treatment of hail/graupel. A detailed evaluation of the experiments against various high temporal resolution and spatially distributed observational data was performed to understand how moist processes responded to the implemented size distribution modifications.

Net vapour consumption by microphysical processes was found to be unaffected by snow or rain size distribution modifications, while it was reduced replacing formulations for hail by those typical for graupel, mainly due to intense sublimation of graupel. Cloud optical thickness was overestimated in all experiments and all cases, likely due to overestimated snow amounts. The overestimation slightly deteriorated by modifying the rain and snow size distributions due to increased snow depositional growth, while it was reduced by including graupel. The latter was mainly due to enhanced cloud water collection by graupel and reduced snow depositional growth. Radar reflectivity and cloud optical thickness could only be realistically represented by inclusion of graupel during a stratiform case, while hail was found indispensable to simulate the vertical reflectivity profile and the surface precipitation structure. Precipitation amount was not much altered by any of the modifications made and the general overestimation was only decreased slightly during a supercell convective case.

1. Introduction

A proper simulation of severe precipitation within numerical weather prediction models requires that moist processes in the atmosphere are adequately represented. An indispensable part in the turnover of water vapour to clouds and precipitation is the parameterisation of microphysical cloud processes. Due to the small scales of processes involved, a large number of simplifications and assumptions on e.g. size distributions of the several hydrometeors have to be made.

Typically, microphysical processes have been represented in numerical models by one-moment bulk (OMB) microphysical schemes, representing a single size distribution on the bulk of the hydrometeor species within a model grid cell and having only one prognostic moment of a hydrometeor's size distribution, being its mixing ratio (third moment if spherical particles are assumed; e.g. Lin et al., 1983; Rutledge and Hobbs, 1983; Cotton et al., 1986). Current advances in microphysics can be subdivided in at least two main directions. A first sophistication involves a higher number of predicted moments, such as the number

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concentration (zeroth moment; e.g. Ferrier, 1994; Seifert and Beheng, 2006) or the radar reflectivity (sixth moment; e.g. Milbrandt and Yau, 2005). A second direction consists of separating the mass contents in several size categories (bin or spectral microphysical schemes, e.g. Kogan, 1991; Khain et al., 1999; Ovtchinnikov and Kogan, 2000). As it remains unclear what the main drawbacks for many processes are of the way size distributions in OMB schemes are represented, thorough evaluation and sensitivity studies using such schemes remain valuable (e.g. Woods et al., 2007; Cohen and McCaul, 2006), however. OMB microphysics schemes remain the workhorse in numerical weather prediction to this day, due to their low computational cost.

Many of the studies to OMB microphysical parameterisations over the past decade were conducted for either warm season convection or frontal stratiform precipitation and had a focus on a single microphysical parameter only. Often that parameter was concerned with hail/graupel in studies on convection (Gilmore et al., 2004; McCumber et al., 1991; Smedsmo et al., 2005) and with snow in studies on frontal stratiform precipitation (Colle et al., 2005; Woods et al., 2007). In operational weather forecasting a single model set up is needed which is providing good simulation for both convective and stratiform situations. For that reason it is interesting to understand what impact a model modification made to improve the moist processes under a certain synoptic situation has in other synoptic situations. Furthermore, most of the studies to the influence of microphysical processes on convective storms have been conducted for idealised conditions, initialising the model with a single sounding. While such studies are more straightforward to interpret, they have the disadvantage that they cannot be easily verified against observational data. In recent years, many efforts have been done to obtain spatially distributed observational data with high temporal resolution from spaceborne and ground-based remote sensors, such as satellite and weather radar, largely increasing knowledge on the three-dimensional atmospheric conditions during intense precipitation events.

This research discusses a number of experiments in which size distribution assumptions of a typical OMB microphysical scheme have been more realistically represented for both stratiform and convective intense precipitation situations. Using a broad range of high resolution observational data this research wants to gain more insight in to what extent a more realistic representation of the size distribution assumptions also leads to a model improvement of the representation of moist processes during intense precipitation events. In this work our primary focus is on the spatial scale and not on the temporal scale. A detailed description of the model setup, the cases studied and the available observational data products is given in Section 2. Section 3 provides an overview of the microphysics experiments and results of these experiments are compared against observational data in Section 4. Conclusions and issues for further research are discussed in Section 5.

2. Model setup and observational data

2.1. ARPS description

ARPS is a nonhydrostatic mesoscale meteorological model developed at the University of Oklahoma (Xue et al., 2000, 2001). The finite-difference equations of the model are discretised on an Arakawa C-grid, employing a terrain-following coordinate in the vertical direction. Advection is solved with a fourth-order central differencing scheme and leapfrog time stepping. Land surface processes are parameterised following Noilhan and Planton (1989). The model was applied using one-way grid nesting with two levels. Data on a 0.25° horizontal resolution from the global operational model operated by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used as initial conditions and as 6-hourly lateral boundary conditions for the model run with a 9-km grid spacing and a domain size of 1620 × 1620 km. Within this domain, a smaller domain centred over Belgium and covering 540 × 540 km with a 3-km grid spacing was nested. An overview of the model domain is shown in Fig. 1. In all simulations, 50 levels were used in the vertical with a spacing of 20 m near the surface, increasing to 1 km near the upper-model boundary, which was located at a 20-km altitude. All simulations were initialised with a 12 h spin-up period, beginning at 1200 UTC on the previous day. All of the analysis in the following sections is concerned with the 0000 UTC – 2400 UTC period, excluding the spin-up period, if not stated otherwise. Turbulence was represented by the 1.5-order turbulent kinetic energy (TKE) model, and Sun and Chang (1986) parameterisation for the convective boundary layer. The Kain-Fritsch (Kain and Fritsch, 1993) cumulus parameterisation was used in the largest domain, while convection was explicitly simulated at the smaller domain. Cloud microphysics was parameterised following Lin et al. (1983) including five hydrometeor types (cloud water, cloud ice, rain water, snow and hail). In order to suppress numerical noise a fourth order monotonic computational mixing was applied, following Xue (2000).

2.2. Case description

In order to assess the impact of more realistic size distribution assumptions in a bulk microphysical scheme under different synoptic conditions three cases were selected with a very different nature of processes leading to heavy precipitation. In a first case (further referred to as the stratiform case) precipitation was initiated by large-scale uplift during a classical warm- and cold-frontal overpass. Further two cases of severe convection were selected, one having strong mid-level wind shear and moderate buoyancy, being a typical environment for supercell thunderstorms (further referred to as the supercell convective case) and the other having no vertical wind shear but strong buoyancy favouring multicell thunderstorms (further referred to as the convective multicell case). A detailed description of the synoptic and mesoscale features of these three cases is provided in the next paragraphs.

2.2.1. Frontal stratiform case

On 23 November 2006 a classical warm frontal system, followed by an active cold front moved over Belgium from the West, bringing long enduring rain for most of the day, intensifying in the late afternoon during cold front passage. At the 500 hPa level (Fig. 2a), the main feature in the North Atlantic was a trough extending between Greenland and Iceland which was strongly amplifying from 22 November to 24 November. At the same time a strong jet streak developed in the baroclinic zone south of the trough with wind speeds exceeding 85 m s^{-1}.