To editor

We have rerun simulations with actual number concentration of water-friendly aerosols, instead of using a background aerosol number concentration of 1/L for Koop's parameterization scheme. In revised manuscript, water-friendly aerosols were included in both CTRL and DUST simulations. The number concentration of water-friendly aerosols was read from the pre-given climatological aerosol profile derived from long-term simulations of global climate models. The aerosol profile was provided by Dr. Thompson and Dr. Eidhammer and used in their paper for evaluating the performance of the Thompson-Eidhammer microphysics scheme (Thompson and Eidhammer, 2014). The mean number density of water-friendly aerosols during the simulation period is shown in Figure R1.

The figures and the results have been updated according to the outputs of the new simulations.

To the anonymous referee

Comments:

I rated the scientific quality as poor based on my comments below. I might be wrong in my understanding of the implementation of the model (in which case I would rate the scientific quality as good), but if I am correct, I believe the work needs some major revisions with new model runs.

I need some more information about the implementation of this scheme before I can give any recommendations regarding this paper, and I have to admit that I have not read the entire manuscript again because I have a major concern:

In the Thompson-Eidhammer scheme it is found that an important contributor to in-situ cirrus clouds is the homogeneous freezing of deliquescent aerosols (Koop et al parameterization). This process can contribute to ice concentration of several hundreds L-1, because this freezing comes from sulfate aerosols which can have concentrations of 1-100 cm-3 (i.e. 1000-100,000 L-1). According to Su et al., homogeneous freezing of deliquescent aerosols is calculated based on aerosol concentration of 1 L-1. This means that ice crystal concentration from homogeneous freezing of deliquescent aerosols can maximum be 1 L-1, much less than what is typical (hundreds L-1).

In the conclusion, Su et al states that they find that dust has a large impact in the upper troposphere and increase in cloud ice is mainly concentrated to the mid to upper troposphere. I can see that this is the case if the background ice concentration is only 1 L-1, instead of for example 200 L-1, which you can find, due to homogeneous freezing.

Su et al also found that they had to reduce the limit for when ice freeze to 100 % RHi, due to too low ice water content. I can also see that this is the case if homogeneous freezing is not effective in their setup.

In effect, I have major concern about the findings in their paper regarding dust, if homogeneous freezing of deliquescent aerosols is not effective. I believe the dust to be found too effective compared to what is actually happening in the atmosphere.

Response:

We deeply thank the referee for pointing out the problem. We agree that the exclusion of water-friendly aerosols for this process in the simulations is unreasonable and could lead to an exaggeration of the effect of dust on the IWP. To address this concern, we have rerun simulations with actual number concentration of water-friendly aerosols, instead of using a background aerosol number concentration of 1/L for Koop's parameterization scheme. In revised manuscript, water-friendly aerosols were included in both CTRL and DUST simulations. The number concentration of water-friendly aerosols was read from the pre-given climatological aerosol profile derived from long-term simulations of global climate models. The aerosol profile was provided by Dr. Thompson and Dr. Eidhammer and used in their paper for evaluating the performance of the Thompson-Eidhammer microphysics scheme (Thompson and Eidhammer, 2014). The mean number density of water-friendly aerosols during the simulation period is shown in Figure R1.

The figures and the results have been updated according to the outputs of the new simulations.

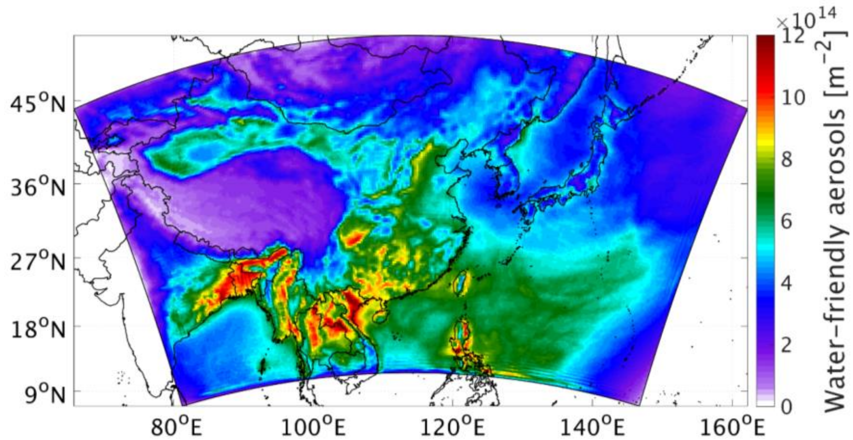

Figure R1. Mean number density of water-friendly aerosols over the simulation period.

Investigating the role of dust in ice nucleation within clouds and further effects on the regional weather system over East Asia

Part II: modification of the weather system

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Keywords: East Asian dust; radiative forcing; clouds; precipitation; regional modeling

Highlights:

The ~~semi-direct and indirect~~direct radiative effect~~s~~ of dust are more pronounced than the cloud radiative ~~direct~~ effect enhanced by dust on ~~the regional weather system~~altering the radiative budget.

The ~~semi-direct and~~ indirect effects of dust result in an increase ~~in mid- to high~~ice clouds at mid- to upper troposphere, and a reduction ~~in low clouds~~of liquid clouds at low to mid-troposphere.

The total precipitation amount over East Asia ~~is reduced over most of China~~remains unchanged, with the locations of the precipitation are shifted~~, but increased over South China by up to 20% or more~~.

Abstract. An updated version of the Weather Research and Forecast model coupled with Chemistry (WRF-Chem) was applied to quantify and ~~discuss~~ investigate the full effects of dust on the meteorological field over East Asia during March and April 2012. The performances of the model in simulating the short-wave and long-wave radiation, surface temperature, and precipitation over East Asia are improved by incorporating the effects of dust in the simulations. The radiative forcing induced by the ~~dust-enhanced cloud~~direct radiative effect of dust is ~~over one order of magnitude larger~~greater than that ~~induced~~ by the dust-enhanced ~~direct effect~~cloud radiative effect ~~of dust~~. The ~~semi-direct and~~ indirect effects of dust result in a substantial increase ~~in mid- to high~~ ice clouds at mid- to upper troposphere, and a ~~significant~~ reduction in ~~low~~ liquid clouds at low to mid-troposphere. The radiative forcing combined with the re-distribution of atmospheric water vapor ~~,~~results in ~~leading to~~ an overall decrease of near-surface temperature and an increase of temperature at the mid- to upper troposphere over East Asia~~. The spatial redistribution of atmospheric water vapor and modification of the vertical temperature profile over East Asia lead to~~, leading to an inhibition of atmospheric instability over most land areas, but an enhancement of atmospheric instability over South China ~~and the ocean~~.~~,~~ Upon considering the effects of dust, the convective precipitation exhibits~~resulting in~~ an ~~significant~~ inhibition ~~of convective precipitation~~ over~~in~~ areas from central to East China, and an ~~substantial~~ enhancement ~~of convective precipitation~~ over South China. Meanwhile, the locations of non-convective precipitation ~~is also reduced significantly over East Asia~~are shifted due to the perturbation of cloud water path~~, as cloud droplets are hindered from growing large enough to form rain droplets, due to the semi-direct and indirect effects of dust. The total precipitation can be reduced or increased by up to 20% or more~~. The total amount of precipitation over East Asia remains unchanged, however, the precipitation locations are shifted. The precipitation can be enhanced or inhibited by up to 20% at particular areas.

1 Introduction

Dust is recognized as an “essential climate variable” because it is a major component of atmospheric aerosols and has significant impacts on the weather and climate system (Solomon, 2007). East Asian dust is an important contributor to global dust emissions (Ginoux et al., 2001), and thus play a significant role in affecting the regional weather system through direct effect, semi-direct and indirect effects.

Dust particles affect the radiation budget directly by absorbing, reflecting and scattering short-wave and long-wave radiation (Satheesh et al., 2006;Seinfeld et al., 2004;Lacis, 1995). The cloud radiative effect induced by dust is referred to as the semi-direct effect of dust. Dust particles within clouds can absorb radiation and heat up the surrounding environment, leading to faster evaporation rate of cloud droplets and thus a reduction of cloud cover. The indirect effects of dust are related to dust–cloud–interaction. (Hansen et al., 1997;Perlwitz and Miller, 2010). Dust particles are recognized as effective ice nuclei (IN) and considered to play an important role in cold cloud processes (Broadley et al., 2012;Connolly et al., 2009;Sassen, 2002), leading to the variation of the ice water content in mixed-phase and ice clouds, which further affects the formation and development of clouds, as well as precipitations (Sassen et al., 2003;Targino et al., 2006;Teller and Levin, 2006;Lohmann and Feichter, 2005).

In light of the significance of dust for the weather and climate system, assessing the effects of dust has become increasingly important. On one hand, the direct (Mallet et al., 2009;Nabat et al., 2015a;Ge et al., 2010;Hartmann et al., 2013;Huang et al., 2009;Bi et al., 2013;Liu et al., 2011a;Liu et al., 2011b;Palacios et al., 2015;Huang, 2017) and semi-direct (Tesfaye et al., 2015;Nabat et al., 2015b;Seigel et al., 2013) effects of dust has being extensively studied worldwide by applying numerical methods. On the other hand, various ice nucleation parameterizations have been implemented into global models to estimate the importance of dust in atmospheric ice nucleation (Lohmann and Diehl, 2006;Karydis et al., 2011;Hoose et al., 2008;Zhang et al., 2014), revealing that the effect of dust as IN should not be neglected in numerical models, especially in the simulations over arid regions during strong wind events (DeMott et al., 2003;Koehler et al., 2010;DeMott et al., 2015;Lohmann and Diehl, 2006;Atkinson et al., 2013). Unfortunately, , only limited work has been carried out to investigate the indirect effects of dust on the regional weather system, especially over East Asia, which is one of the major contributors to the global dust emission in the world (Ginoux et al., 2001).

This series of study aimed to investigate the role of East Asian dust in affecting the regional weather system. In the first part of the study, The Goddard Chemistry Aerosol Radiation and Transport (GOCART) model has been coupled with the aerosol-aware Thompson-Eidhammer microphysics scheme (Thompson and Eidhammer, 2014), enabling the model to estimate the indirect effect of dust along with the direct and semi-direct effects, which improved the simulation of the ice nucleation process involving dust particles (Su and Fung, 2017). In this work, by applying an updated version of WRF-Chem, we aim to investigate the full effects of dust, including direct, semi-direct, and indirect effects, on the regional weather system over East Asia during a dust-intensive period. As the semi-direct effect and indirect effect of dust cannot be separated in our simulation, these two effects are merged and discussed as a part of the effects of dust apart from the direct effect, and represented by "indirect effects" in the rest of the paper. This is the first study to document the full effects of dust during a typical dust-intensive period over East Asia by applying an online-coupled regional numerical model.

The remainder of the manuscript is organized as follows. The model configurations is described in Section 2, followed by the model validation in Section 3. The results along with the discussion will be presented in section 4, followed by the concluding remarks in Section 5.

2 Model configurations

The simulations were performed using an updated version of WRF-Chem based on version 3.8.1 (Grell et al., 2016). The GOCART-Thompson, which is the coupling of the GOCART aerosol model and the aerosol-aware Thompson-Eidhammer microphysics scheme, has been implemented in the updated WRF-Chem, to evaluate the indirect effects of dust on the atmospheric ice nucleation process by serving as IN. In the GOCART-Thompson microphysics scheme, the condensation and immersion freezing is parameterized by the DeMott2015 ice nucleation scheme, and two factors of the DeMott2015 scheme were tuned through sensitivity experiments in the first part of this study. c_f is a calibration factor in the DeMott2015 ice nucleation parameterization scheme, which was used for the nucleation of the heterogeneous nucleation of ice crystals by dust particles in the GOCART-Thompson scheme, and it ranges from 1 to 6. According to the results of the sensitivity experiments in Part I, the calibration factor c_f was set to be 4 for the simulations in this study. Furthermore, it was also demonstrated that the ice water content was still underestimated by using the GOCART-Thompson scheme. To improve the simulation of the ice nucleation by dust particles, the threshold relative humidity with respect to ice (RH_i) was lowered from 105% to 100% in the ice nucleation parameterization, to allow the heterogeneous nucleation of ice crystals by dust particles to occur at a lower RH_i (Su and Fung, 2017). Therefore, a threshold RH_i of 100% was for the simulations run with dust emissions in this study. In addition, the deposition nucleation is determined by the Phillip's parameterization scheme ~~of Phillips et al.~~ (Phillips et al., 2008), and the freezing of deliquesced aerosols using the hygroscopic aerosol concentration is parameterized following Koop's parameterization scheme ~~et al.~~ (Koop et al., 2000)~~, with the background aerosol concentration set to be 1/L~~. The GOCART aerosol model was applied to simulate aerosol processes (Ginoux et al., 2001;Ginoux et al., 2004) and produce ice nuclei that served by dust particles in DUST. Shao's dust emission (Kang et al., 2011;Shao et al., 2011) with soil data from the United states Geological Survey (Soil Survey Staff, 1993), which have been demonstrated to have good performance in reproducing dust emissions over East Asia, was used to generate dust emission in the simulations of TEST. The ice nuclei were then fed into the GOCART-Thompson microphysics scheme for calculating the indirect effects of dust by DeMott2015 parameterization scheme. In addition, the pre-given climatological profiles applied in Thompson-Eidhammer scheme (Thompson and Eidhammer, 2014) were used to provide the number concentration of water-friendly aerosols for the freezing of deliquesced aerosols to consider the background indirect effects of aerosols on ice nucleation for all the simulations in this study.~~In addition, the condensation and immersion freezing is parameterized by the DeMott2015 ice nucleation scheme, and two factors of the DeMott2015 scheme were tuned through sensitivity experiments in the first part of this study. c_f is a calibration factor in the DeMott2015 ice nucleation parameterization scheme, which was used for the nucleation of the heterogeneous nucleation of ice crystals by dust particles in the GOCART-Thompson scheme, and it ranges from 1 to 6. According to the results of the sensitivity experiments in Part I, the calibration factor c_f was set to be 4 for the simulations in this study. Furthermore, it was also demonstrated that the ice water content was still underestimated by using the GOCART-Thompson scheme. To improve the simulation of the ice nucleation by dust particles, the threshold relative humidity with respect to ice (RH_i) was lowered from 105% to 100% in the ice nucleation parameterization, to allow the heterogeneous nucleation of ice crystals by dust particles to occur at a lower RH_i (Su and Fung, 2017). Therefore, a threshold RH_i of 100% was for the simulations run with dust emissions in this study.~~

Four numerical simulations were carried out to evaluate the separate effects of dust over East Asia. The configurations for the four simulations are summarized in Table 1. The first simulation was termed NO-DUST/NO-CLOUD, and was conducted without dust, with both the aerosol radiative feedback and cloud radiative feedback turned off. The second simulation, NO-DUST/CLOUD, was also conducted without dust, with the aerosol radiative feedback turned off, but the cloud radiative feedback turned on to estimate the intrinsic radiative effect of cloud. The third simulation, DUST/NO-CLOUD, was conducted with the presence of dust, with the aerosol radiative feedback turned on, while the cloud radiative feedback still turned off. The difference between NO-DUST/NO-CLOUD and DUST/NO-CLOUD therefore represented the direct effect of dust on the radiation budget and other meteorological parameters. The last simulation, DUST/CLOUD, was conducted with the presence of dust, and with both aerosol radiative feedback and cloud radiative feedback turned on, to estimate the full effect of dust on the meteorological field over East Asia.

The important physical and chemical parameterization schemes applied for the four simulations are as follows. The GOCART aerosol model was applied to simulate the aerosol processes (Ginoux et al., 2001;Ginoux et al., 2004). For the dust emission simulation in DUST/NO-CLOUD and DUST/CLOUD, the Shao dust emission scheme (Shao, 2004;Shao et al., 2011) was applied, which had been demonstrated to closely reproduced the dust emissions over East Asia (Su and Fung, 2015). Note that no aerosol emissions were considered in the simulations other than dust. The Mellor–Yamada–Janjic (MYJ) turbulent kinetic energy scheme was used for the planetary boundary layer parameterization (Janjić, 2002, 1994); the moisture convective processes were parameterized by the Grell–Freitas scheme (Grell and Freitas, 2014); the short-wave (SW) and long-wave (LW) radiation budgets were calculated by the Rapid Radiative Transfer Model for General Circulation (RRTMG) SW and LW radiation schemes (Mlawer et al., 1997;Iacono et al., 2008); gravitational settling and surface deposition were combined for aerosol dry deposition (Wesely, 1989); a simple washout method was used for the below-cloud wet deposition of aerosols; and the aerosol optical properties were calculated based on the volume-averaging method. The newly-implemented wet scavenging scheme described in Part I of this study was used for the in-cloud wet scavenging of dust particles caused by the microphysical processes. As no dust was simulated in NO-DUST/NO-CLOUD and NO-DUST/CLOUD, these two simulations did not included a dust emission scheme, aerosol dry and wet deposition schemes, and aerosol optical schemes. ~~Note that in the two NO-CLOUD simulations, a default IN concentration of 1 per Liter is used for the heterogeneous ice nucleation process.~~

As described in the first part of this manuscript, two nested domains were used for all four simulations, the outer domain had a horizontal resolution of 27 km, covering the entire East Asia region, and the inner domain had a horizontal resolution of 9 km, covering the entire central to East China. Both domains have 40 layers, with the top layer at 50 hPa. The simulation period was March 9 to April 30, 2012, with the first eight days as "spin-up" time. Only the results from March 17 to April 30, 2012 were used for further analysis. Final reanalysis data provided by the United States National Centre of Environmental Prediction, with a horizontal resolution of 1°, were used for generating the initial and boundary conditions for the meteorological field. The simulations were re-initialized every 4 days, with the aerosol field being recycled, i.e., the output of the aerosol field from the previous 4-day run was used as the initial aerosol state for the next 4-day run.

3 Model validation

The simulation for dust emission was validated in Part I of this study, and the model was demonstrated to closely reproduce dust emissions over East Asia during the investigated period by comparison with comprehensive observational data. As this study focused on the modification of the meteorological field by the effects of dust over East Asia, the capability of the model in simulating the meteorological field itself over this region requires further validation.

The China meteorological forcing dataset (Yang et al., 2010;Chen et al., 2011) was used to assess the performance of the model in reproducing the spatial distribution of the meteorological field over China. The dataset was developed by the hydrometeorological research group at the Institute of Tibetan Plateau Research, Chinese Academy of Science, by merging the Princeton meteorological forcing data (Sheffield et al., 2006), the Global Energy and Water Cycle Experiment–Surface Radiation Budget (GEWEX-SRB) forcing data (Pinker and Laszlo, 1992), and the Global Land Data Assimilation System forcing dataset (Rodell et al., 2004). The dataset contains gridded observations of the near-surface temperature, precipitation rate, surface downward SW and LW radiation across China, with a spatial resolution of 0.25°, dating from 1996.

Note that only simulation results from NO-DUST/CLOUD and DUST/CLOUD are shown, as they represent the intrinsic meteorological field and the meteorological field modified by the effects of dust, respectively. For March, the comparison is restricted to the observational data from March 17 to March 31, 2012, to ensure temporal overlay with the corresponding simulation period. No observational data over the ocean were available, so the simulated results over the ocean are also omitted to simplify the comparison.

The spatial distributions for the monthly average observational downward surface SW radiation for March and April 2012 are shown in Figure 1a and b. Overall, the SW radiation was stronger in April than in March. The SW radiation was significantly higher over the West and Northwest China, due to the higher elevation of terrain over these regions, and lower over East and South China, due to the lower elevation and greater cloud coverage over those regions. The model closely reproduced the spatial distributions of the SW radiation in both months and accurately captured the trend from March to April in the simulation results from both NO-DUST/CLOUD and DUST/CLOUD, despite a certain overestimation, especially over coastal areas of East and South China. This overestimation was likely due to the underestimation of clouds by the model over these areas. Compared with inland areas, cloud coverage is always greater over the coastal areas of East and South China due to the abundant water vapor. Therefore, the SW radiation budget over coastal areas was more sensitive to the underestimation of clouds by the model. Nevertheless, an improvement in the simulation of the SW radiation budget over East Asia can be seen in the results from DUST/CLOUD compared with those from NO-DUST/CLOUD. Specifically, the SW radiation produced in DUST/CLOUD (Figure 1e and f) was substantially lower than that produced in NO-DUST/CLOUD (Figure 1c and d) over China, especially at the dust sources and surrounding areas over the north and northwest of the country, which is clearly more consistent with the observations.

For downward surface LW radiation, two high-value areas can be observed (Figure 2a and b). One is over Northwest China, where the Taklimakan Desert is located. The strong downward LW radiation over this region was likely due to the abundance of dust particles in the local atmosphere. The other area of strong LW radiation was located over South China, which is warmer and contains more atmospheric water vapor. Water vapor is a potent greenhouse gas, which efficiently absorbs LW radiation emitted by the Earth and heat the surrounding area, and thus increases the emission of LW radiation downward (and upward) by the heated atmosphere. The model accurately simulated the spatial distributions of the LW radiation over this region for both March and April in both NO-DUST/CLOUD (Figure 2c and d) and DUST/CLOUD (Figure 2e and f), and indeed closely captured the spatial pattern of the LW radiation over China. The LW radiation over the Gobi Desert produced by DUST/CLOUD (Figure 2e and f) is slightly higher than that produced by NO-DUST/CLOUD, indicating that the model reproduced the LW radiation budget more accurately upon taking the effects of dust into account.

Similarly to the spatial distributions for the LW radiation, higher near-surface temperatures were observed over Northwest China, which is a dry, arid area, and South China, which is closer to the equator (Figure 3a and b). The spatial distributions of the near-surface temperature over this region were well reproduced by the model for both March and April in both NO-DUST/CLOUD (Figure 3c and d) and DUST/CLOUD (Figure 3e and f). The model accurately captured the spatial pattern of the surface temperature, and the two simulations did not show remarkable difference in their results.

During the simulation period, the precipitation increased from North to South China in both months, and increased from March to April over the entire region (Figure 4a and b). The spatial patterns of precipitation in March and April were mostly reproduced by the model in both NO-DUST/CLOUD (Figure 4c and d) and DUST/CLOUD (Figure 4e and f), but the model underestimated the precipitation in March in both simulations, especially over central and North China. In April, the observed precipitation center was located over South China. Apart from underestimating the precipitation over Central and North China, the NO-DUST/CLOUD simulation predicted the precipitation center to be located in an area to the north of the observed center (Figure 4d), and it also underestimated the precipitation over South China. In contrast, in the results of DUST/CLOUD (Figure 4f), the precipitation band ~~from Hunan~~ to the north of S~~s~~outh China was ~~markedly~~ weaker, ~~while~~ and the precipitation over South China was slightly stronger that produced by NO-DUST/CLOUD, which was more consistent with the observations~~was enhanced, which was clearly much more consistent with the observations~~.

The foregoing comparison of the simulation results with the observational data demonstrated that the model reasonably reproduced the meteorological field over East Asia. Moreover, the meteorological field was produced more accurately when the effects of dust were considered in the simulations, which consequently allows the dust-induced modification of the meteorological field to be investigated.

4 Results and discussion

4.1 Atmospheric water vapor

4.1.1 Spatial distribution

The indirect effects of dust particles lead to modifications of cloud format and cloud lifetime, and a re-distribution of atmospheric water vapor. The spatial distributions of the simulated ice water path (IWP) and cloud water path (CWP) from NO-DUST/CLOUD and DUST/CLOUD, as well as the difference between the two simulations (DUST/CLOUD − NO-DUST/CLOUD), are presented in Figure 5. The atmospheric IWP and CWP are the column sums of cloud ice water content, and cloud water content in the atmosphere per unit area. Note that the difference between NO-DUST/CLOUD and DUST/CLOUD is entirely due to the full effects of dust, i.e., the direct effect of dust, the cloud radiative effect enhanced by dust, and the microphysical effect of dust serving as IN in the atmosphere. The spatial distributions shown in Figure 5 are the mean IWP and CWP averaged over the whole simulation period.

Figure 5a and b show the spatial distributions of the mean atmospheric IWP over East Asia produced from NO-DUST/CLOUD and DUST/CLOUD. The IWP is concentrated over mid-latitude areas (30-40°N) in the results of NO-DUST/CLOUD (Figure 5a), with values of 10-20 g/m^2. These ice crystals are mostly formed through the freezing of the deliquesced water-friendly aerosols. By contrast, the IWP produced by DUST/CLOUD is substantially higher than that produced by NO-DUST/CLOUD over mid-latitude areas in the simulation domain, which are the dust sources and their downstream areas (Figure 5b). This corresponds to an increase by 25% to 50% over vast areas, from dust source regions to the Northwest Pacific (Figure 5c), due to the dust particles serving as IN, and leading to a substantial enhancement of ice crystals in the atmosphere. Dust nuclei in the atmosphere enable the super-cooled water droplets to freeze into ice crystals at a much higher temperature and lower relative humidity.

The spatial distributions for the mean CWP over East Asia produced from NO-DUST/CLOUD and DUST/CLOUD are shown in Figure 5d and e, in both of which the CWPs are concentrated over South China and the West Pacific Ocean, with comparable values to each other. However, the comparison of CWPs produced from DUST/CLOUD and NO-DUST/CLOUD in Figure 5f shows the existence of dust leads to a slight reduction of CWP over West, North and central China, where the IWP increases substantially. Moreover, there are perturbations of CWP over East and South China, as well as the West Pacific Ocean. Particularly, the CWP is generally reduced by up to 10 g/m^2 over West, North and central China, and increased by up to 10 g/m2 over South China, which account for over 10% or more of the total cloud water vapor at these regions.

4.1.2 Vertical profile

As the spatial distributions of IWP and CWP over East Asia are altered by the effects of dust, the cloud ice mixing ratio and cloud water mixing ratio are also modified vertically. Figure 6 shows the modifications on vertical profiles of the cloud ice and cloud water mixing ratios induced by the full effects of dust. Note that the vertical profiles over land, over the ocean, and over the entire simulation domain for East Asia are averaged across the whole simulation period.

Due to the effects of dust, the cloud ice mixing ratio is increased at all altitudes from the near-surface layer to higher than 10 km over the whole of East Asia, as shown in Figure 6a. The cloud ice mixing ratio is uniformly increased between surface to 10 km over land with a peak located at around 7km (Figure 6b), which results from the increase of IN served by the abundant dust particles in the atmosphere. In contrast, the increase of the cloud ice mixing ratio over the ocean is much less significant, with a higher peak located at 8-9 km (Figure 6c). A possible cause of the higher peak over the ocean is that only those particles fined enough to be lifted to high altitudes can be transported as far as the open ocean of the West Pacific, whereas over land, more dust particles with larger sizes are suspended in lower layers before settling down to the surface.

The vertical modification of the cloud water mixing ratio due to the effects of dust is fundamentally different from that of cloud ice mixing ratio. Due to the effects of dust, the cloud water mixing ratio shows a decrease in average over East Asia from surface to 7 km (Figure 6d). The overall decrease is dominated by the reduction in the cloud water mixing ratio over land (Figure 6e). The cloud water mixing ratio is also decreased over the ocean near surface and above 4 km, but slightly increase between 1 and 4 km (Figure 6f). The vertical modification of the cloud water mixing ratio suggests that the effects of dust reduce liquid clouds at low to mid-troposphere over East Asia, especially over land.

To summarize, the effects of dust result in a general increase of ice clouds and a slight decrease of liquid clouds over East Asia as a whole, whereby the increase in cloud ice is mainly concentrated at the mid- to upper troposphere, while the decrease of cloud water mostly occurs in low and mid-altitude clouds.

The increase in ice clouds at the mid- to upper troposphere is attributed to the indirect effects of dust. The abundant IN in the atmosphere served by dust particles substantially increase the amount of ice crystals in mixed-phase and ice clouds at these altitudes. In contrast, the decrease of liquid clouds at low to mid- troposphere is the result of two factors. One is the warming within the atmosphere induced by the dust, leading to a much higher saturation pressure required for atmospheric water vapor to form clouds, and a much faster evaporation rate of cloud droplets, which is due to the cloud burning effect of dust. The other factor is that the super-cooled cloud droplets in the upper layers of the troposphere freeze into ice crystals at a much higher temperature and lower relative humidity when dust particles serve as IN in the atmosphere, leading to an increase of atmospheric IWP. Combined with the direct radiative effect of dust, the modifications of the ice and liquid clouds induced by dust will alter the radiation budget over the region. Compared to that of the increase for the ice clouds, the magnitude of the decrease for liquid clouds is smaller. However, the radiative effect of liquid clouds, especially those low clouds, is much greater than that of ice clouds, therefore, the decrease of liquid clouds might have a greater impact on the radiative budget over East Asia, which will be discussed in the following section.

4.2~~1~~ Radiative effect

The radiative effect of dust particles is demonstrated by dust-induced SW, LW, and net radiative forcing at the top of the atmosphere (TOA), at the bottom of the atmosphere (BOT), and within the atmosphere (ATM) in this study.

The spatial distributions for the mean radiative forcing induced by dust at the top of the atmosphere, at the bottom of the atmosphere, and within the atmosphere over East Asia during the simulation period are shown in Figures 7~~5~~ and 8~~6~~. Note that all of the spatial distributions for radiative forcing shown in the two figures are the temporal mean over the entire simulation period. The SW radiative forcing was calculated as follows.

$$SW_{TOA} = SWDOWN_{TOA} - SWUP_{TOA} \tag{1}$$

$$SW_{BOT} = SWDOWN_{BOT} - SWUP_{BOT} \tag{2}$$

$$SW_{ATM} = SW_{TOA} + SW_{BOT} \tag{3}$$

where SW_{TOA} is the SW radiative forcing at the top of the atmosphere, and SW_{BOT} is the SW radiative forcing at the bottom of the atmosphere, both with positive values representing downwelling radiation; SW_{ATM} is the radiative forcing within the atmosphere, which is the sum of SW_{TOA} and SW_{BOT}, with positive values representing a net warming effect within the atmosphere; $SWDOWN_{TOA}$ and $SWUP_{TOA}$ are the downwelling and upwelling SW radiation at the top of the atmosphere, respectively; $SWUP_{BOT}$ and $SWDOWN_{BOT}$ are the upwelling and downwelling SW radiation at the bottom of the atmosphere, respectively.

The LW radiative forcing was calculated as follows.

$$LW_{TOA} = -LWUP_{TOA} \tag{4}$$

$$LW_{BOT} = LWDOWN_{BOT} - LWUP_{BOT} \tag{5}$$

$$LW_{ATM} = LW_{TOA} + LW_{BOT} \tag{6}$$

Where LW_{TOA} is the LW radiative forcing at the top of the atmosphere, and LW_{BOT} is the LW radiative forcing at the bottom of the atmosphere, both with positive values representing downwelling radiation; LW_{ATM} is the radiative forcing within the atmosphere, which is the sum of LW_{TOA} and LW_{BOT}, with positive values representing warming effect within the atmosphere; $LWUP_{TOA}$ is the upwelling LW radiation at the top of the atmosphere; $LWUP_{BOT}$ and $LWDOWN_{BOT}$ are the upwelling and downwelling LW radiation at the bottom of the atmosphere.

The net radiative forcing is the sum of SW and LW radiative forcing.

$$Ra_{TOA} = SW_{TOA} + LW_{TOA} \tag{7}$$

$$Ra_{BOT} = SW_{BOT} + LW_{BOT} \tag{8}$$

$$Ra_{ATM} = SW_{ATM} + LW_{ATM} \tag{9}$$

4.2~~1~~.1 Clear-sky radiative forcing

The ~~direct~~ radiative forcing induced by dust shown in Figure 7~~5~~ is also referred to as clear-sky radiative forcing, and is due to the reflection, absorption and emission of radiation by dust particles suspended in the atmosphere.

The clear-sky downwelling SW radiation ~~ve forcing~~ at the top of the atmosphere is slightly ~~negative~~ reduced over most land areas of East Asia (Figure 7~~5~~a), indicating that the upwelling SW radiation at the top of the atmosphere increases due to the reflection and scattering of SW radiation by dust particles. The clear-sky SW radiative forcing at the bottom of the atmosphere is negative over most of East Asia (Figure 7~~5~~g), especially over dust source regions, which suggests that the ~~downwelling SW radiation~~solar radiation that reaches the Earth's surface is ~~significantly~~ substantially reduced through the absorption by dust particles suspended in the atmosphere. The absorption of solar radiation by dust particles heats up the dust layers,~~,~~ leading~~ing~~ to a significant net warming effect within the atmosphere (Figure 7~~5~~d~~d~~). Averaged over the entire simulation domain, the SW radiative forcing over East Asia is -0.63~~-1.22~~ W/m^2 at the top of the atmosphere, -2.19~~44~~ W/m^2 at the bottom of the atmosphere, and 1.56~~23~~ W/m^2 within the atmosphere, accounting for 0.19~~37~~%, 0.87~~0.97~~%, and 1.98~~58~~% of the total clear-sky radiation budget in these three zones, respectively, as shown in Table 2.

In Figure 7~~5~~b, the clear-sky downwelling LW radiation at the top of the atmosphere is slightly increased over dust source regions and downstream~~wind~~ areas, due to the absorption of LW radiation by the thick dust layer with large fraction of coarse particles in the atmosphere. In comparison,~~, it is slightly reduced over other areas of East Asia, indicating an increase of the upwelling LW radiation, which might be attributable to the greater emission of LW radiation by the dust layer, which in turn is due to the heating of the atmosphere caused by the absorption of SW radiation by dust particles (Figure 5d).~~ t~~T~~he clear-sky downwelling LW radiation ~~forcing~~ is reduced at the bottom of the atmosphere (Figure 7~~5~~h), which is attributed to the Earth's surface being cooled~~r~~ as it receives less solar radiation (Figure 7~~5~~g). Combining the LW radiative forcing at the top of the atmosphere and at the bottom of the atmosphere, there is a net negative LW radiative forcing within the atmosphere (Figure 7~~5~~e). Overall, the mean LW radiative forcing averaged over the entire East Asia is relatively slight, being 0.18~~-0.02~~ W/m^2 at the top of the atmosphere, 1.44~~09~~ W/m^2 at the bottom of the atmosphere, and -1.94~~07~~ W/m^2 within the atmosphere, accounting for 0.07~~1~~%, 1.57~~18~~%, and 0.74~~0.63~~% of the total clear-sky radiation budget in those three zones, respectively.

Combining the SW and LW radiative forcing, the net downwelling clear-sky radiation at the top of the atmosphere is reduced over most of East Asia (Figure 7~~5~~c). The downwelling clear-sky net radiation at the bottom of the atmosphere is also reduced over most part of East Asia, especially over dust source regions and downstream areas (Figure 7~~5~~i), leading to a net warming effect within the atmosphere (Figure 7~~5~~f), which is slightly smaller than the warming caused by SW radiative forcing (Figure 7~~5~~d). The net radiative forcing is -0.45~~1.20~~ W/m^2 at the top of the atmosphere, -0.75~~1.36~~ W/m^2 at the bottom of the atmosphere, and 0.30~~15~~ W/m^2 within the atmosphere, accounting for 0.67~~1.78~~%, 0.47~~85~~%, and 0.33~~16~~% of the total clear-sky radiation budget in those three zones.

4.2~~1~~.2 All-sky radiative forcing

The all-sky radiative forcing induced by dust shown in Figure 8~~6~~ is the total radiative forcing, including the radiative forcing directly induced by dust displayed in Figure 7~~5~~, and that induced by the cloud radiative effect enhanced by dust.

As SW radiation is not sensitive to ice crystals in the atmosphere, ~~In Figure 6a, t~~the all-sky downwelling SW radiation shows a smaller reduction at the top (Figure 8a) and the bottom (Figure 8g) of the atmosphere over dust sources and downstream areas compared to the clear-sky case ~~is markedly reduced over most of China compared with the clear-sky case~~. The perturbations of all-sky SW radiation over southern part of the simulation domain and the Pacific Ocean in Figure 8a and g are likely due to the fluctuation of cloud cover~~, due to greater reflection from dust and enhanced cloud cover induced by dust over the continent~~. Similarly, ~~However, it is increased over the southern part of northwest Pacific, indicating less SW radiation is reflected back into space due to the cloud radiative effect, which implies less cloud cover induced by dust over this area.~~ the all-sky SW radiative radiation shows a warming effect within the atmosphere (Figure 8d), with an identical magnitude and spatial distribution to the ckear-sky case, as the warming is mostly attributed to the absorption of SW radiation by dust particles~~Compared with the clear-sky case, the all-sky upwelling SW radiation at the bottom of the atmosphere in Figure 6g is increased significantly over the continent, as more solar radiation is blocked due to the enhanced cloud cover induced by dust; however, the downwelling all-sky SW radiation at the bottom of the atmosphere is reduced over most of the West Pacific, indicating that more solar radiation that reaches the Earth's surface due to the cloud radiative effect, which also implies less cloud cover over this area. The cloud radiative effect strengthens the warming within the atmosphere over land in the all-sky case compared with the clear-sky case, while there is a slight cooling over the ocean in the all-sky case, as shown in Figure~~

~~6d, in contrast to the slight warming in the clear-sky case~~. Averaged over the entire simulation domain, the mean SW radiative forcing is -~~7.81~~0.49 W/m^2 at the top of the atmosphere, and ~~-7.87~~-1.94 W/m^2 at the bottom of the atmosphere, and 1.44 W/m^2 within the atmosphere (Table 2), accounting for 0.17~~2.62~~%, 0.93%, and 1.81~~3.60~~% of the total all-sky radiation budget in the~~ose~~ three~~wo~~ zones, respectively. ~~Within the atmosphere, the positive SW radiative forcing over land and negative SW radiative forcing over the ocean balance each other out.~~

Compared to~~with~~ the clear-sky case, the ~~all-sky downwelling~~positive LW radiative forcing~~tion~~ at the top of the atmosphere ~~-~~is slightly~~ignificantly~~ increased over ~~almost the whole of East Asia~~dust sources and downstream land areas over East Asia (Figure 8~~6~~b), indicating ~~much~~ less upwelling LW radiation at the top of the atmosphere, which is likely caused by the combination of the lower surface temperature due to less solar radiation reaching the Earth's surface, and the absorption of LW radiation by more ice clouds induced by dust plumes over these areas. The absorption of the LW radiation by more ice clouds also leads to less cooling~~increase of downwelling all-sky LW radiation at the bottom of the atmosphere~~ within the atmosphere (Figure 8e) compared to the clear-sky case~~over land in Figure 6h is due to the greater emission of LW radiation by the warmer atmosphere, and the larger radiative forcing than that in the clear-sky case implies that the cloud cover is significantly increased over land due to dust. Conversely, there is no warming effect at the surface of the ocean, and the reduction in downwelling LW radiation over the ocean implies less cloud cover over the ocean. The combination of the direct radiative effect of dust and the cloud radiative effect enhanced by dust causes an overall increase of LW radiation within the atmosphere, leading to a warming effect, which is more pronounced over the ocean, as shown in Figure 6e~~. Moreover, a greater cloud amount results in an increase of surface temperature, leading to more upwelling LW radiation emitted by the surface, and thus a smaller positive LW radiative forcing at the bottom of the atmosphere (Figure 8h). As shown in Table 2, t~~T~~he mean all-sky LW radiative forcing over the entire simulation domain is 0.31~~9.52~~ W/m^2 at the top of the atmosphere, 1.19 W/m^2 at the bottom of the atmosphere, and -1.26 W/m^2 within the atmosphere, accounting for 0.07%, 1.57%, and 0.74% of the total all-sky radiation budget in the three zones, respectively~~accounting for 3.79% of the total all-sky LW radiation budget in that zone~~. ~~The increase of the all-sky LW radiation at the bottom of the at atmosphere over land and its reduction over the ocean almost cancel each other out, leaving a mean all-sky LW radiation over the entire simulation domain of 0.25W/m^2, accounting for 0.34% of the total LW radiation budget at the bottom of the atmosphere. The mean all-sky LW radiative forcing within the atmosphere over the simulation domain is 9.26 W/m^2, accounting for 5.25% of the total all-sky LW radiation budget within the atmosphere.~~

Summing the SW and LW radiative forcing, the net downwelling all-sky radiation at the top of the atmosphere is generally increased over dust sources, whereas reduced ~~to the north of Central China, Korea, and Japan, and increased significantly over most of the ocean~~over the downstream land areas (Figure 8~~6~~c). By contrast, the net downwelling all-sky net radiation at the bottom of the atmosphere is reduced significantly over ~~the same land areas, and increased over most of the ocean~~most land areas over East Asia (Figure 8~~6~~i). Radiative forcing results in pronounced warming within the atmosphere over East Asia as a whole (Figure 8~~6~~f). Averaged over the simulation domain, the net all-sky radiative forcing is ~~1.70~~-0.18 W/m^2, ~~-7.62~~0.75 W/m^2, and 0.57~~9.33~~ W/m^2 at the top of the atmosphere, at the bottom of the atmosphere, and within the atmosphere during the simulation period, accounting for ~~3.61~~0.38%, 0.56~~5.28~~%, and 0.66~~9.61~~% of the total net radiation budget in those three zones, respectively.

In summary, the direct radiative effect of dust combined with the cloud radiative effect enhanced by dust generally causes a net loss of radiation at the Earth's surface, but a net gain ~~of radiation~~ within the atmosphere, leading to a cooling at the surface and lower troposphere, and a warming in mid- to upper troposphere. Nevertheless, as ice clouds enhanced by dust are thin clouds, which contributes little to the modifications of both LW and SW radiations, the radiative forcing induced by the indirect effects of dust is much less significant than that by the direct radiative effect of dust, therefore, the dust-induced radiative forcing over East Asia is dominated by the direct radiative effect of dust.~~The radiative forcing caused by the dust-enhanced cloud radiative effect is much greater than that caused by the direct radiative effect of dust, especially for LW radiative forcing, which is highly affected by cloud cover . The LW radiative forcing caused by the dust-enhanced cloud radiative effect is one order stronger than that cased by the direct radiative effect of dust at the top of the atmosphere and within the atmosphere. The spatial distribution of radiative forcing further implies a shift of the spatial distribution of cloud cover, such that the cloud cover is likely increased over land, but reduced over the ocean due to the presence of dust, indicating a re-distribution of atmospheric water vapor over East Asia. The shift of the vertical distribution of the radiation budget, the re-distribution of atmospheric water vapor, and the modification of atmospheric stability resulting from those two processes will be discussed in more detail in later sections~~However, the perturbation of the radiation budget, especially over south part of the simulation domain and the Pacific Ocean, is likely due to the fluctuation of the liquid cloud amount. On average, the radiative effect caused by the increase of ice clouds compensates with that resulted from the decrease of liquid clouds, leaving comparable modifications of the net radiative forcing in the clear-sky case and the all-sky case.

4.3 Vertical temperature profile

Due to the radiative forcing ~~directly~~ induced by the effects of dust ~~discussed in Section 4.1.1, and the cloud radiative effect enhanced by dust discussed in Section 4.1.2~~, the vertical temperature profile is modified. Figure 9~~10~~ shows the modifications of the vertical temperature profiles ~~induced~~ resulted from~~by~~ the direct radiative effect of dust, the cloud radiative effect enhanced by dust, and the full radiative effect of dust over ~~the whole of~~ East Asia, over land, and over the ocean during the investigated period.

On average, the temperature over the simulation domain as a whole is ~~slightly increased~~decreased ~~in the near-surface atmosphere~~below 2 km, increased~~decreased~~ from ~~1~~ 2 km to 7~~3~~ km, ~~increased significantly from 1 km up to 13 km,~~ and then decreased above 7~~13~~ km (Figure 9~~10~~a). The contributions of the direct radiative effect of dust and dust-enhanced cloud radiative effect to the vertical temperature modification are shown in Figure 9~~10~~b and c. The direct radiative effect of dust (Figure 9~~10~~b) results in a decrease of temperature ~~at the near-surface layer~~below 3 km, and an increase ~~above~~ from 3~~1~~ km to 14 km. In contrast, the pattern of the vertical temperature modification caused by dust-enhanced cloud radiative effect (Figure 9~~10~~c) is ~~similar~~ opposite to that caused by the ~~full~~ direct effect of dust~~, and is one order of magnitude larger magnitude than that caused by the direct radiative effect of dust~~. The temperature is increased from surface to 3 km, and then decreased from 3 km to 15 km.

As the radiative forcing induced by dust over land differs from that over the ocean, the effects on the vertical temperature profile requires further discussion. The ~~decrease in temperature at the lower level of the troposphere mainly occurs over land. The temperature over land decreases significantly below 2 km, then increases gradually from 2 km to 12 km, and decreases again over 12 km~~modifications of vertical temperature profile over land induced by the full effects (Figure 6d), direct effect (Figure 6e) and indirect effects (Figure 6f) of dust exhibit similar distributions to those over the entire domain, but with larger magnitudes ~~(Figure 10d)~~. The decrease in temperature at the lower level is composed of roughly equal contributions from the direct radiative effect and the dust-enhanced cloud radiative effect. ~~However, the increase in the temperature between 2 km and 12 km is mainly attributable to the dust-enhanced cloud radiative effect (Figure 10f), the contribution of which is one order larger than that of the direct radiative effect of dust (Figure 10e).~~ The decrease in temperature at lower layers is mainly attributable to the negative SW radiative forcing at the surface induced by dust, and the increase of temperature at the mid ~~- to upper~~ troposphere is due to the absorption of ~~LW~~ SW radiation by ~~dust-enhanced ice clouds~~dust plumes, and the decrease of temperature at the upper troposphere might be due to that the enhancement of ice clouds in mid- to upper troposphere prevents the upwelling

LW radiation being absorbed by those ice clouds at higher altitudes.

The modification of the vertical temperature profile over the ocean is ~~similar to~~different from that over ~~East Asia as a whole~~land. The temperature is increased from surface to mid-troposphere~~, especially at lower layers from the surface to 3 km, with an increase in temperature at the near-surface below 2 km, and a decrease in temperature from 1 km to 3 km~~ (Figure 9~~10~~g), which is contributed by two factors. One is the increase of temperature at lower layers (Figure 9i) attributed to more absorption of LW radiation and latent heat released by the enhancement of low clouds. The other is the increase of temperature at mid-troposphere (Figure 9h) caused by the absorption of SW radiation by dust plumes~~.~~ ~~The direct radiative effect of dust results in a slight decrease in temperature at the surface and at altitudes from 7 km to 9 km, but a slight increase from 1 km to 7 km and above 10 km (Figure 10h). The dust-enhanced cloud radiative effect causes an overall increase in temperature from the surface to 13 km, with a minor peak at an altitude of 1 km and a major peak at an altitude of 11 km (Figure 10i). The modification of the vertical temperature profile over the ocean is mostly contributed by the dust-enhanced cloud radiative effect over the ocean, with an almost identical pattern and magnitude to the temperature variation over East Asia as a whole (Figure 10i)~~.

4.4 Atmospheric stability

As discussed above, the radiative forcing and the re-distribution of atmospheric water content induced by dust result in a modification of the vertical temperature profile over East Asia. The corresponding shift of the thermal energy in the atmosphere eventually lead to a modification of the atmospheric stability over this region.

The K-index (*KI*) is a metric widely used in meteorology to evaluate atmospheric stability, and is calculated with the following equation (George, 2014):

$$KI = T_{850} - T_{500} + Td_{850} - (T_{700} - Td_{700}) \tag{10}$$

where T_{850}, T_{700}, and T_{500} are the respective temperatures at 850 hPa, 700 hPa, and 500 hPa, and Td_{850} and Td_{700} are the dew points at 850 hPa and 700 hPa. The calculation of *KI* considers the atmospheric stability as a function of the vertical temperature lapse rate, the moisture content of the lower atmosphere, and the vertical extent of the moist layer. The larger the value of *KI*, the more unstable the atmosphere. To evaluate the effect of dust on atmospheric stability, *KI* was calculated from the simulation outputs.

Figure 10~~1~~ shows the spatial distributions for the mean *KI* from NO-DUST/CLOUD over East Asia during the simulation period, which represents the intrinsic average atmospheric stability free from the effects of dust, and Figure

11~~2~~ shows the spatial distributions for the mean difference in *KI* between DUST/NO-CLOUD and NO-DUST/NO-CLOUD (Figure 11~~2~~a), between DUST/CLOUD and NO-DUST/CLOUD (Figure 11~~2~~b), and between DUST/CLOUD and NO-DUST/ CLOUD (Figure 11~~2~~c). The differences represent the modification in *KI* induced by the direct radiative effect of dust in Figure 11~~2~~a;~~,~~ the ~~semi-direct and~~ indirect effects, including cloud radiative effects and re-distribution of atmospheric water content enhanced by dust, in Figure 11~~2~~b;~~,~~ ~~and~~ as well as the combined effects of the previous two in Figure 11~~2~~c.

As shown in Figure 10~~1~~, the mean *KI* over East Asia is lower in the north and increases gradually from north to south, with the highest values located over the South China Sea and Southeast Asia, and the lowest values over the Central to North Pacific.

~~Under the full effects of dust, the mean modification of *KI* over most land areas in East Asia is a significant decrease. The largest decrease occurs over the dust source regions and central to East China (Figure 12c), and results from the vertical modification over land. In contrast, *KI* significantly increases over most areas of the ocean and South China, due to the different effects of dust on the vertical temperature over these areas, as discussed in Section 4.3.~~ The contributions of the direct radiative effect of dust and the indirect effects of dust on the modification of the mean *KI* are shown in Figure 11a~~12a~~ and ~~and~~ b. The direct radiative effect of dust is to inhibit the atmospheric instability is inhibited over most land areas, indicated by a ~~significant~~ decrease of the mean *KI*, as shown in Figure 11~~2~~a. However, the indirect effects of dust result in an opposite ~~overall~~ modification of mean *KI*, with a slight enhancement of mean *KI* over most areas of the investigated domain ~~is even greater over the ocean when the semi-direct and indirect effects of dust are taken into account~~. Upon considering the ~~semi-direct and indirect~~full effects of dust, the mean modification of *KI* over most land areas in East Asia is a general decrease (Figure 11c). The largest decrease occurs over the dust source regions and central to East China, and results from the vertical modification over land. In contrast, *KI* increases over South China and most Southern part of the, due to the different effects of dust on the vertical temperature over these areas. ~~the modification of *KI* is much greater over areas with more water vapor in the simulation domain, such as South China and most ocean areas, as shown in Figure 12b.~~

Overall, the atmosphere is ~~significantly~~ stabilized over the dust source regions and central to East China, but ~~significantly~~ destabilized over South China and most ocean areas, due to the effects of dust. ~~The dust-enhanced cloud radiative forcing and the re-distribution of atmospheric water content due to dust contribute much more to the modification of atmospheric stability than the direct radiative effect of dust does, especially over areas with abundant~~

~~water vapor.~~

4.5 Precipitation

The modification of atmospheric stability and the re-distribution of atmospheric water content induced by dust eventually alter the precipitation over East Asia. The spatial distributions for the mean precipitation rate, including total precipitation, convective precipitation, and non-convective precipitation from NO-DUST/CLOUD and DUST/CLOUD, as well as the difference between the two simulations, are shown in Figure 12~~3~~. Note that the precipitation rate shown in Figure 12~~4~~ is the mean daily precipitation rate averaged over the simulation period.

The spatial pattern of the mean total precipitation rate from NO-DUST/CLOUD shown in Figure 12a~~13a~~ is generally similar to that from DUST/CLOUD shown in Figure 12~~3~~b. However, Figure 12c shows clearly that the precipitation is modified due to the effects of dust, leading to an overall reduction of the total precipitation being reduced by as much as 1 mm/day or more to the east of Central to South China, where the main precipitation area is located, while an increase by up to 1 mm/day to the west. ~~as discussed in Section 3.2.2, the simulated precipitation center produced in NO-DUST/NO-CLOUD spans an area from Hunan to Jiangxi (Figure 13a), to the north of the observed precipitation, and~~Meanwhile, ~~the simulated precipitation rate over South China is significantly lower than the observational values. By contrast, in DUST/CLOUD (Figure 13b), the precipitation band from Hunan to Jiangxi is markedly inhibited, while~~ the precipitation rate over South China is slightly enhanced~~, which is clearly more consistent with the observations~~. ~~As shown in Figure 13c, the total precipitation is reduced by as much as 1 mm/day or more over most land areas, but increased by up to 1 mm/day over South China, due to the effects of dust.~~ The modifications of~~in~~ precipitation account for ~~over~~ up to 20% of the total simulated precipitation rate over ~~both land and the ocean~~land areas in the simulation domain.

The simulated convective precipitation mostly occurs over the southern part of the simulation domain, with precipitation centers located over East and ~~central to East China,~~ South China, the South China Sea, and Southeast Asia (Figure 12~~3~~d and e). ~~The total precipitation over these areas is chiefly affected by the modification of convective precipitation.~~ Due to the effects of dust, convective precipitation is ~~significantly reduced~~enhanced ~~at the precipitation center from central to East China~~over South China, but ~~substantially enhanced~~inhibited over East China ~~over South China and the ocean~~ (Figure 12~~3~~f). The inhibition of convective precipitation over Central to East China ~~has two reasons. One is the~~is likely due to the general enhancement of atmospheric stability, which reduces the convective motion over this region. ~~The other is the decrease in low clouds over South China and the ocean, which reduces the~~ atmosphere, which promotes convective motions.

~~The simulated non-convective precipitation is produced by the microphysics scheme.~~ The Non-convective precipitation mainly occurs at the western rim of the Taklimakan Desert, northeast China, Japan, and the areas between 27°N and 36°N over East Asia during the simulation period. The spatial distribution of the non-convective precipitation rate produced in DUST/CLOUD (Figure 12~~3~~h) is ~~markedly lower than~~similar to that produced in NO-DUST/CLOUD (Figure 12~~3~~g)~~ at the northern precipitation centers~~. However, F~~F~~igure 12~~3~~i shows that the non-convective precipitation rate is ~~reduced~~ modified upon considering the effects of dust. The non-convective precipitation band over Central China exhibits a shift of location, with less precipitation to the east and west, while more in the middle. This is likely due to the modification of liquid clouds over the same area, with less clouds to the east and west, while more in the middle (Figure 5f). Similarly, the enhancement or inhibition of the non-convective precipitation over South to East China is also related with the perturbation of the cloud amount over these areas. On average, the amount of non-convective precipitation is increased or decreased by ~~more than~~up to 2~~3~~0% at the ~~western of the Taklimakan Desert and in the rain band from East China to Japan~~main precipitation regions.

To summarize, the total amount of the precipitation over the entire investigated domain remains the same by taking the effects of dust into account, however, the locations of the precipitation might be shifted, the precipitation can be enhanced or inhibited by up to 20% over regions with relatively abundant precipitation during the investigated period, such as Central to East China, as well as South China.~~More super-cooled water droplets can freeze into ice crystals in the upper troposphere due to the abundant IN served by dust particles, leading to much lower atmospheric cloud water content and cloud droplet number concentration directly above the non-convective precipitation center. Furthermore, the warming within the atmosphere, which is caused by radiative forcing and latent heat released by the freezing of super-cooled water droplets, results in a higher saturation pressure for water vapor and faster evaporation rate for cloud droplets. This, in turn, suppresses the growth of cloud droplets into rain droplets, leading to an inhibition of non-convective precipitation. Conversely, the increase in cloud ice in some cases leads to more precipitation. The ice crystals in mixed-phase clouds can grow large enough to induce precipitation given sufficient water vapor in the atmosphere. An example is the enhancement of non-convective precipitation over the East China Sea.~~

5 Conclusions

By applying the updated WRF-Chem, which is capable of evaluating indirect effects of dust along with the direct ~~and semi-direct~~ effect in dust simulations, the full effects of dust, including direct radiative, cloud radiative, and indirect microphysical effects, on the meteorological field over East Asia during March and April 2012 were quantified and discussed.

By considering the effects of dust in the simulation, t~~T~~he atmospheric ~~ice water path~~IWP ~~and ice crystal number density are~~is substantially~~ignificantly~~ increased from West China to Northwest Pacific Ocean~~over East Asia,~~ ~~when~~which are the dust sources and their downstream areas with abundant dust particles ~~are~~ available to serve as IN. By contrast, the atmospheric ~~cloud water path~~CWP ~~and cloud droplet number density~~ is~~are~~ generally ~~substantially~~ reduced over the same areas, while shows perturbations over the rest of areas in East Asia. Vertically, the effects of dust result in a general increase of cloud ice and decrease of cloud water over East Asia as a whole, whereby the increase of ~~cloud ice~~ice clouds is mainly concentrated at the mid- to upper troposphere, while the decrease of~~in cloud water~~liquid clouds mostly occurs at~~in~~ low- to mid-troposphere~~ clouds~~. The increase of ice~~in~~ clouds ~~at the mid- to upper troposphere~~ is due to the ~~indirect effect~~enhancement of ice nucleation process with abundant~~of~~ dust ~~by~~particles serving as IN. The reduction in ~~low~~liquid clouds is attributed to two factors. One is the ~~semi-direct~~burning effect of dust. Dust particles within clouds absorb radiation and warm up the surrounding environment, leading to a much greater saturation pressure required for atmospheric water vapor to form clouds, and a much faster evaporation rate of cloud droplets. The other factor is that the ice nucleation process enhanced by dust facilitates the freezing of atmospheric super-cooled water droplets into ice crystals.

For the radiative forcing induced by dust, the direct radiative effect of dust combined with the dust-enhanced cloud radiative effect causes a net loss of radiation at the Earth's surface, but a net gain of radiation within the atmosphere, leading to cooling at the surface and lower troposphere, and warming in the mid- to upper troposphere. The radiative forcing caused by the direct radiative effect of dust is greater than that induced by the dust-enhanced cloud radiative effect~~-~~ over land areas, as the thin ice clouds enhanced by dust particles have limited impacts on altering the radiation budget~~is much greater than that caused by the direct radiative effect of dust, especially for LW radiative forcing, which is highly affected by cloud cover.~~. ~~The LW radiative forcing caused by the dust-enhanced cloud radiative effect is one order stronger than that cased by the direct radiative effect of dust at the top of the atmosphere and within the atmosphere. The spatial distribution of radiative forcing further implies a shift of the spatial distribution of cloud cover, such that the cloud cover is likely increased over land, but reduced over the ocean, due to the presence of dust,~~

~~indicating a re-distribution of atmospheric water vapor over East Asia.~~

The ~~radiative forcing and~~ re-distribution of atmospheric water vapor and radiative forcing induced by dust lead to a modification of the vertical temperature profile. Consequently, the atmosphere is stabilized over most land areas, but destabilized over ~~most of the ocean~~South China and most oceanic areas ~~in East Asia~~. ~~The cloud radiative forcing enhanced by dust and the re-distribution of atmospheric water content due to dust contribute much more to the modification of atmospheric stability than the direct radiative effect of dust does.~~

Convective precipitation is inhibited over ~~most land areas in East Asia~~South China~~, because of~~ due the enhanced atmospheric stability, ~~and the reduction in cloud droplets capable of growing into rain droplets under atmospheric conditions~~ while enhanced over Central China, resulted from the more unstable atmosphere. ~~Conversely, convective precipitation is enhanced over South China and the ocean due to the greater atmospheric instability over these areas.~~ The modification of cloud amount results in a shift of locations of the non-convective precipitation over China. On average, the total amount of the precipitation over the entire investigated domain remains the same by taking the effects of dust into account, however, the locations of the precipitation might be shifted, the precipitation can be enhanced or inhibited by up to 20% over particular regions with relatively abundant precipitation during the investigated period.~~The presence of much fewer cloud droplets in the atmosphere, combined with the atmospheric warming caused by radiative forcing and the release of latent heat by the freezing of super-cooled water droplets, results in a higher saturation pressure for water vapor and faster evaporation rate for cloud droplets, which in turn inhibit non-convective precipitation. The decrease in convective and non-convective precipitation results in a reduction of total precipitation over East Asia. Nevertheless, the increase of cloud ice also leads to more precipitation in some cases. The ice crystals in mixed-phase clouds can grow large enough to induce a precipitation given sufficient atmospheric water vapor.~~

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818 **Table 1:** Model configurations for the numerical simulations.

Scheme \ Experiment	**NO-DUST/NO-CLOUD**	**NO-DUST/CLOUD**	**DUST/NO-CLOUD**	**DUST/CLOUD**
Dust emission scheme	----	----	Shao	Shao
Dry deposition	----	----	Gravitational settling/surface deposition	Gravitational settling/surface deposition
Wet deposition	----	----	In-cloud and below-cloud	In-cloud and below-cloud
Aerosol optical scheme	----	----	Maxwell-Garnett	Maxwell-Garnett
Aerosol radiative feedback	off	off	on	on
Cloud radiative feedback	off	on	off	on

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Table 2: WRF-Chem-simulated SW, LW, and net radiative forcing (W/m^2) induced by dust over East Asia at TOA, BOT, and ATM.

	Clear-sky			**All-sky**		
	SW	LW	Net	SW	LW	Net
TOA (+down)	-0.63	0.18	-0.45	-0.49	0.31	-0.18
ATM (+warm)	1.56	-1.26	0.30	1.44	-0.88	0.57
BOT (+down)	-2.19	1.44	-0.75	-1.94	1.19	-0.75

SW: short-wave radiative forcing; LW: long-wave radiative forcing; Net: net radiative forcing.
TOA: radiative forcing at the top of the atmosphere; ATM: radiative effect within the atmosphere; BOT: radiative effect at the bottom of the atmosphere.

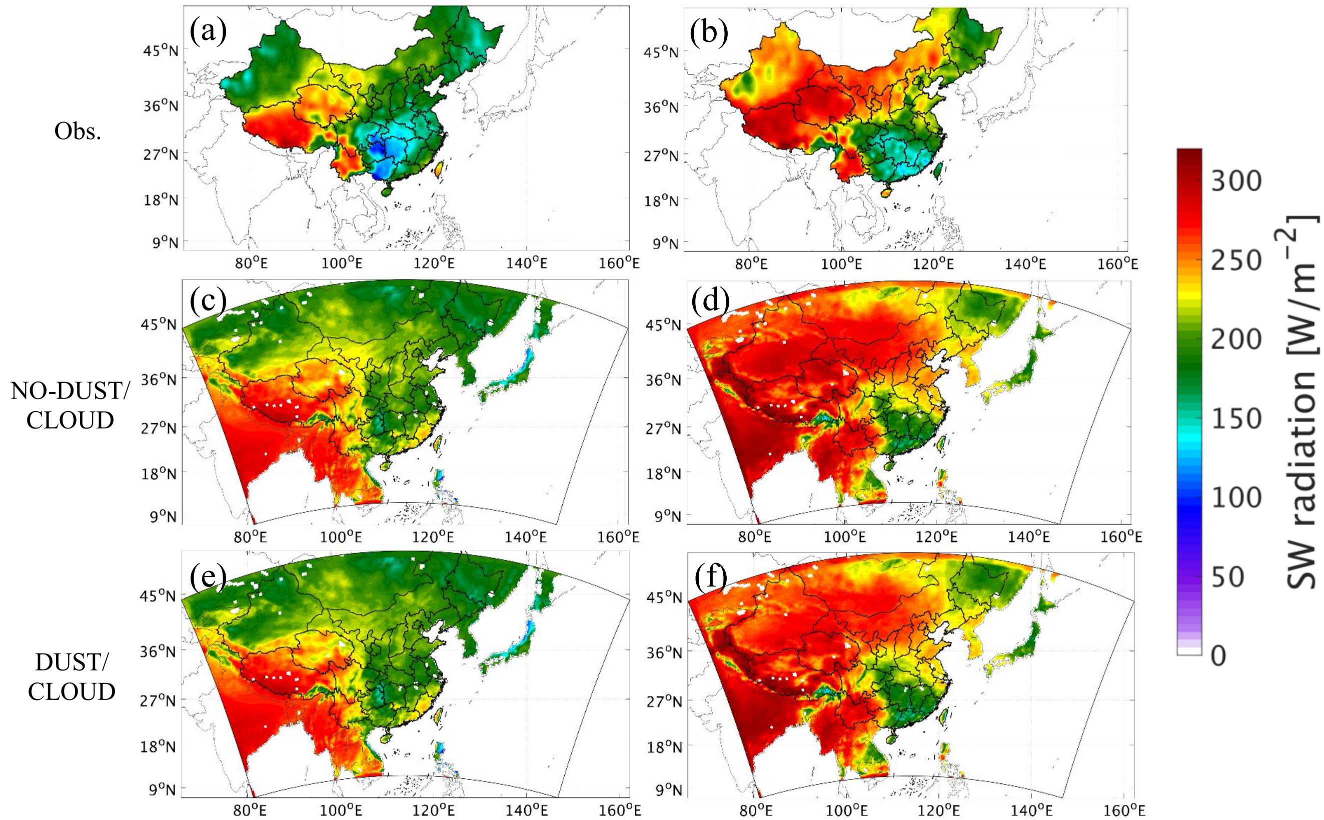


Figure 1: Spatial distributions of the average downward SW radiation at surface from observations (a, b), from NO-DUST/CLOUD (c, d), and from DUST-CLOUD (e, f) during March (left panel) and April (right panel) 2012.

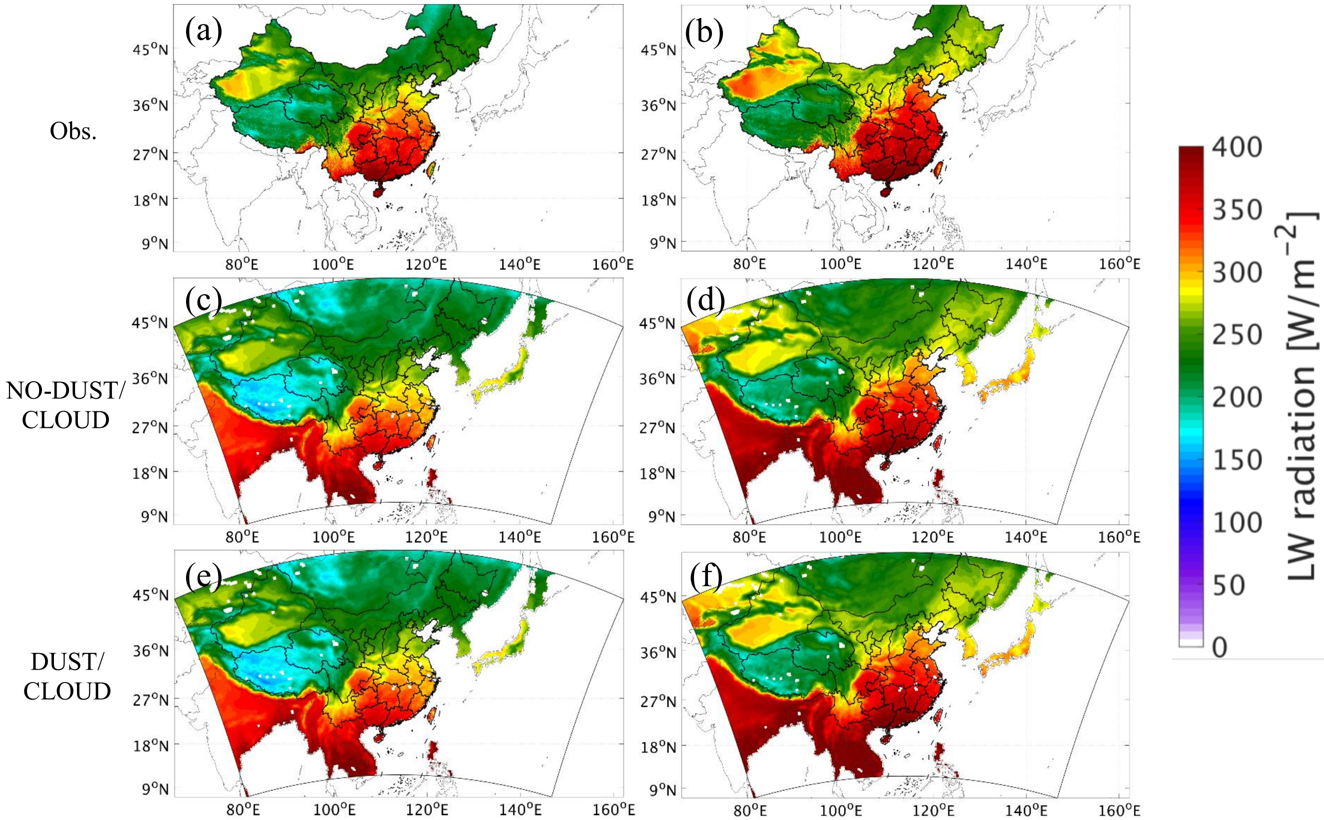


Figure 2: Spatial distributions of the average downward LW radiation at surface from observations (a, b), from NO-DUST/CLOUD (c, d), and from DUST-CLOUD (e, f) during March (left panel) and April (right panel) 2012.

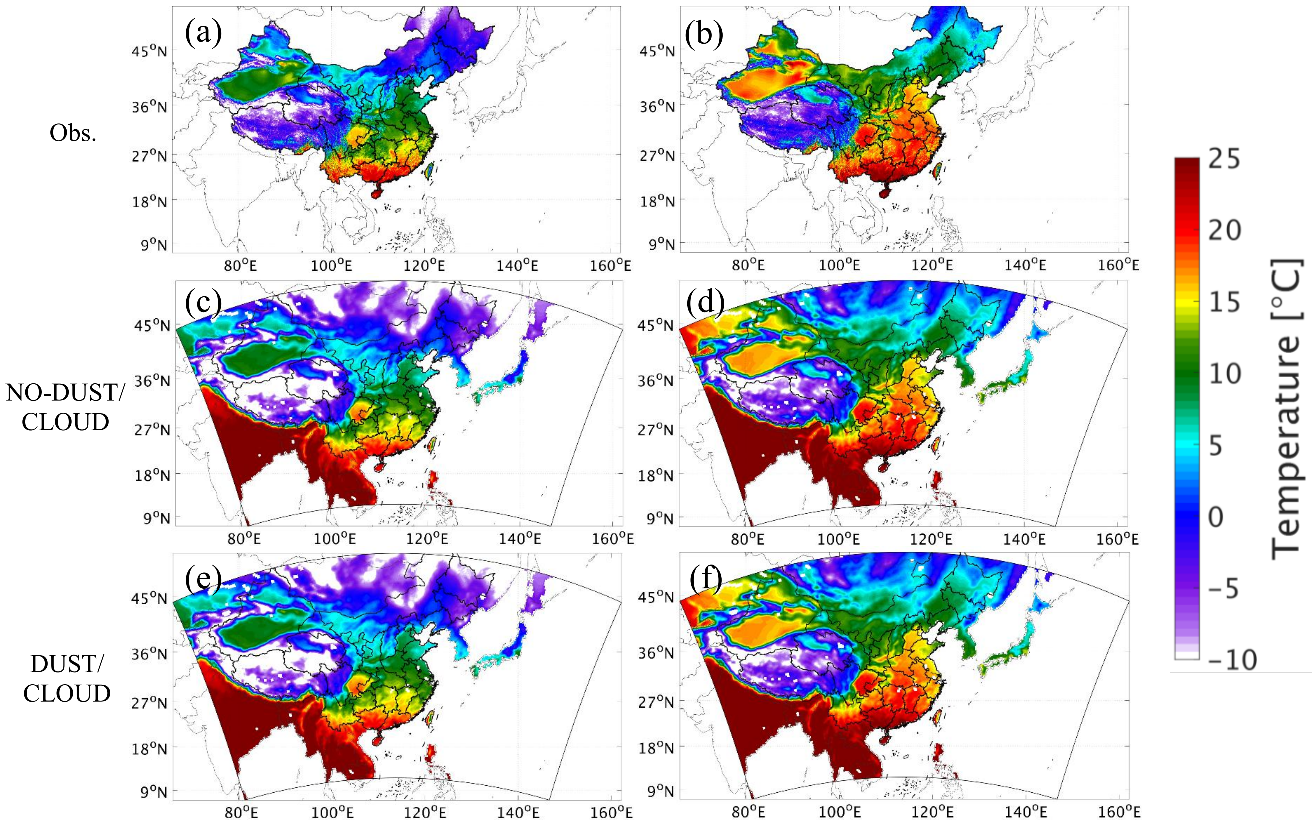


Figure 3: Spatial distributions of the average near-surface temperature from observations (a, b), from NO-DUST/CLOUD (c, d), and from DUST-CLOUD (e, f) during March (left panel) and April (right panel) 2012.

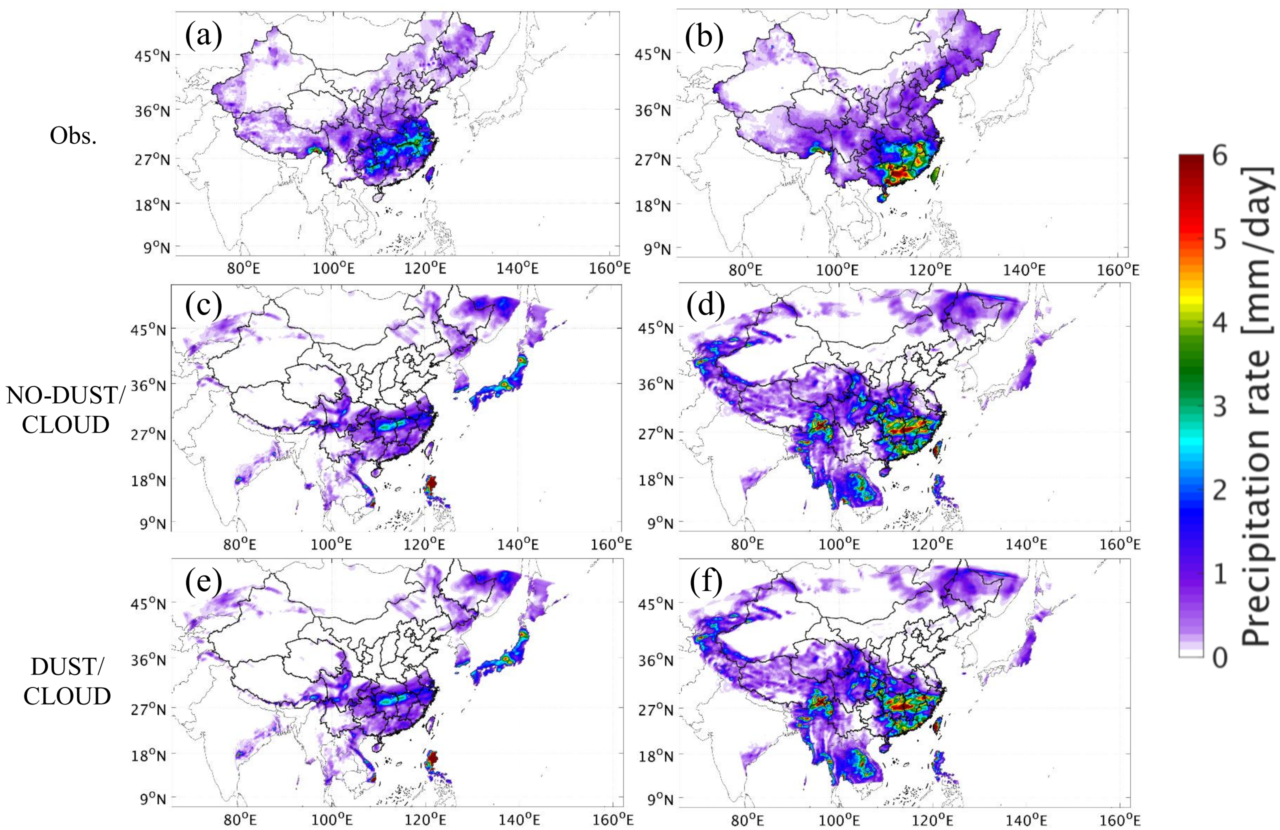
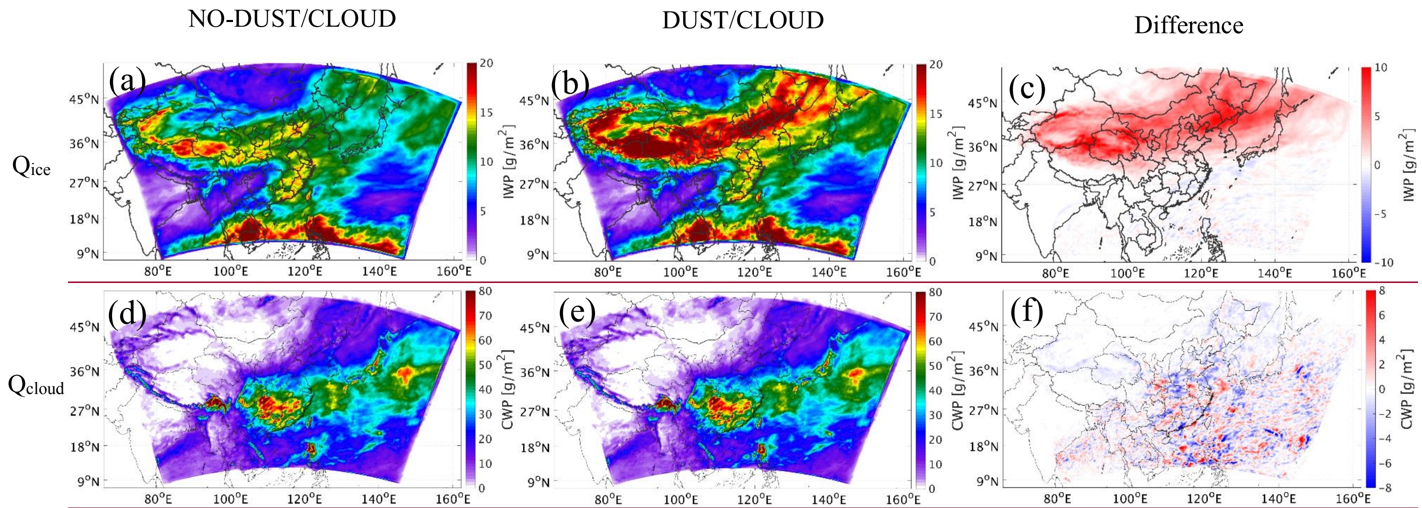


Figure 4: Spatial distributions of the average precipitation rate from observations (a, b), from NO-DUST/CLOUD (c, d), and from DUST/CLOUD (e, f) during March (left panel) and April (right panel) 2012.



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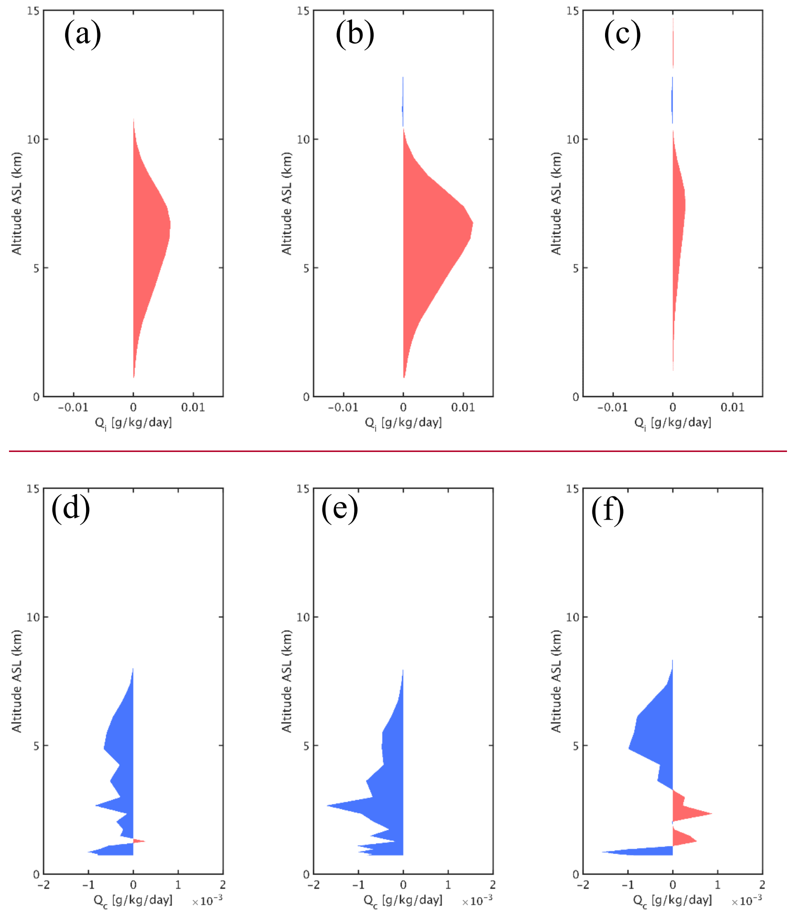

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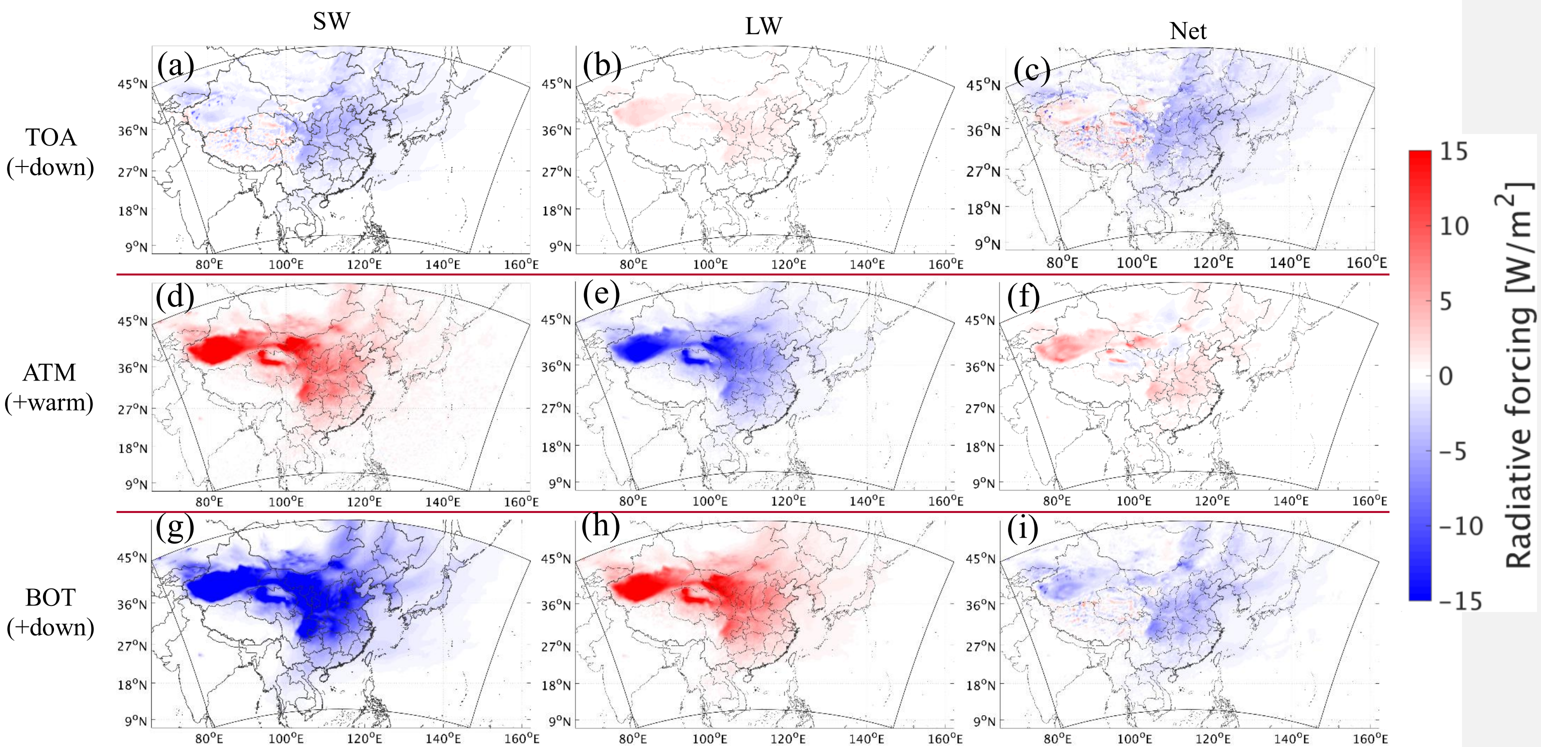

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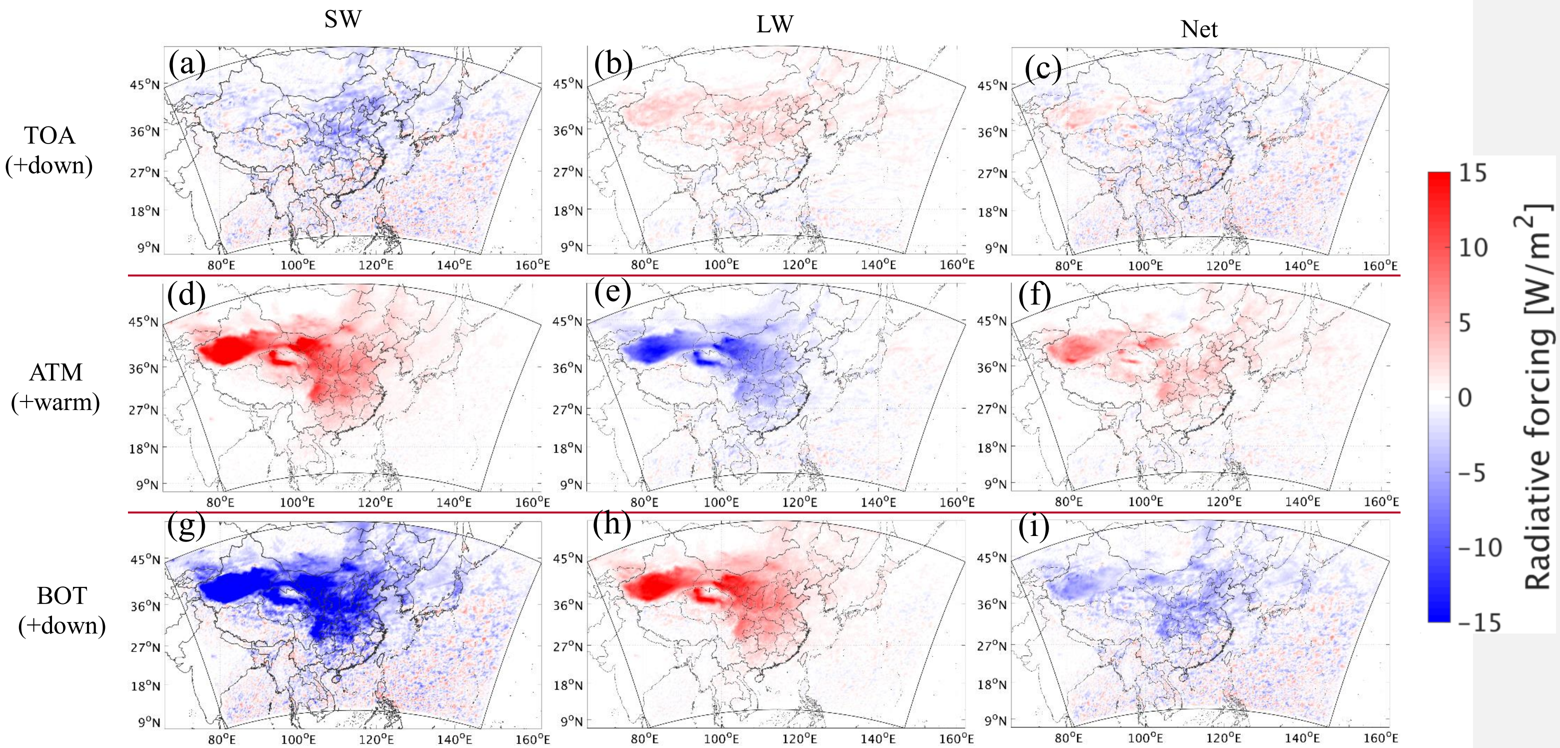

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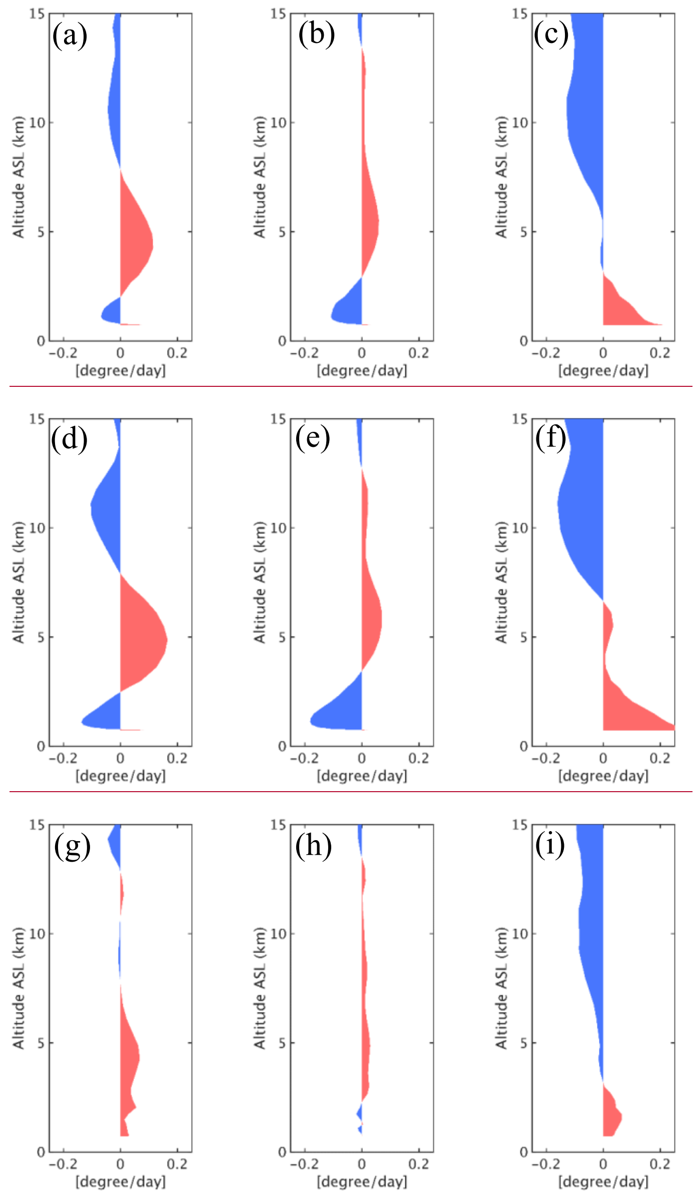

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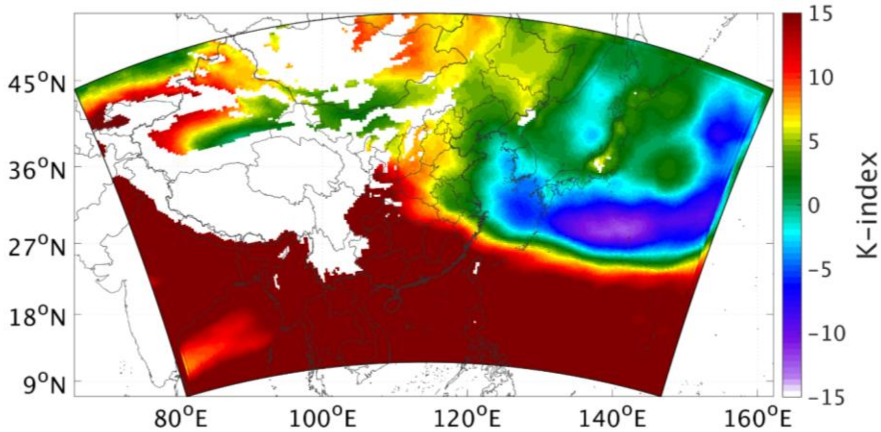

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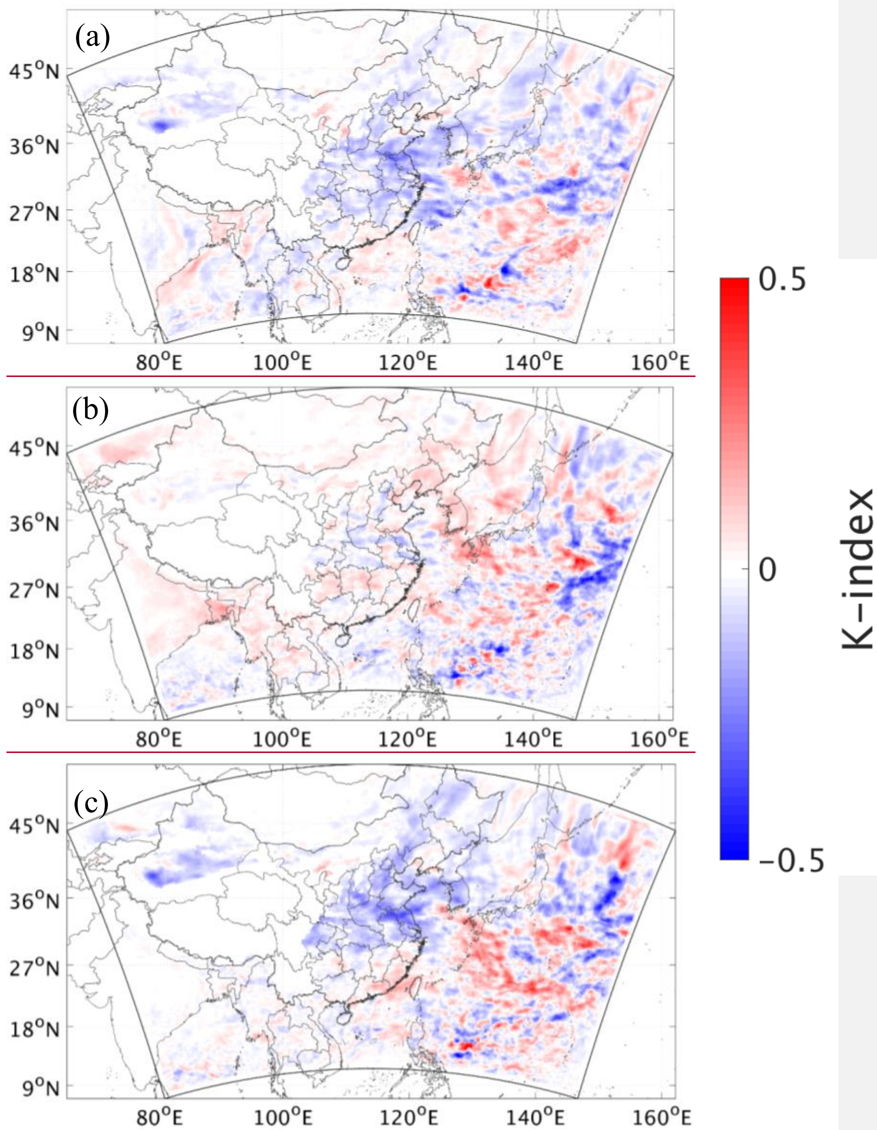

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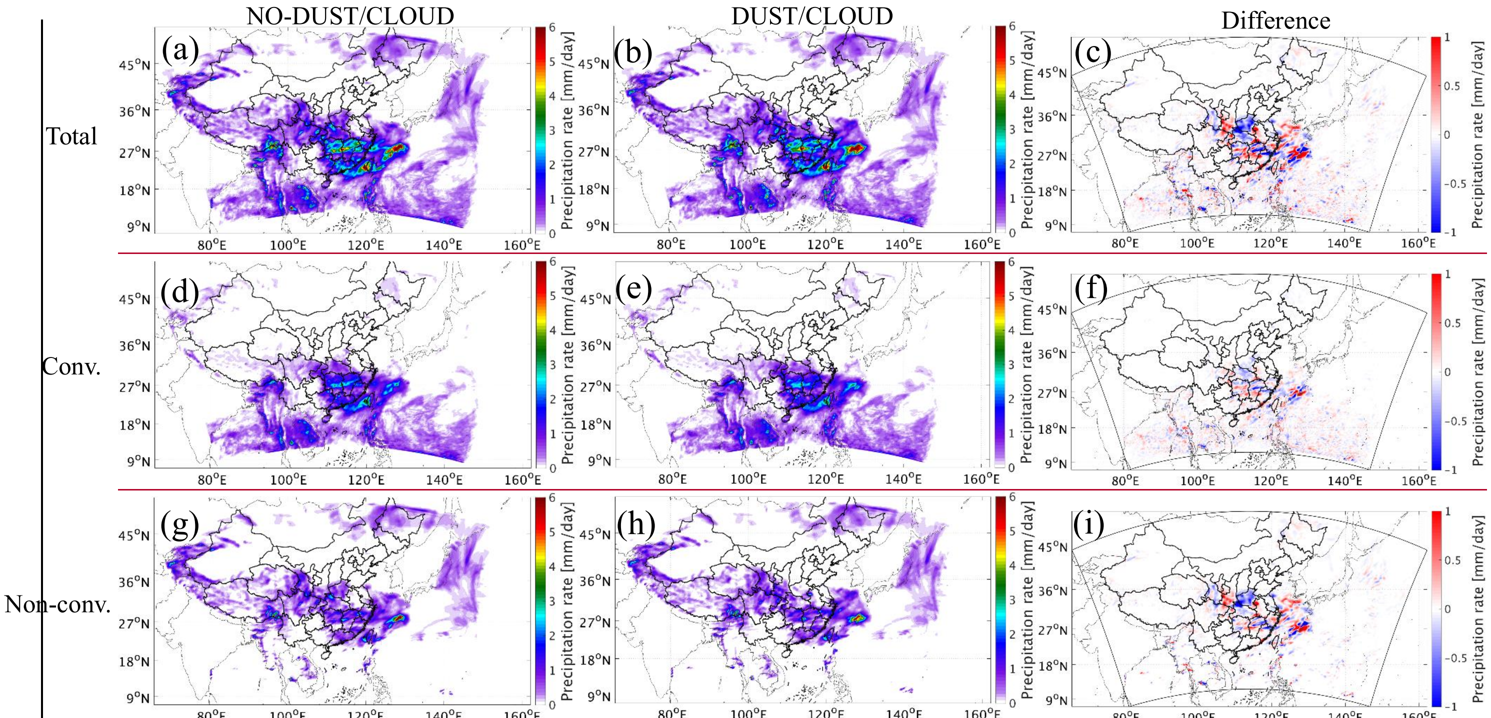

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