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Invited review article

Latent cooling and microphysics effects in deep convection

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ABSTRACT

Water phase changes within a storm are responsible for the enhancement of convection and therefore the elongation of its lifespan. Specifically, latent cooling absorbed during evaporation, melting and sublimation is considered the main cause of the intensification of downdrafts. In order to know more accurately the consequences of latent cooling caused by each of these processes (together with microphysical effects that they induce), four simulations were developed with the Wisconsin Dynamical and Microphysical Model (WISCDYMM): one with all the microphysical processes; other without sublimation; melting was suppressed in the third simulation; and evaporation was disabled in the fourth.

The results show that sublimation cooling is not essential to maintain the vertical currents of the storm. This is demonstrated by the fact that in the simulation without sublimation, maximum updrafts are in the same range as in the control simulation, and the storm lifespan is similar or even longer. However, melting was of vital importance. The storm in the simulation without melting dissipated prematurely, demonstrating that melting is indispensable to the enhancement of downdrafts below the freezing level and for avoiding the collapse of low level updrafts. Perhaps the most important finding is the crucial influence of evaporative cooling above the freezing level that maintains and enhances mid-level downdrafts in the storm. It is believed that this latent cooling comes from the evaporation of supercooled liquid water connected with the Bergeron-Findeisen process. Therefore, besides its influence at low levels (which was already well known), this evaporative cooling is essential to strengthen mid-level downdrafts and ultimately achieve a quasi-steady state.

Contents

1. Introduction

Severe convection can be defined as the transfer of moisture and heat through vertical currents associated with buoyancy, which can cause meteorological risks such as gale-force wind gusts, lightning,

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large hail, flash flooding, or even tornadoes (García-Ortega et al., 2014). Accurate knowledge of severe convective storms is vital because of the dramatic damage caused each year at mid-latitudes, a result of adverse phenomena connected with deep convection (Czernecki et al., 2016). In recent decades, damage caused by severe convection appears to have increased because of climate change (Lin et al., 2005). According to projected climate change scenarios, global temperatures may increase as much as 2 °C by 2050 (IPCC, 2012), which could dramatically increase damage from convective episodes in midlatitudes during coming decades (Botzen et al., 2010).

Moreover, in the context of global warming, some microphysical processes may increase in importance because of modification of atmospheric thermodynamic behavior (Wang et al., 2010), making the study of the contributions of individual microphysical processes critical. For instance, an increase in altitude of the 0 °C isotherm could augment the importance of collision-coalescence, which is responsible for the formation of rain in warm clouds (Lin et al., 2005).

The impacts of severe convective episodes can be minimized by accurate forecasts, even saving lives and preventing economic loss (Bauer et al., 2015). In the present research, we analyzed the influence of sublimation, evaporation, and melting processes on a supercell storm on the High Plains of the USA during 1981. This storm has been accurately analyzed in previous studies (Johnson et al., 1993; Wang et al., 2010), which allows us to compare the results of our simulations. Our investigation is original in that microphysical effects are also evaluated, complimenting several studies of latent cooling effects (e.g., Yang and Houze, 1995; Wang et al., 2010). The microphysical effects are assessed using the 3D Wisconsin Dynamical and Microphysical Model (WISCDYMM), which allows a clear visualization of these effects.

Precipitation originating from convective cells in midlatitudes is mainly from cold rain processes (Szyrmer and Zawadzki, 1999). The dynamics within a storm are influenced by water phase changes. For instance, according to Liu et al. (1997), latent heat absorbed during melting, evaporation, and sublimation strengthens downdrafts, while updrafts are fortified by condensation, freezing, and deposition. These effects are stronger in continental clouds than in maritime ones, because cold rain processes are more predominant in the former (Phillips et al., 2007).

Latent heat released and absorbed during water-phase change processes can strengthen storms. In warm rain processes, there are only evaporation-condensation processes. In cold clouds of deep convection, the processes of melting-freezing and sublimation-deposition also occur (Li et al., 2013). When warm air rises and water vapor condenses, latent heat is released into the atmosphere, increasing instability and strengthening updrafts. The same applies when latent heat is released during the freezing of liquid droplets. Latent cooling absorbed during sublimation, evaporation and melting processes can increase negative buoyancy and strengthen downdrafts, which also increases instability and can intensify updrafts (Szeto and Stewart, 1997). These phenomena are why latent heat is considered the main driving force of vertical currents within a storm.

In addition to dynamic and thermodynamic effects of evaporation, sublimation and melting, microphysical effects are important to understand the behavior of convective episodes (Kraut, 2015). Aerosols emitted to the atmosphere by natural and anthropogenic sources may act as CCN or ice nuclei, favoring the formation of cloud drops and ice crystals (Altaratz et al., 2014). Consequently, a higher concentration of CCN increases the number of cloud droplets but decreases their mean size, reducing the efficiency of collision-coalescence (Loftus and Cotton, 2014). In addition, environments with high aerosol concentrations may favor the development of stronger updrafts and higher cloud-top altitudes (Khain et al., 2005). Moreover, the origin of CCN can alter the behavior of convection. For instance, continental CCN leads to stronger updrafts and heavier precipitation than maritime CCN (Seifert and Beheng, 2006). Furthermore, the temperature at which ice nuclei become active depends on the type of aerosol (Wang, 2013). Changes in the distribution of aerosols can promote nucleation at relatively high temperatures (near 0 °C) or hinder nucleation even at low temperatures (−10 °C) (Kumjian et al., 2012). Because of the importance of all factors mentioned above, there is a desire to improve the accuracy of microphysical parameterizations in numerical models (Hazra et al., 2016).

Moreover, the different terminal velocities of distinct hydrometeors may alter the distance between the principal updraft and downdraft, which is connected with the fall of precipitation. Therefore, the rate and type of precipitation can modify the vertical currents. When hydrometeors are too heavy, they may descend very close to the updraft and even cause its collapse (Zeng et al., 2001; Wang et al., 2010).

This paper is organized as follows. In Section 2, there is a brief description of the WISCDYMM. Section 3 describes the initial conditions used in the simulations. Results of four simulations are addressed in Section 4, together with an exhaustive analysis of the thermodynamic and microphysical causes of the differences between the simulations. Finally, a discussion of the results and concluding remarks are in Section 5.

2. Methodology

This study was developed using the WISCDYMM, which is a 3D, single-moment cloud model used mainly for the study of microphysics and dynamics of convective clouds. This model was described by Straka (1989) and subsequently modified by others (Johnson et al., 1994; Wang, 2003). The model uses a primitive equation, non-hydrostatic, quasi-compressible system (Anderson et al., 1985). The advection schemes of finite differences and boundary conditions used by Lin et al. (2005) were selected, with settings for subgrid-scale features of the flow defined in Straka (1989). Radiation, the Coriolis force, and topography were ignored in the modeling.

The grid was configured with a horizontal resolution of 1 km and vertical resolution 200 m. A horizontal domain of 100 × 100 km and 20 km vertically was established. The temporal resolution was 2 s. Total simulation time was 150 min, with data files saved every 5 min. The simulation was reinitialized every 30 min to maintain the convection within the domain, by subtracting the storm translation speed. This configuration has been selected according to the results of previous studies using the same model (Johnson et al., 1994; Wang et al., 2010).

There are 38 microphysical processes incorporated in the WISCDYMM, including nucleation, condensation, evaporation, freezing, melting, sublimation, deposition, autoconversion, collision-coalescence, aggregation, and riming. The model is able to predict the three wind components, potential temperature, turbulent kinetic energy, pressure deviation, and mixing ratios of water vapor, cloud water, raindrops, cloud ice, snow, and graupel/hail.

Data assimilation of the WISCDYMM model simulations has two components. First, it requires data from a pre-storm radiosonde, taken before the formation of condensate, in which surface pressure is specified. Radiosonde raw data, which have a variable vertical resolution, are interpolated linearly (without smoothing) for grid levels established in the model, in this case every 100 m. Second, the simulation requires an impulse for initiating the modeled storm. A hot ellipsoidal bubble at the bottom center of the domain model is considered an initial perturbation, with the same relative humidity as the base state. The bubble had a 10-km radius and 4-km thickness. It was centered 2 km above ground level, and had an excess of maximum potential temperature at its center of 3.5 °C. Water vapor mixing ratio of the bubble was adjusted to maintain relative humidity equal to its base state.

3. Initial conditions

We selected a midlatitude supercell storm on 2 August 1981 that crossed the Cooperative Convective Precipitation Experiment (CCOPE) observational network in southeastern Montana (Knight, 1982). This storm has been described by several authors (Wade, 1982; Miller