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A three-dimensional WRF-based precipitation equation and its application in the analysis of roles of surface evaporation in a torrential rainfall event

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ABSTRACT

Based on the governing equations for water species in the Weather Research and Forecasting (WRF) model, a three-dimensional WRF-based surface precipitation equation was obtained and applied to investigate the surface rainfall processes of a torrential rain event. Sensitivity experiments were performed to further explore roles of surface evaporation in the heavy rainfall event. The results show that the contributions of moisture-related processes to precipitation (Q_{WV}, including water vapor local change (Q_{WVL}), surface evaporation (Q_{WVE}), moisture advection (Q_{WVA}), and so on) dominate the torrential rain event, while the contributions of cloud-related processes (Q_{CM}) also play indispensable roles whose maximum net contributions could exceed 20%. Q_{WVA} dominates the budget of water vapor, while Q_{WVL} and Q_{WVE} play smaller but by no means negligible roles in the event. Sensitivity experiments show that the changes of surface evaporation affect both moisture-related processes and cloud-related processes, and then influence the intensity and regional redistribution of precipitation. Surface evaporation favors the accumulation of convective available potential energy and enhances the instability of atmosphere, being prone to the development of convective systems. Meanwhile, it also affects the development of vertical motions and cloud systems. Thus accurate estimation of surface evaporation is necessary for accurate simulation and forecast of surface precipitation.

1. Introduction

Precipitation, especially torrential rainfall, has important impact on people's daily life, development of society and economy. Torrential rainfall, occurring in mountainous regions in particular, can cause floods, debris flows and other natural disasters, leading to tremendous losses in lives and properties of people.

Precipitation is produced from interactions among large-scale or synoptic-scale dynamic, thermodynamic and cloud microphysical processes. Precipitation-related physical processes include moisture budget and cloud hydrometeor budget. In numerical models, the moisture budget is depicted by the governing equation of water vapor and the cloud hydrometeor budget is depicted by governing equations of various liquid-phase and ice-phase hydrometeors. Gao et al. (2005) derived a diagnostic equation, called surface rainfall equation, in a two-dimensional (2D) cloud-resolving model (CRM) framework by combining the water vapor budget with the cloud hydrometeor budget. In their 2D CRM-based surface rainfall equation, surface rain rate is directly connected and determined by water vapor related processes (water vapor budget) and cloud-related processes (cloud hydrometeor budget). The moisture-related processes include local change of water vapor, water vapor convergence/divergence, and surface evaporation. The cloud-related processes include local change of cloud hydrometeors and hydrometeor convergence/divergence. They found that both moisture-related and cloud-related processes have important contributions to tropical surface rainfall. The 2D CRM-based surface rainfall equation has been widely applied to quantitatively diagnose and analyze precipitation processes, especially tropical ones (Cui, 2008, 2009; Cui and Li, 2006, 2009; Gao et al., 2009; Gao and Li, 2008a, 2010; Li, 2006; Shen et al., 2011a,2011b,2011c; Wang et al., 2007). Cui and Li (2006) investigated the role of surface evaporation in tropical surface rainfall processes using the 2D CRM-based surface rainfall equation. They found that the moisture from surface evaporation over rainfall-free regions supplies rainfall regions via moisture advection and then produces the surface rainfall. Li (2006) investigated precipitation responses to large-scale forcing in tropical deep convective regimes using the same 2D equation. He found that the moisture-related sources

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determine the surface rain rate in the strong-forcing case, while cloud-related processes could become important in the weak-forcing case. The 2D CRM-based surface rainfall equation has also been used to study the surface rainfall processes of monsoonal convection (Wang et al., 2007), oceanic convection and its diurnal variations in tropical western Pacific (Gao et al., 2009; Gao and Li, 2010), and the effects of vertical wind shear and cloud radiation processes of a pre-summer heavy rainfall event over Southern China (Shen et al., 2011b).

The surface rainfall/precipitation equation, involving both water vapor and cloud hydrometeor budgets, is very useful and important to improve the understanding of complex precipitation processes. Based on this equation, individual precipitation processes are well understood from explicit cloud-resolving model simulations. However, most of the above studies were performed in tropical regions, and all of the studies were carried out using the above 2D CRM-based surface rainfall equation (Gao et al., 2005) in a 2D CRM framework, in which spatially uniform large-scale advection tendencies and zonal winds were imposed to force the model integration (Gao and Li, 2008a,2008b).

Two-dimensional CRMs have been used in many pioneering studies (Krueger, 1988; Xu et al., 1992; Xu and Randall, 1996). The 2D and 3D CRMs may produce similar simulations in terms of thermodynamic fields, vertical transports of mass, moisture, surface heat fluxes, and surface precipitation (Grabowski et al., 1998; Tao et al., 1987; Tompkins, 2000). Xu et al. (2002) found that there should be some differences between 2D and 3D dynamics through an intercomparison study of eight 2D and two 3D CRMs' simulations. As mentioned in Xu et al. (2002, 2005), the energy cascade is different between 2D and 3D convections, and the horizontal hydrometeor advection can impact the timing of convection. Tompkins (2000) also found that a 2D model may give reasonable results for modeling highly two-dimensionally organized convection, but it is highly preferable to use a 3D cloud model for modeling randomly distributed or clustered convection. In CRMs, the lateral periodic boundary-layer condition does not allow convection to propagate out or advect into the domain, which is not realistic, while it is not the case in the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) used in this study. Spatially varying large-scale forcing in simulations using the WRF model could also produce different dynamic and thermodynamic structures of atmosphere from the spatially uniform large-scale forcing imposed in the CRMs, affecting the cloud processes and then the surface precipitation processes. Thus, precipitation equation should be extended to 3D framework and 3D cloud-scale models (such as the WRF model) rather than CRMs should be used to study surface rainfall processes in a more realistic way. This is because 3D settings allow aperiodic boundary-layer condition, spatially varying large-scale vertical velocities and detailed hydrometeor advections.

As is well known, surface evaporation is indispensable to long-term regional or global precipitation, while roles of surface evaporation in short-term rainfall processes over land have not been thoroughly investigated, especially heavy ones. Cui and Li (2006) pointed out in their 2D CRM study that surface evaporation is very important to long-term tropical rainfall processes. Paegle et al. (1996) found that surface evaporation was more important in changing the buoyancy for short-term rainfall than in providing additional moisture to the already abundant moisture influx from the Gulf of Mexico during the 1993 United States summer floods. Cui and Li (2011) found that surface evaporation played a minor role in short-term tropical surface rainfall processes based on 2D cloud-resolving simulation data. Therefore, further discussion and research on roles of surface evaporation in short-term heavy rainfall events should be conducted.

In this study, a 3D WRF-based surface precipitation equation was obtained from the governing equations for water species in the WRF model and applied to investigate the surface rainfall processes, especially the roles of surface evaporation in a torrential rain event in Sichuan, China. The 3D WRF-based surface precipitation equation is described in Section 2. The surface rainfall processes and roles of surface evaporation in the torrential rainfall event are presented in Section 3. Summary and conclusions are given in Section 4.

2. 3D WRF-based surface precipitation equation

To examine complicated surface rainfall processes, Gao et al. (2005) derived the 2D CRM-based surface rainfall equation. In this section, a 3D WRF-based surface precipitation equation is obtained accordingly. The governing equations for water species in the WRF model (Skamarock et al., 2008) are expressed as:

$$\frac{\partial(\rho_a Q_v)}{\partial t} = \mathrm{ADV}_{Q_v} + \mathrm{DIFF}_{Q_v} + E_S + \rho_a S_{Q_v}, \tag{1}$$

$$\frac{\partial(\rho_a Q_c)}{\partial t} = \mathrm{ADV}_{Q_c} + \mathrm{DIFF}_{Q_c} + \rho_a S_{Q_c}, \tag{2}$$

$$\frac{\partial(\rho_a Q_x)}{\partial t} = \mathrm{ADV}_{Q_x} + \mathrm{DIFF}_{Q_x} + \mathrm{SEDI}_{Q_x} + \rho_a S_{Q_x}, x\in(\mathrm{r,i,s,g,h}). \tag{3}$$

The 3D advection terms are expressed as $\mathrm{ADV}_{Q_v} = -\nabla_3 \cdot (\rho_a Q_v \mathbf{V})$, $\mathrm{ADV}_{Q_c} = -\nabla_3 \cdot (\rho_a Q_c \mathbf{V})$, and $\mathrm{ADV}_{Q_x} = -\nabla_3 \cdot (\rho_a Q_x \mathbf{V})$, and the sedimentation term is expressed as $\mathrm{SEDI}_{Q_x} = \frac{\partial(\rho_a Q_x V_{Q_x})}{\partial z}$, where Q_v, Q_c, and Q_x are the mixing ratios of water species (v: water vapor; c: cloud water; r: rain water; i: cloud ice; s: snow; g: graupel; h: hail), E_S is the surface moisture flux, ρ_a is the air density, $\mathbf{V}$ is the 3D wind vector, V_{Q_x} is the mass-weighted terminal particle fall speed, and S_{Q_v}, S_{Q_c}, and S_{Q_x} are source and sink terms.

Since all of the source/sink terms satisfy (Skamarock et al., 2008)

$$S_{Q_v} + S_{Q_c} + \sum_{x\in(\mathrm{r,i,s,g,h})} S_{Q_x} = 0, \tag{4}$$

combining Eqs. (1)–(4), we can get:

$$\begin{aligned} -\sum_{x\in(\mathrm{r,i,s,g,h})} \mathrm{SEDI}_{Q_x} &= -\frac{\partial(\rho_a Q_v)}{\partial t} + \mathrm{ADV}_{Q_v} + \mathrm{DIFF}_{Q_v} + E_S \\ &+ \sum_{x\in(\mathrm{c,r})}\left[-\frac{\partial(\rho_a Q_x)}{\partial t}\right] + \sum_{x\in(\mathrm{c,r})}\left(\mathrm{ADV}_{Q_x} + \mathrm{DIFF}_{Q_x}\right) \\ &+ \sum_{x\in(\mathrm{i,s,g,h})}\left[-\frac{\partial(\rho_a Q_x)}{\partial t}\right] + \sum_{x\in(\mathrm{i,s,g,h})}\left(\mathrm{ADV}_{Q_x} + \mathrm{DIFF}_{Q_x}\right). \end{aligned} \tag{5}$$

Integrating Eq. (5) using $\int_{z_s}^{z_t}()dz$ (where z_t and z_s are the top and surface of the model atmosphere, respectively), we get the 3D WRF-based surface precipitation equation:

$$\begin{aligned} \underbrace{\int_{z_s}^{z_t}\left(-\sum_{x\in(\mathrm{r,i,s,g,h})}\mathrm{SEDI}_{Q_x}\right)dz}_{P_S} &= \underbrace{\int_{z_s}^{z_t}\left[-\frac{\partial(\rho_a Q_v)}{\partial t}\right]dz}_{Q_{WVL}} + \underbrace{\int_{z_s}^{z_t}\mathrm{ADV}_{Q_v}dz}_{Q_{WVA}} + \underbrace{\int_{z_s}^{z_t}\mathrm{DIFF}_{Q_v}dz}_{Q_{WVD}} + \underbrace{\int_{z_s} E_S dz}_{Q_{WVE}} \\ &+ \underbrace{\int_{z_s}^{z_t}\left[-\sum_{x\in(\mathrm{c,r})}\frac{\partial(\rho_a Q_x)}{\partial t}\right]dz}_{Q_{CLL}} + \underbrace{\int_{z_s}^{z_t}\sum_{x\in(\mathrm{c,r})}\mathrm{ADV}_{Q_x}dz}_{Q_{CLA}} + \underbrace{\int_{z_s}^{z_t}\sum_{x\in(\mathrm{c,r})}\mathrm{DIFF}_{Q_x}dz}_{Q_{CLD}} \\ &+ \underbrace{\int_{z_s}^{z_t}\left[-\sum_{x\in(\mathrm{i,s,g,h})}\frac{\partial(\rho_a Q_x)}{\partial t}\right]dz}_{Q_{CIL}} + \underbrace{\int_{z_s}^{z_t}\sum_{x\in(\mathrm{i,s,g,h})}\mathrm{ADV}_{Q_x}dz}_{Q_{CIA}} + \underbrace{\int_{z_s}^{z_t}\sum_{x\in(\mathrm{i,s,g,h})}\mathrm{DIFF}_{Q_x}dz}_{Q_{CID}}. \end{aligned} \tag{6}$$

The equation can be simply expressed as:

$$P_S = Q_{WV} + Q_{CM}, \tag{7}$$

where $P_S = \int_{z_s}^{z_t}(-\sum_{x\in(\mathrm{r,i,s,g,h})}\mathrm{SEDI}_{Q_x})dz$ is the surface rain rate.