Precipitation responses to radiative processes of water- and ice-clouds: an equilibrium cloud-resolving modeling study

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ABSTRACT
Cloud radiative processes are important in regulating weather and climate. Precipitation responses to radiative processes of water- and ice-clouds are investigated by analyzing mean equilibrium simulation data from a series of two-dimensional cloud-resolving model sensitivity experiments in this study. The model is imposed by zero vertical velocity. The exclusion of water radiative processes in the presence of ice radiative processes, as well as the removal of ice radiative processes, enhances tropospheric longwave radiative cooling and lowers air temperature and the saturation mixing ratio. The reduction in the saturation mixing ratio leads to an increase in vapor condensation and an associated release of latent heat, which increases rainfall. The elimination of water radiative processes strengthens local atmospheric warming in the upper troposphere via a reduction in longwave radiative cooling. The enhanced warming increases the rain source via an increase in the melting of graupel, which increases rainfall.

1. Introduction
Cloud radiative processes play an important role during the development of precipitation systems. Gray and Jacobson (1977) revealed that the nocturnal precipitation peak – a major component of the diurnal cycle of precipitation – is associated with the secondary circulation forced by the different radiative heating between cloudy and clear-sky regions. Lilly (1988) described the cloud radiative effects on unstable thermal stratification for the growth of stratiform clouds in the upper troposphere. Dudhia (1989) found important cloud radiative effects on environmental destabilization. Tao and Simpson (1993) revealed that enhanced precipitation corresponds to strengthened longwave radiative cooling over both the tropics and midlatitudes. Fu, Krueger, and Liou (1995) showed that enhanced precipitation is associated with increased clear-sky longwave radiative cooling, while reduced precipitation is related to weakened longwave radiative cooling. Sui et al. (1997); Sui, Li, and Lau (1998), Gao, Cui, and Li (2009), and Gao and Li (2010) revealed an enhanced nocturnal precipitation peak in response to the nocturnal longwave radiative cooling by a weakened saturation mixing ratio. Cloud radiative processes also have important impacts on climate change. For example, doubled carbon dioxide may change precipitation through the radiation-induced change in vertical thermal stratification (e.g. Li, Shen, and Liu 2014), although the enhanced water vapor owing to doubled carbon dioxide may increase precipitation ultimately (e.g. Allen and Ingram 2002). The diurnal cycle of radiation may produce a warm and humid climate equilibrium state (e.g. Gao, Zhou, and Li 2007). Thus, cloud radiative processes are crucial in regulating weather and climate.

The release of latent heat associated with precipitation corresponds to radiation in the thermal balance in the absence of heat divergence. However, the heat divergence associated with large-scale circulations may make such latent heat–radiation responses complicated. For example,
the exclusion of cloud radiative processes can reduce or enhance pre-summer rainfall, depending on the response of heat divergence to cloud radiative processes (e.g., Wang, Shen, and Li 2010; Shen, Wang, and Li 2011a, 2011b; Liu, Shen, and Li 2014; Shen et al. 2016).

When large-scale circulations are absent, the precipitation responses to cloud radiative processes become rather simple. However, interaction between water- and ice-cloud may affect the precipitation responses to cloud radiative processes. The objective of this study is to investigate the dominant thermal and cloud microphysical responses to water and ice radiative processes in the absence of large-scale circulations. The questions to be discussed include: What is the nature of the precipitation responses to water and ice radiative processes? What are the differences in the precipitation responses to water (ice) radiative processes in the presence and absence of ice (water) radiative processes? And what is the physical link responsible for the differences in precipitation responses to radiation? To discuss these concerns, we analyze equilibrium model simulation data from a set of two-dimensional cloud-resolving model sensitivity experiments conducted by Gao, Zhou, and Li (2007), Ping, Luo, and Li (2007), and Gao (2008), by employing the analysis method developed by Liu, Shen, and Li (2014). The model is imposed with zero vertical velocity, which excludes the effects of large-scale circulations. The model setup and sensitivity experiments are briefly described in section 2. The results are presented in section 3. A summary is given in section 4.

2. Model and experiments

The data used in this study come from Gao, Zhou, and Li (2007), Ping, Luo, and Li (2007), and Gao (2008). The model used in these studies was a modified two-dimensional cloud-resolving model (Soong and Ogura 1980; Soong and Tao 1980; Tao and Simpson 1993; Sui et al. 1994; Sui, Li, and Lau 1998; Li et al. 1999; Li, Sui, and Lau 2002). The prognostic equations of specific humidity and five cloud species, including cloud water, raindrops, cloud ice, snow and graupel, had the source/sink terms from cloud microphysical schemes (Lin, Farley, and Orville 1983; Rutledge and Hobbs 1983, 1984; Tao, Simpson, and McCumber 1989; Krueger et al. 1995). The prognostic equation of potential temperature had the source/sink terms from radiation schemes (Chou, Kratz, and Ridgway 1991; Chou and Suarez 1994; Chou et al. 1998) and the release of latent heat from cloud microphysical schemes. The model was furnished with lateral periodic boundaries. The basic model setup was a model domain of 768 km, with a horizontal grid mesh of 1.5 km, 33 vertical levels, and a time step of 12 s. The top of the model was at 42 hPa.

The control experiment (CTL) included cloud radiative effects (Gao, Zhou, and Li 2007). The three sensitivity experiments without water (no water radiation, NWR), ice (no ice radiation, NIR), and cloud (no cloud radiation, NCR) radiative effects were identical to the CTL except that water, ice, and the total hydrometeor mixing ratio were set to zero in the calculation of radiation in NWR (Gao 2008), NIR (Ping, Luo, and Li 2007), and NCR (Gao 2008), respectively. In the four experiments, the model was forced by zero vertical velocity and a constant zonal wind of 4 m s−1 zonally and vertically, and a constant SST of 29 °C. The vertical temperature and specific humidity profiles observed during TOGA COARE at 0400 LST 19 December 1992 were used as the initial conditions. The model was integrated for 40.5 days to reach a quasi-equilibrium state (Figure 1 in Gao 2008).

Comparisons between the results of NWR and CTL, and NCR and NIR, are conducted to study the effects of water radiative processes on precipitation in the presence and absence of ice radiative processes, respectively. Comparisons between NIR and CTL, and NCR and NWR, are carried out to study the effects of ice radiative processes on precipitation in the presence and absence of water radiative processes, respectively. Model domain mean data from the last 10 days of integration are used in the following discussion.

3. Results

The exclusion of water radiative processes increases the rain rate from CTL to NWR by 12.3% in the presence of ice radiative processes, and increases the rain rate from NIR to NCR by 6.5% in the absence of ice radiative processes (Table 1). The removal of ice radiative processes increases the rain rate from CTL to NIR by 43.1% in the presence of water radiative processes, and increases the rain rate from NWR to NCR by 35.6% in the absence of water radiative processes.

Rainfall separation analysis using the scheme of Tao et al. (1993) shows that the increases in the rain rate come mainly from the increases in the convective rain rate. The exclusion of water or ice radiative processes reduces the fractional coverage of stratiform rainfall. The removal of water (ice) radiative processes barely changes the fractional coverage of convective (FCCR) rainfall in the presence of ice (water) radiative processes, but it increases the FCCR rainfall in the absence of ice (water) radiative processes.

To examine the cloud processes responsible for surface precipitation, the cloud budget is analyzed. The cloud budget is expressed by:

\[
P_s = Q_{NC} + Q_{CM}
\]

where,
\[ Q_{NC} = P_{S} + P_{CND} + P_{DEP} + P_{GDEP} - P_{REV} - P_{MLTS} - P_{MLTG} \]  
(1a)

\[ Q_{CM} = Q_{CMC} + Q_{CMR} + Q_{CMI} + Q_{CMS} + Q_{CGMS} \]  
(1b)

Here, \( P_{S} \) is the surface rain rate; \( Q_{NC} \) is the net condensation; \( P_{CND} \) is vapor condensation to cloud ice; \( P_{DEP} \) and \( P_{GDEP} \) are vapor deposition to cloud ice, snow, and graupel.
Here, \( P_{\text{RAUT}} \) is the auto-conversion from cloud water to raindrops; \( P_{\text{RACW}} \) is the collection of cloud water by raindrops; \( P_{\text{GACW}} \) is the accretion of cloud water by graupel; \( P_{\text{SmLT}} \) and \( P_{\text{GmLT}} \) are the melting of snow and graupel, respectively; and \( T_0 = 0 \, ^\circ \text{C} \). The calculations of the rain budget, Equation (2), show that the increase in the mean rain rate from CTL to NWR is associated with the increase in \( P_{\text{RACW}} \), which corresponds to the increase in \( P_{\text{CND}} \).

To examine the cloud microphysical responses to water radiative processes, the heat budget is analyzed. Local temperature change is associated with condensational heating, convergence of vertical heat flux, and radiation. In the presence of ice radiative processes, the exclusion of water radiative processes from CTL to NWR generally enhances longwave radiative cooling below 10 km by emitting more longwave radiation.

\[
Q_{\text{CMR}} = P_{\text{RAUT}} - P_{\text{RACW}} - P_{\text{GACW}} (T > T_0) + P_{\text{REVP}} - P_{\text{SmLT}} - P_{\text{GmLT}} + P_s.
\]  

Table 2. Breakdown of \( Q_{\text{NC}} \) averaged from day 31 to day 40 over the model domain in CTL, NWR, NIR, and NCR; and their differences (NWR–CTL, NIR–CTL, and NCR–NWR).

|       | CTL    | NWR    | NIR    | NCR    |
|-------|--------|--------|--------|--------|
| \( Q_{\text{NC}} \) | 3.24   | 3.43   | 4.54   | 4.56   |
| \( P_{\text{CND}} \) | 3.91   | 4.14   | 5.68   | 5.85   |
| \( P_{\text{Dep}} \) | 0.83   | 0.90   | 0.96   | 0.93   |
| \( P_{\text{GDep}} \) | 0.19   | 0.19   | 0.20   | 0.17   |
| \( -P_{\text{REVP}} \) | -1.72  | -1.84  | -2.33  | -2.40  |
| \( -P_{\text{SmLS}} \) | -0.01  | 0.00   | -0.01  | -0.02  |
| \( -P_{\text{GmLG}} \) | -0.01  | 0.00   | -0.08  | -0.11  |

|       | NWR–CTL | NIR–CTL | NCR–NWR |
|-------|---------|---------|---------|
| \( Q_{\text{NC}} \) | 0.19    | 1.30    | 1.13    |
| \( P_{\text{CND}} \) | 0.23    | 1.77    | 1.71    |
| \( P_{\text{Dep}} \) | 0.07    | 0.13    | 0.03    |
| \( P_{\text{GDep}} \) | 0.00    | 0.01    | -0.02   |
| \( -P_{\text{REVP}} \) | -0.12   | -0.61   | -0.56   |
| \( -P_{\text{SmLS}} \) | 0.01    | 0.00    | -0.02   |
| \( -P_{\text{GmLG}} \) | 0.01    | -0.07   | -0.11   |

Note: Units are mm d\(^{-1}\).

The enhanced precipitation from CTL to NWR corresponds to the strengthened net condensation and hydrometeor change from a gain in CTL to a loss in NWR. The increase in precipitation from NIR to NCR is mainly related to the hydrometeor change from a gain in NIR to a loss in NCR. The strengthened precipitation from CTL to NIR and NWR to NCR is mainly associated with the enhanced net condensation.

The enhanced net condensation from CTL to NWR results mainly from the increases in \( P_{\text{CND}} \) (Table 2). The hydrometeor change from the gain in CTL to the loss in NWR is mainly associated with the raindrop change from the increase in CTL to the decrease in NWR. The raindrop change \( Q_{\text{CMR}} \) in the rain budget can be written as:

\[
Q_{\text{CMR}} = P_{\text{RAUT}} - P_{\text{RACW}} - P_{\text{GACW}} (T > T_0) + P_{\text{REVP}} - P_{\text{SmLT}} - P_{\text{GmLT}} + P_s.
\]

Table 3. Breakdown of \( Q_{\text{CM}} \) averaged from day 31 to day 40 over the model domain in CTL, NWR, NIR, and NCR; and their differences (NWR–CTL and NCR–NIR).

|       | CTL    | NWR    | NIR    | NCR    |
|-------|--------|--------|--------|--------|
| \( Q_{\text{CM}} \) | -0.11  | 0.07   | -0.07  | 0.18   |
| \( Q_{\text{CMC}} \) | -0.06  | -0.01  | -0.12  | -0.10  |
| \( Q_{\text{CMR}} \) | -0.05  | 0.06   | 0.03   | 0.32   |
| \( Q_{\text{CMI}} \) | 0.00   | 0.01   | 0.00   | 0.02   |
| \( Q_{\text{CMS}} \) | 0.00   | 0.01   | 0.01   | -0.04  |

|       | NWR–CTL | NCR–NIR |
|-------|---------|---------|
| \( Q_{\text{CM}} \) | 0.18    | 0.25    |
| \( Q_{\text{CMC}} \) | 0.05    | 0.02    |
| \( Q_{\text{CMR}} \) | 0.11    | 0.29    |
| \( Q_{\text{CMI}} \) | 0.01    | -0.02   |
| \( Q_{\text{CMS}} \) | 0.00    | 0.01    |
| \( Q_{\text{CNG}} \) | 0.01    | -0.05   |

Note: Units are mm d\(^{-1}\).
Table 4. The rain budgets averaged from day 31 to day 40 over the model domain in CTL, NWR, NIR and NCR; and their differences (NWR–CTL and NCR–NIR).

|                | CTL  | NWR  | NIR  | NCR  |
|----------------|------|------|------|------|
| \(Q_{\text{CMR}}\) | -0.05| 0.06 | 0.03 | 0.32 |
| \(-P_{\text{RAUT}}\) | -0.10| -0.10| -0.12| -0.14|
| \(-P_{\text{GACW}}\) | -3.25| -3.55| -4.08| -4.09|
| \(-P_{\text{GAWS}}\) | -0.01| -0.06| -0.24| -0.26|
| \(-P_{\text{GALT}}\) | 1.72 | 1.84 | 2.33 | 2.40 |
| \(-P_{\text{GALT}}\) | -0.38| -0.38| -0.21| -0.16|
| \(-P_{\text{GALT}}\) | -1.09| -1.16| -2.10| -2.17|
| \(P_{\text{RE}}\) | 3.13 | 3.50 | 4.47 | 4.74 |

\[\text{NWR–CTL}\]

|                |      |      |      |      |
|----------------|------|------|------|------|
| \(Q_{\text{CMR}}\) | 0.11 | 0.29 |      |      |
| \(-P_{\text{RAUT}}\) | 0.00 | -0.02|      |      |
| \(-P_{\text{GACW}}\) | -0.30| -0.01|      |      |
| \(-P_{\text{GAWS}}\) | -0.05| -0.02|      |      |
| \(-P_{\text{GALT}}\) | 0.12 | 0.07 |      |      |
| \(-P_{\text{GALT}}\) | 0.00 | 0.05 |      |      |
| \(-P_{\text{GALT}}\) | -0.05| -0.07|      |      |
| \(P_{\text{RE}}\) | 0.37 | 0.27 |      |      |

Note: Units are mm d\(^{-1}\).

Figure 2. Vertical profiles of differences between NCR and NIR (NCR–NIR), averaged for 10 days over the model domain, (a) in local temperature change (LTC; black), release of latent heat (RLH; red), convergence of vertical heat flux (CVHF; green), and radiation (Rad; orange); and (b) in radiation (Rad; orange) and its components of solar radiative heating (SRad; red) and longwave radiative cooling (LRad; blue). Units: °C d\(^{-1}\).

radiation into space in NWR than in CTL, since the change in radiation is determined by the change in longwave radiation (Figure 1). The enhanced longwave radiative cooling from CTL to NWR turns to lower air temperature and associated saturation mixing ratio, which increases vapor condensation and the associated release of latent heat. Thus, the increase in the...
release of latent heat corresponds to the enhancement in radiative cooling.

The hydrometeor change from the gain in NIR to the loss in NCR is mainly related to the strengthened raindrop loss (Table 3). The calculations of the rain budget, Equation (2), also reveal that the increase in precipitation from NIR to NCR corresponds mainly to the strengthened raindrop loss (Table 4). The increase in raindrop loss from NIR to NCR may result from the increase in rain hydrometeors (mass integration of the mixing ratio of rain hydrometeors) from 1.24 mm in NIR to 1.27 mm in NCR, which may correspond mainly to the increase in rain source from $P_{\text{GMLT}}$.

In the absence of ice radiative processes, the removal of water radiative processes from NIR to NCR enhances longwave radiative cooling in the lower troposphere by emitting more longwave radiation in NIR than in NCR (Figure 2(b)). The elimination of water radiative processes generally reduces the longwave radiative cooling in the upper troposphere by trapping more longwave radiation due to strengthened ice hydrometeors by the enhanced radiative cooling in the lower troposphere. This leads to the enhanced local atmospheric warming (Figure 2(a)). Since $P_{\text{GMLT}}$ is proportional to the air temperature, the enhanced melting of graupel to rain corresponds to the suppressed longwave radiative cooling.

The enhanced mean net condensation from CTL to NIR and NWR to NCR (Table 1) results mainly from the increased $P_{\text{GMLT}}$ (Table 2). The exclusion of ice radiative processes enhances the longwave radiative cooling regardless of the water radiative processes below 8 km (Figures 3(a) and 4(a)), while it slightly strengthens solar radiative heating (Figures 3(b) and 4(b)). The enhanced radiative cooling lowers air temperature and the associated saturation mixing ratio, which increases relative humidity and vapor condensation and the associated release of latent heat. Above 8 km, the weakened solar radiative heating is largely offset by the reduced longwave radiative cooling, which barely changes radiation. Thus, the increased mean net condensation from CTL to NIR and NWR to NCR corresponds to the

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**Figure 3.** Vertical profiles of differences between NIR and CTL (NIR–CTL), averaged for 10 days over the model domain, (a) in local temperature change (LTC; black), release of latent heat (RLT; red), convergence of vertical heat flux (CVHF; green), and radiation (Rad; orange); and (b) in radiation (Rad; orange) and its components of solar radiative heating (SRad; red) and longwave radiative cooling (LRad; blue). Units: °C d⁻¹.
enhanced radiative cooling via the strengthened release of latent heat.

4. Summary

In this study, the precipitation responses to the radiative processes of water- and ice-clouds are examined by analyzing the data from a two-dimensional equilibrium cloud-resolving model imposed with zero vertical velocity. In the presence of ice radiative processes, the exclusion of water radiative processes generally enhances the mean longwave radiative cooling throughout the troposphere, which enhances the release of latent heat associated with the increase in vapor condensation through the decrease in air temperature and saturation mixing ratio. In the absence of ice radiative processes, the removal of water radiative processes reduces the longwave radiative cooling in the upper troposphere, which increases local atmospheric warming. As a result, the enhancement in warming causes a rain source via an increase in the melting of graupel, which leads to an increase in rainfall. The exclusion of ice radiative processes enhances the longwave radiative cooling in the mid and lower troposphere through an increase in the release of latent heat, regardless of the water radiative processes.

The model was imposed with zero vertical velocity in this study, whereas it was imposed with non-zero vertical velocity in the simulation of pre-summer rainfall event by Liu, Shen, and Li (2014) and Shen et al. (2016). Comparison between the experiments imposed with zero and non-zero vertical velocity shows the differences and similarities in the radiative effects on rainfall. In the presence of radiative effects of ice (water) clouds, the exclusion of radiative effects of water (ice) clouds increases rainfall in the experiment imposed with zero vertical velocity, but it decreases rainfall in the experiment imposed with non-zero vertical velocity. In the absence of the radiative effects of ice (water) clouds, the removal of the radiative effects of water (ice) clouds increases rainfall in both experiments. Even if cloud radiative processes cause similar changes in rainfall, the associated physical processes may be different. For example, in the absence of the radiative effects of

![Figure 4. Vertical profiles of differences between NCR and NWR (NCR-NWR), averaged for 10 days over the model domain, (a) in local temperature change (LTC; black), release of latent heat (RLT; red), convergence of vertical heat flux (CVHF; green), and radiation (Rad; orange); and (b) in radiation (Rad; orange) and its components of solar radiative heating (SRad; red) and longwave radiative cooling (LRad; blue). Units: °C d⁻¹.](image)
water clouds, the exclusion of the radiative effects of ice clouds increases rainfall through an increase in net condensation in the experiment imposed with zero vertical velocity, and a hydrometeor change from a gain to a loss in the experiment imposed with non-zero vertical velocity. This indicates the effects of large-scale dynamics on the rainfall responses to cloud radiative processes.

Acknowledgements
The authors thank W.-K. TAO at NASA/GSFC for his cloud-resolving model.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This work was supported by the National Natural Science Foundation of China [grant number 41475039]; the National Basic Research Program of China [grant number 2015CB953601].

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