Impacts of cloud radiative processes on the convective and stratiform rainfall associated with Typhoon Fitow (2013)

Authors: Xu Huiyan

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Abstract

The three-dimensional Weather Research and Forecasting (WRF) model is used to conduct sensitivity experiments during the landfall of Typhoon Fitow (2013) to examine the impacts of cloud radiative processes on thermal balance. The vertical profiles of heat budgets, vertical velocity and stability were analyzed to examine the physical processes responsible for cloud radiative effects on surface rainfall for Typhoon Fitow (2013). The inclusion of clouds reduced radiative cooling in ice and liquid cloud layers via reducing outgoing radiation. The suppressed radiative cooling reduces from ice cloud layers to liquid cloud layers. This was conducive to enhancing instability. The decreased instability was associated with the reduced upward motions. The reduced upward motion led to the decreased vertical mass convergence. As a result, heat divergence was weakened to warm the atmosphere, this effects and the suppressed radiative cooling jointly suppressed net condensation and rainfall. Furthermore, the reduced rainfall due to the cloud radiative effects was mainly associated with the reduced convective and stratiform rainfall. The reduced convective rainfall was associated with the reduced net condensation, whilst the reduced stratiform rainfall was related to the constraint hydrometeor convergence.

Full Text

Preamble

Impacts of Cloud Radiative Processes on the Convective and Stratiform Rainfall Associated with Typhoon Fitow (2013)

Huiyan Xu[1], Dengrong Zhang[1]*
[1]Zhejiang Provincial Key Laboratory of Urban Wetlands and Regional Change, Hangzhou Normal University, Hangzhou, China

Key Points: - The control experiment is compared to the sensitivity experiment that excludes cloud radiative processes to study cloud radiative effects on heat budget. - The reductions in divergence of heat flux and radiative cooling from the control experiment to the sensitivity experiment have similar vertical profiles. - The reduced rainfall due to the cloud radiative effects was mainly associated with the reduced convective rainfall.

Abstract

The three-dimensional Weather Research and Forecasting (WRF) model is used to conduct sensitivity experiments during the landfall of Typhoon Fitow (2013) to examine the impacts of cloud radiative processes on thermal balance. The vertical profiles of heat budgets, vertical velocity, and stability were analyzed to examine the physical processes responsible for cloud radiative effects on surface rainfall for Typhoon Fitow (2013). The inclusion of clouds reduced radiative cooling in ice and liquid cloud layers by reducing outgoing radiation. The suppressed radiative cooling decreases from ice cloud layers to liquid cloud layers, which was conducive to enhancing instability. The decreased instability was associated with reduced upward motions.

The reduced upward motion led to decreased vertical mass convergence. As a result, heat divergence was weakened, warming the atmosphere. These effects and the suppressed radiative cooling jointly suppressed net condensation and rainfall. Furthermore, the reduced rainfall due to cloud radiative effects was mainly associated with reduced convective and stratiform rainfall. The reduced convective rainfall was associated with reduced net condensation, whilst the reduced stratiform rainfall was related to constrained hydrometeor convergence.

Keywords: Heat budget, radiative cooling, heat divergence, release of latent heat, Typhoon

1. Introduction

Cloud radiative processes have important impacts on the development of convective clouds and associated precipitation by regulating vertical thermal stratification. They consist of both solar shortwave radiation and infrared longwave radiation. Radiative cooling may affect the development of clouds [?, ?], convection [?, ?], surface rainfall [?, ?], relative humidity [?, ?], and precipitable water [?, ?, ?, ?]. Heat budget is one of the most important physical constraints linking radiative cooling to the release of latent heat, sensible heat, and divergence of heat flux. When large-scale circulation is absent, equilibrium modeling studies show that the release of latent heat is generally balanced by radiative cooling [?]. The exclusion of cloud radiative processes for liquid or ice clouds may enhance the release of latent heat in response to strengthened radiative cooling, leading to enhanced surface rainfall. Cloud radiation effects may also affect surface rainfall by impacting hydrometeor distributions; for example, [?] improved the 24-h heavy rainfall during the period from 0000 UTC 21 to 0000

UTC 22 July 2012 in the East Asia Monsoon Region by improving raindrop and snow size distributions.

When a cloud-resolving model is imposed by large-scale forcing, [?] revealed that the release of latent heat is largely balanced by the divergence of heat flux, while radiative cooling is relatively less important in the heat budget. Cloud radiative effects on heat budget show that changes in radiative cooling may play a role in regulating changes in the release of latent heat and the divergence of heat flux, thereby affecting surface rainfall. [?] and [?, ?] conducted a series of sensitivity experiments of severe tropical storm Bilis (2006) and a pre-summer torrential rainfall case over southern China, respectively, revealing that the exclusion of cloud radiative effects barely changes the release of latent heat while the suppressed heat divergence corresponds to enhanced radiative cooling, leading to increased surface rainfall. [?] examined the thermodynamics in tropical precipitation processes and showed that in the case with mean water vapor divergence, the mean heat divergence mainly balances the mean latent heat and affects surface rainfall. [?] conducted sensitivity experiments of Typhoon Soudelor in 2015 to examine the responses of surface rainfall to radiative effects of different cloud species, showing that different cloud species affect precipitation through different cloud radiation feedback mechanisms. The inclusion of radiative effects of cloud ice reduced vertical mass divergence and divergence of heat flux, resulting in reduced net condensation and rainfall, and vice versa when including radiative effects of snow [?]. [?] investigated thermal and microphysical effects of ice clouds on rainfall by examining heat budgets of a torrential rainfall simulation in northern China during July 2013, showing that the thermal feedback of ice clouds differs during the day and at night. Their results showed that the inclusion of latent-heat effects of ice clouds reduced surface rainfall by suppressing instability and upward motions at night, whilst the inclusion of radiative effects of ice clouds increased surface rainfall by increasing instability and upward motions during early morning.

Precipitation systems are decomposed into convective and stratiform rainfall to achieve deeper comprehension of convection-generated rainfall. Convective and stratiform rainfall differ in their distributions of vertical velocity, microphysical processes, and rainfall characteristics. [?] and [?] show that stratiform rainfall generally has weak horizontal gradients and/or a bright band, and vertical air motions are generally stronger in convective rainfall regions than in non-convective rainfall regions. Other studies show that collection of cloud water and vapor deposition are dominant in convective rainfall and stratiform rainfall, respectively [?, ?, ?, ?]. Convective rainfall is dominant in the hydrological cycle since it tends to be intense, whilst stratiform rainfall is important in cloud radiation budgets since it is widespread with large cloud coverage [?]. Understanding cloud radiation effects on convective and stratiform rainfall may be favorable for accurately predicting convective rainfall intensity and stratiform rainfall coverage, thus having potential effects on improving rainfall prediction. Cloud radiative processes may affect rainfall as well as convective and stratiform rainfall by changing atmospheric stratification. Motivated by the potentially different effects of cloud radiation on convective and stratiform rainfall, this paper will first investigate cloud radiation effects on rainfall, and then analyze cloud radiation effects on convective and stratiform rainfall. Unlike cloud-resolving models imposed by large-scale forcing, the Weather Research and Forecasting (WRF) Model allows interaction between clouds and environmental circulations.

In this study, the WRF model is used to conduct a pair of sensitivity experiments of Typhoon Fitow (2013) during its landfall. The model and experimental designs are briefly described in Section 2. The impacts of cloud radiative processes on thermal balance are analyzed in Section 3. A summary is given in Section 4.

2. Model and Experiment Design

Typhoon Fitow formed on 30 September 2013 over the eastern Philippines, strengthened to a typhoon around 2100 UTC 2 October, and made landfall with a minimum pressure of 955 hPa and a maximum wind speed of 42 m s^{-1} in Fuding, Fujian at 1715 UTC 7 October [?, see a detailed overview in]]Yu2014.

The Weather Research and Forecasting model version 3.5.1 (WRFV3.5.1) is employed to investigate the impacts of cloud radiative processes on thermal balance associated with Typhoon Fitow in this study. Three model domains with two-way nesting are used with horizontal grid resolutions of 27, 9, and 3 km and dimensions of 174$×120*inthewest* − *eastandsouth* − *northdirectionsfordomain*1(*d*01), 211×196*fordomain*2(*d*02), *and*361×$223 for domain 3 (d03) [?, see Fig. 1a in]]Xu2017. The WRF model setups are summarized in Table 1 . The control experiment has been validated with available observations in terms of typhoon track, minimum sea level pressure, surface precipitation, radar reflectivity, and vertical profiles of temperature, specific humidity, and winds [?]. In addition to the control experiment, three sensitivity experiments are conducted to examine how cloud radiative effects influence thermal balance. The sensitivity experiment is identical to the control experiment except that cloud hydrometeor mixing ratios are set to zero in the calculations of both solar and infrared radiative processes.

For typhoon cases, commonly used methods to partition convective or stratiform rainfall are those based on surface rainfall [?]. [?] (hereafter Braun10) identified convective rainfall at grid points where surface rain rates exceed 20 mm/hr or are at least twice as large as the mean value of their nearest 24 neighbors. Air columns with vertical velocity over 3 m/s or cloud liquid water over 0.5 g/kg are also identified as convective rainfall. The remaining grid points are considered stratiform where surface rain rate exceeds 0.1 mm/hr. More details about the Braun10 convective-stratiform rainfall partition scheme can be found in [?].

3. Results

To examine cloud radiative effects on surface rainfall, the surface rainfall equation and heat budget are first analyzed. Following [**?**, **?**, **?**], the surface rainfall budget in the 3D WRF model framework can be written as:

$$P_S = Q_{NC} + Q_{CM}$$

Here, P_S is rain rate, Q_{NC} is net condensation, and Q_{CM} is cloud hydrometeor convergence/divergence.

The inclusion of radiative effects of clouds reduces surface rainfall from NCR to CTL. The rainfall decrease in the CTL experiment is mainly associated with decreased net condensation (Table 2).

To explain surface rainfall responses to cloud radiative processes, the heat budget is analyzed. Following [**?**], the heat budget can be written as:

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \frac{\kappa T}{p}\omega + \frac{1}{c_p}\frac{dQ}{dt}$$

where T and θ are air temperature and potential temperature, respectively; $\mathbf{V}$ is the three-dimensional wind vector; $p_0 = 1000$ hPa; $\kappa = R/c_p$; R is the gas constant; c_p is the specific heat of dry air at constant pressure; F^*_{rad} is the tendency term due to radiation; F^*_{pbl} is sensible heat; and F^*_{mp} is latent heat. The equation states that temperature tendency (F_{loc}) is associated with divergence of heat flux (F_{hd}), solar and infrared radiative processes (F_{rad}), sensible heat (F_{pbl}), and release of latent heat (F_{mp}). Note that some terms including diffusion and Rayleigh damping are not included because they are negligibly small.

The comparison of heat budgets between CTL and NCR (Fig. 1 [Figure 1: see original paper]) reveals that the inclusion of cloud radiative processes reduces radiative cooling in the troposphere (below 11 km). The decreased net condensation (Table 2) was mainly associated with weakened release of latent heat. The weakened release of latent heat was due to reduced radiative cooling and suppressed divergence of heat flux.

The above analysis indicates that the change in release of latent heat corresponds to the change in divergence of heat flux from NCR to CTL. Thus, the change in divergence of heat flux is further analyzed. The divergence of heat flux (F_{hd}) can be broken down into three components:

$$F_{hd} = F^{xy}_{hd} + F^{z}_{hd}$$

The divergence of heat flux (F_{hd}) can be broken down into the divergence of horizontal (*xytend*) and vertical (*ztend*) heat flux.

Figure 2 [Figure 2: see original paper] reveals that the reduction in divergence of heat flux from the sensitivity experiment to the control experiment is associated with the decrease in divergence of vertical heat flux. Thus, the decrease in suppression of divergence in vertical heat flux corresponds to the reduction in radiative cooling. In total, the weakened divergence of heat flux from NCR to CTL below 11 km is mainly related to the suppressed divergence of vertical heat flux (Fig. 2 [Figure 2: see original paper]).

The divergence of vertical heat flux can be decomposed as:

$$ztend = ztend_1 + ztend_2 + ztend_3$$

where ω is vertical velocity in p-coordinate, overbar denotes domain mean, $ztend_1$, $ztend_2$, and $ztend_3$ are mean vertical temperature advection, interaction between mean temperature and mean vertical divergence, and the divergence of perturbation vertical heat flux, respectively.

Figure 3 [Figure 3: see original paper] shows that the reduction in $ztend$ is related to the decrease in $ztend_2$. Thus, the decrease in interaction between mean temperature and mean vertical divergence is related to the reduction in radiative cooling. $ztend_2$ can be further expressed as:

$$ztend_2 = \overline{\omega}\frac{\partial\overline{\theta}}{\partial p}$$

where $\overline{\theta}$ is mean temperature and $\overline{\omega}$ is mean vertical divergence.

Figure 3 [Figure 3: see original paper] further shows that the vertical structure of the $ztend_2$ change is related to that of the change in mean vertical divergence in the troposphere. We further analyze vertical profiles of vertical velocity (Fig. 4 [Figure 4: see original paper]). The radiative cooling was suppressed from NCR to CTL in the upper troposphere and in the lower troposphere (Fig. 1 [Figure 1: see original paper]), which leads to weakened upward motions decreasing from the upper troposphere to the lower troposphere (Fig. 4 [Figure 4: see original paper]). As a result, less vertical mass convergence occurs from NCR to CTL (Fig. 3 [Figure 3: see original paper]), which causes the increase in $ztend_2$ from NCR to CTL.

Since the difference between CTL and NCR is in cloud radiative process, the reduced radiative cooling in the upper troposphere was larger than that in the lower troposphere (Fig. 1 [Figure 1: see original paper]), which led to stability in the troposphere. Thus, the suppressed instability from NCR to CTL in the troposphere (Fig. 4 [Figure 4: see original paper]) is associated with the suppressed radiative cooling (Fig. 1 [Figure 1: see original paper]).

In total, although enhanced radiative cooling from the sensitivity experiment to the control experiment occurs above 11 km and weakened radiative cooling appears below 11 km (Fig. 1 [Figure 1: see original paper]), the tropopause is usually about 10-11 km where radiative cooling is similar in both control and sensitivity experiments. As a result, weakened radiative cooling from the sensitivity experiment to the control experiment appears in the troposphere, which leads to reduced upward motions (Fig. 4 [Figure 4: see original paper]).

To investigate cloud radiation effects on convective and stratiform rainfall, we further separate surface rainfall into convective and stratiform components. Table 3 shows temporally and spatially averaged rainfall budgets in CTL and NCR and their difference. It shows that reduced rainfall from NCR to CTL is mainly associated with reduced convective rainfall. The reduced convective rainfall is about one magnitude larger than the stratiform rainfall. Time-mean stratiform rainfall is not sensitive to cloud radiative processes. Reasons may be as follows: stratiform rainfall is only associated with ice clouds, where radiative cooling is suppressed with increasing height from 6 km to 8 km but enhanced with increasing height from 8 km to 11 km. Furthermore, the reduced convective rainfall was mainly related to decreased net condensation over convective rainfall areas (Table 3a).

To examine cloud radiation effects on convective and stratiform rainfall in more detail, Figure 5 [Figure 5: see original paper] shows temporal variations of spatially averaged rainfall budgets in CTL and NCR and their differences. It shows that reduced rainfall from NCR to CTL is mainly associated with reduced convective rainfall during daytime, while stratiform rainfall plays a minor role. The reduced convective rainfall was mainly related to decreased net condensation over convective rainfall areas during daytime (Figs. 5a-c [Figure 5: see original paper]). Stratiform rainfall mainly decreased from NCR to CTL during daytime, whilst it occasionally increased. Therefore, the difference in stratiform rainfall is negligibly smaller than that in convective rainfall in area-mean analysis. The reduced stratiform rainfall from NCR to CTL is mainly associated with decreased hydrometeor convergence, and increased rainfall is mainly related to increased net condensation (Figs. 5d-f [Figure 5: see original paper]).

We also examined whether the explanation of cloud radiative effects on temporally and spatially averaged rainfall can be applied to temporal variation of spatially averaged rainfall, since cloud radiative effects may differ between daytime and nighttime. Cloud solar radiative and infrared radiative effects on rainfall may be different. Figure 6 [Figure 6: see original paper] shows that solar radiation heats the whole troposphere, decreasing top infrared cooling and reducing base warming, leading to stability in the troposphere (Figs. 6a-c [Figure 6: see original paper]), whilst infrared radiation increases top cooling and base warming, leading to a destabilizing effect on the troposphere (Figs. 6d-f [Figure 6: see original paper]). Solar radiation effects are more important than infrared radiation during daytime, leading to more stabilized troposphere and weaker upward motions (Fig. 7 [Figure 7: see original paper], Fig. 8 [Figure 8: see original paper]), resulting in less rainfall during daytime in the control simulation compared to the NCR simulation. Conversely, infrared radiation dominates during nighttime (generally 1000-1600 UTC), leading to more destabilized troposphere and stronger upward motions (Fig. 7 [Figure 7: see original paper], Fig. 8 [Figure 8: see original paper]), resulting in more rainfall during nighttime in the control simulation compared to the NCR simulation.

Cloud radiative effects on temporally and spatially averaged rainfall are suppressed from NCR to CTL during the peak of rainfall. More radiative cooling due to exclusion of cloud radiative effects causes stronger rainfall in NCR than in control, which is consistent with previous results about the effects of IR cooling on convection [**?**, **?**].

4. Summary

Sensitivity experiments of Typhoon Fitow (2013) are conducted with the three-dimensional WRF model to examine cloud radiative effects on heat budget and surface rainfall during its landfall. The simulation data are used to analyze the difference in heat budget between the control experiment and the sensitivity experiment excluding cloud radiative effects. The analysis shows that the reduction in divergence of heat flux from the experiment removing cloud radiative effects to the control experiment has similar magnitude and vertical profile to the reduction in radiative cooling.

The inclusion of radiative effects of clouds reduces radiative cooling by reducing outgoing radiation. The enhanced radiative cooling decreases from the upper troposphere to the lower troposphere, and the decreased instability increases from the mid-troposphere to the lower troposphere, which reduces vertical mass convergence. The weakened mass convergence leads to decreased divergence of vertical heat flux that increases air temperature and saturation mixing ratio. As a result, net condensation and associated release of latent heat are reduced and rainfall decreases.

The rainfall is further partitioned into convective rainfall and stratiform rainfall. Cloud radiation effects on convective and stratiform rainfall are further analyzed. The inclusion of cloud radiation effects decreased rainfall, which is associated with reduced convective and stratiform rainfall. Both convective and stratiform rainfall increased at nighttime due to increased net condensation and hydrometeor convergence, respectively. The decreased convective rainfall is related to reduced net condensation during daytime, whilst the decreased stratiform rainfall is associated with reduced hydrometeor convergence during daytime.

In summary, the inclusion of cloud radiative effects reduced latent heat release, resulting in constrained surface rainfall. Further partitioning of rainfall into convective and stratiform components shows that different processes affect convective and stratiform rainfall. Decreased surface rainfall is mainly associated with decreased convective and stratiform rainfall. However, the constrained convective rainfall is associated with decreasing net condensation, whilst the constrained stratiform rainfall is associated with decreasing hydrometeor convergence (Figure 9 [Figure 9: see original paper]).

Caution should be exercised when applying these results since they are based on a case study of Typhoon Fitow in 2013. Further examinations of more cases should be conducted to validate and generalize the results from this study.

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Table Captions

Table 1. WRF Model setup

Table 2. Daily and model domain means of surface rain rate (P_S), net condensation (Q_{NC}), and hydrometeor convergence/divergence (Q_{CM}) for surface rainfall in CTL and NCR, and their differences (CTL-NCR).

Table 3. Daily and model domain means of surface rain rate (P_S), net condensation (Q_{NC}), and hydrometeor convergence/divergence (Q_{CM}) for (a) convective rainfall and (b) stratiform rainfall in CTL and NCR, and their differences (CTL-NCR).

Figure Captions

Figure 1. Vertical profiles of differences in temperature tendency (F_{loc}; blue) and its tendency due to heat divergence (F_{hd}; red), sensible heat (F_{pbl}; green), latent heat (F_{mp}; black), and radiative processes (F_{rad}; orange) between the control experiment and the sensitivity experiment. Unit is °C day^{-1}.

Figure 2. Vertical profiles of differences in divergence of heat flux (F_{hd}; red) and its components: divergence of horizontal heat flux (*xytend*; orange) and divergence of vertical heat flux (*ztend*; blue) between the control experiment and the sensitivity experiment. Unit is °C day^{-1}.

Figure 3. Breakdown of vertical profiles of divergence of vertical heat flux (*ztend*; black; Unit: °C day^{-1}): interaction between mean temperature and mean vertical divergence ($ztend_2$; red; Unit: °C day^{-1}), mean temperature ($\overline{\theta}$; orange; 10^{-1} °C), vertical divergence ($\overline{\omega}_d$; magenta; 10^{-2} day^{-1}), mean vertical temperature advection ($ztend_1$; blue; 10^{-1} °C day^{-1}), divergence of perturbation vertical heat flux ($ztend_3$; green; °C day^{-1}) between the control experiment and the sensitivity experiment.

Figure 4. Vertical profiles of differences in (a) stability (K) and (b) vertical velocity (ω; 10^{-3} Pa s^{-1}) between the control experiment and the sensitivity experiment.

Figure 5. Time series of domain-mean surface rain rate (P_S), net condensation (Q_{NC}), and hydrometeor convergence/divergence (Q_{CM}) for (a-c) convective rainfall and (d-f) stratiform rainfall in (a, d) CTL, (b, e) NCR, and (c, f) their differences (CTL-NCR).

Figure 6. The temporal-vertical cross-section of (a, d) control, (b, e) NCR, and (c, f) their difference (CTL-NCR) in spatially averaged (a, b, c) solar radiative heating and (d, e, f) infrared radiative cooling. Unit: $\mathrm{K \cdot h^{-1}}$.

Figure 7. The temporal-vertical cross-section of (a) control, (b) NCR, and (c) their difference (CTL-NCR) in spatially averaged temperature (unit: °C).

Figure 8. The temporal-vertical cross-section of (a) control, (b) NCR, and (c) their difference (CTL-NCR) in spatially averaged vertical velocity (ω; $\mathrm{cm \cdot s^{-1}}$).

Figure 9. A conceptual model for the probable mechanism of how cloud radiation processes affect precipitation.

Note: Figure translations are in progress. See original paper for figures.

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