Research Article

Numerical Modeling of Topography-Modulated Dust Aerosol Distribution and Its Influence on the Onset of East Asian Summer Monsoon

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A regional climate model coupled with a dust module was used to simulate dust aerosol distribution and its effects on the atmospheric heat source over the TP, East Asian summer monsoon onset, and precipitation in East Asia modulated by the uplift of the northern TP. We carried out four experiments, including a modern (i.e., high-mountain) experiment with (HMD) and without (HM) the major deserts in Northwest China and a low-mountain experiment with (LMD) and without (LM) the deserts. The results show that dust greatly increases in the Taklamakan Desert accompanied with the uplift of the northern TP, and the increase exceeds $150 \mu\text{g kg}^{-1}$ in spring. A strong cyclone in the Tarim Basin produced by the uplifted northern TP enhances dust emissions in the Taklamakan Desert in summer. Meanwhile, the dust loading over the TP also increases induced by the uplift of the northern TP, causing the heat source over the TP decreased. Under the condition of the northern TP uplift to present altitude, dust delays the East Asia summer monsoon onset by two pentads and one pentad, respectively, in the southern and northern monsoon regions and greatly suppresses precipitation in East Asia compared with results in the low terrain experiments.

1. Introduction

Dust aerosol receives much attention due to its substantial effects on the environment and climate [1]. It not only adversely affects air quality and endangers human health [2, 3] but also impacts biogeochemical cycles and ocean CO_2 uptake [4, 5]. Additionally, it can change regional and even global climate through modifying the radiation balance and cloud-precipitation physics [6–8].

Important progress focusing on the East Asian dust cycle, dust radiative effects, and its effects on the East Asian monsoon has been made recently using various global and regional climate models [9–16]. The distribution of dust aerosol can directly determine its induced climatic effects, and so some scientists have studied the impacts of various factors on the distribution of dust, including meteorological parameters [17], dust sources [18], and different underlying surfaces [19]. There are two large deserts located in East Asia: the Taklamakan Desert and the Gobi Desert [20].

The distribution of dust aerosol in Asia is closely related to the activity of strong dust storms which mainly occur in spring in East Asia [21–23].

Dust can influence the climate through direct and indirect effects [6–8]. Dust aerosol can change atmospheric temperatures via its direct radiative effects [24, 25] and, meanwhile, satellite observations show that the dust load over the Tibetan Plateau (TP) can be transported from the Taklamakan Desert [26], meaning that the heat source over the TP can be influenced by such dust radiative effects. Meanwhile, numerous studies have shown that variation in the heat source over the TP bears a close relationship with East Asian summer monsoon onset in late spring or early summer [27–29]. Previous research shows that aerosol can change the heat source over the TP and further influences the Asia summer monsoon [30]. Therefore, it is crucial to determine the distribution of dust over the TP, as it can indirectly impact upon East Asian summer monsoon onset through modifying the heat source over the TP.

On the other hand, the uplift of the TP, as one of the most important geological events in Cenozoic era, has had profound influences on the Asian and global climate and environment evolution in geological periods [31]. Presently, most studies show that the TP uplift is phased and process, and some researches show that the uplift of northern TP and its nearby mountains has mainly occurred since the Miocene [31]. Meanwhile, the major Asian inland deserts may form and develop with the northern TP uplifting.

Recently, Shi et al. [32] carried out a numerical simulation of the impacts of the uplifting of the TP on the dust cycle in Asia using a GCM, and their results showed that topography has a great effect on dust sedimentation in East Asia. Liu et al. [33], using the latest version of RegCM4.1/Dust, studied the impacts of the uplifting of the northern TP on regional climate, and their research indicated that uplift of the northern TP is closely related with inland desert formation. However, they did not analyze how the northern TP uplift modulates the distribution of dust in East Asia, nor did they discuss the effects of dust on the heat source over the TP and ultimately how it induces anomalies in East Asia summer monsoon onset.

In this paper, therefore, we conduct a set of sensitivity experiments under conditions of low and high orography in the northern TP using a regional climate model with and without the dust module to further discuss two main issues: (1) How does the northern TP modulate the dust distribution in East Asia? (2) What are the impacts of dust effects on the heat source over the TP and East Asia summer monsoon onset under different terrain settings? This study will help to deep explore the modulation of topography on dust-monsoon relationship and also to understand the paleoclimate change in East Asia.

2. Numerical Model and Experiment Design

2.1. Numerical Model. RegCM4.1/Dust is a hydrostatic, sigma vertical coordinate model, based on the major physical parameterizations of RegCM3 [34]. The dynamical framework in RegCM4.1/Dust is similar to the mesoscale model MM5 [35] and it adopts CCM3 [36] for atmospheric radiative transfer processes at solar (SW) and thermal (LW) wavelengths. In addition, the Biosphere-Atmosphere Transfer Scheme (BATS1e) [37] is coupled in the model to diagnose the land surface processes. The mass flux scheme of Grell et al. [38] and the subgrid explicit moisture scheme of Pal et al. [39] are used to describe cumulus convective precipitation and nonconvective precipitation, respectively.

The coupled dust module of RegCM4.1 based on the dust producing model of Marticorena and Bergametti [40] and Alfaro and Gomes [41], generally includes dust emission, transport, and deposition processes. Parameterization of the dust emission processes comprises four components [14, 42]. First, each model grid cell is classified either as desert or as nondesert and the soil characteristics including texture, particle size, and composition in each model grid cell are specified based on the USDA textural classification. Second, dust emission is represented as a function of a threshold value, surface roughness, and soil moisture. Third, horizontal

mass flux is represented as a function of friction velocity [42]. Finally the vertical flux corresponding to each emission mode is obtained. The dust particles in the dust module are divided to four size bins (or modes): the fine (0.01–1.0 μm), accumulation (1.0–2.5 μm), coarse (2.5–5 μm), and giant (5.0–20.0 μm). Dust transport, deposition, and removal processes are given by Solmon et al. [43], Qian et al. [44], and Qian and Giorgi [45]. The dust mixing ratio is represented by the tracer transport equation:

$$\frac{\partial \chi^i}{\partial t} = -\bar{V} \cdot \nabla \chi^i + F_H^i + F_V^i + F_c^i + S^i - R_{Wls}^i - R_{Wc}^i - D_d^i, \quad (1)$$

where $-\bar{V} \cdot \nabla \chi^i$ is advection, F_H^i is horizontal turbulent diffusion, F_V^i is vertical turbulent diffusion, and F_c^i is convective transport [43–45]. R_{Wls}^i and R_{Wc}^i are the wet removal terms represented by large-scale and convective rain [46, 47]. D_d^i is dry deposition represented by assuming fixed deposition velocities over land and water.

The δ -Eddington approximation is employed by RegCM4 for radiative flux calculations. The calculation of dust SW radiation uses an asymmetry factor, single scattering albedo, and mass extinction coefficient based on Mie theory. The dust LW radiation is accounted for introducing the dust emissivity given by Kiehl et al. [36].

2.2. Model Sensitivity Tests. Four experiments were performed in this study (Table 1), the first three of which followed the protocol of Liu et al. [33], while the fourth was a newly designed experiment. The first is the modern (i.e., high-mountain) experiment, in which all of boundary conditions including terrain are set to the present-day state and the dust emissions from the major deserts in northwest China (HMD) are opened. The second is the high-mountain experiment with modern terrain stage but an absence of East Asian inland deserts (HM). The third is the low-mountain experiment with reduced topography in the northern TP (by as much as 2400 m) and also an absence of deserts (LM). The final one is the low-mountain experiment with the same terrain conditions as LM but with dust emissions from the major deserts of East Asia opened up (LMD). Therefore, by comparing the results of HMD minus HM (hereafter HMD – HM) and those of LMD minus LM (hereafter LMD – LM), we can determine the distribution of dust in East Asia and its related effects on East Asia summer monsoon onset as modulated by the uplift of the northern TP and its nearby major mountains.

The initial and lateral boundary conditions for the model were extracted from the National Centers for Environmental Prediction, Department of Energy (NCEP–DOE) Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (R-2) [48], and the default land use types were based on Global Land Cover Characterization (GLCC) data [49]. Soil texture data were from the USDA texture classification [50]. The sea surface temperature (SST) is from the National Oceanic and Atmospheric Administration SST dataset [51]. Each simulation began on January 1, 1988, and ran until

FIGURE 1: (a) Modern terrain used in HMD and HM and the locations of the major mountain ranges. The dotted areas indicate the three major deserts in China. A = southern Xinjiang in the Taklamakan desert; B = western Inner Mongolia in the Gobi desert; C = northern Xinjiang in the Gurbantunggut Desert. (b) Lowered terrain distribution used in LM and LMD. The lightest grey region in (a, b) is the model domain.

TABLE 1: Information on the topography and dust emissions in the experiments.

Experiment name	Topography	Emissions from the major deserts
HMD	Modern (high-mountain)	Open
HM	Modern (high-mountain)	Closed
LMD	Lowered	Open
LM	Lowered	Closed

December 31, 2009; however, only the last 20 years is analyzed, leaving the first two years as model spin-up time. The model center is located at 40°N and 90°E, with 160 grid cells in the W-E direction and 95 in the N-S direction. The interval of model integration time is 1 minute. Model horizontal resolution is 50 km. It was run in its standard configuration of 18 vertical σ -layers, with the model top at 10 hPa. Besides the change of terrain and deserts, all experiments used the same conditions. Only the dust direct effect is included in this study.

The height of the lowered region in LMD and LM was 1500 m plus 20% of the modern terrain altitude. The reduced area was mainly located in the northern TP and its nearby mountains, including the Pamir Plateau, the Tianshan Mountain, the Kunlun Mountain, the Altun Mountain, the Qilian Mountain, the Altai Mountains, and the Sayan Mountains (Figure 1). In order to close the dust emissions in HM and LM, the land cover types of the Taklamakan Desert, Gurbantunggut Desert, and Gobi Desert are replaced with nearby vegetation types.

2.3. Observation Data. Three datasets are used in this study for comparison with the RegCM4.1/Dust simulated results. The first is monthly mean surface air temperature and precipitation data, with a high resolution of $0.5^\circ \times 0.5^\circ$, provided by the Climate Research Unit (CRU), University of East Anglia [52]. The second is the NCEP–DOE reanalysis

($2.5^\circ \times 2.5^\circ$) wind fields at 850 hPa [48]. The third is the Multiangle Imaging Spectroradiometer (MISR) aboard the NASA Earth Observation System's Terra satellite Level 3 monthly mean aerosol optical depth (AOD) from 2000 to 2009.

3. Validation

Spring and summer are not only the seasons of strong dust emissions in East Asia but also the seasons of Asian monsoon onset and prevalence. So, model performance during this period directly affects the predication of dust climatic effects. The comparison between the CRU observed and HMD simulated surface temperature in spring and summer is illustrated in Figure 2. Both spring and summer surface temperatures simulated by HMD are consistent with those of CRU observation. In spring, the model successfully captures the major patterns of surface temperature distribution, including a reasonable northwest-southeast gradient, minimum temperature center in the TP and Mongolia, and maximum temperature center in south China and north India. However, it simulates a cold bias of 1–3°C in northwest China (Figures 2(a) and 2(b)). The simulation is better in summer than in spring, and the maximum temperature center in the Thar Desert located in northwest India is well captured compared with the observation (Figures 2(c) and 2(d)). Our simulation only includes dust aerosol, and there are other kinds of aerosols in the atmosphere. However, the CRU observation includes comprehensive effects of all aerosols (dust, black carbon, organic carbon, sulphate, and sea salt). Sandstorm mainly outbreaks in spring in northwestern China, so the cold bias in northwest China is from the dust cooling effect. Meanwhile, dust storm activities decrease in summer, and the cold bias weakens in summer. Therefore, the simulation is better in summer than in spring.

The comparison between observed and simulated 850 hPa wind and precipitation in spring and summer is illustrated in Figure 3. Southeasterly winds and southwest wind prevail in south China and to the south of the TP in spring, respectively. The region to the north of the Yangtze

FIGURE 2: Observed (a, c) and simulated (b, d) surface mean temperature (units: °C) in spring (a, b) and summer (c, d).

river is affected by strong northwest wind (Figure 3(a)). In summer, northwest wind weakens in north China, and the southerly wind is enhanced in south China, accompanied by the outbreak of the East Asia summer monsoon. The southerly wind is divided into two branches: one moves across the southeast coast of China and eventually enters the East China Sea, while the other continues to north, passing over central China, and then changes into a southwesterly wind before entering into north and northeast China (Figure 3(c)). Compared with the NCEP observation, RegCM4.1/Dust basically captures the above major features of 850 hPa wind during spring and summer (Figures 3(b) and 3(d)).

RegCM4.1/Dust also captures well the characteristics of the precipitation distribution in East Asia. In spring, the maximum center of precipitation is mainly located in south China, the southeast of the Himalaya Mountains, and the Pamirs Plateau (Figure 3(a)). The precipitation rate is less than 1.5 mm day^{-1} over the TP, northern India, and the areas to the north of the Yangtze river. The model results are consistent with the above precipitation distribution, albeit an overestimation of precipitation is apparent in the Pamirs Plateau, Tianshan Mountains, and southeast Himalaya Mountains, and an underestimation in southeast China (Figure 3(b)). The simulation of summer precipitation

is better than that in spring, in which there is a slight overestimation in the Tianshan Mountains, northern TP, and south China (Figure 3(b)). The terrain of the TP is quite complicated, and the cumulus convection parameterization applied in this extremely complex area has high sensitivity [53]. Therefore, the overestimated precipitation over the TP and its nearby mountains comes from the cumulus parameterization scheme chosen in RegCM4.1/Dust, namely, the Grell scheme with Fritsch-Chappell closure. On the other hand, the bias in south China mainly relates to the model physics scheme applied in this area: for example, the Grell mass flux scheme may be more suitable for the midlatitudes rather than tropical and subtropical areas of China [54].

The rainy season in East Asia usually starts from late spring to summer under the influences of the East Asia summer monsoon and the Indian monsoon. The RegCM4.1 simulated precipitation seasonal variation is well consistent with those of CRU observed in northern and southern China, which indicates that our simulation is reliable (Figure 4).

The distribution of MISR-observed aerosol AOD and model-simulated dust AOD is illustrated in Figure 5. The comparison shows that the patterns of model-simulated dust AOD are consistent with those of the MISR observation in spring and summer. The model successfully captures the maximum center of dust AOD in the Taklamakan Desert in

FIGURE 3: Observed (a, c) and simulated (b, d) mean precipitation rate (units: mm day^{-1}) and 850 hPa wind (units: m s^{-1}) in spring (a, b) and summer (c, d). The black lines are the terrain contours of 2000 m.

FIGURE 4: Comparison between RegCM4.1 simulated and CRU observed annual cycles of monthly precipitation (mm/day) regional averaged for the north China (a) ($38^{\circ}\text{--}42^{\circ}\text{N}$, $110^{\circ}\text{--}120^{\circ}\text{E}$) and south China ($25^{\circ}\text{--}30^{\circ}\text{N}$, $110^{\circ}\text{--}115^{\circ}\text{E}$).

spring and summer. However, it overestimates the dust AOD in the Gobi and Gurbantunggut Desert. The simulation of dust AOD in summer is better than that in spring. It should be noted that only dust aerosol is featured in our experiment, so the heavy MISR AOD in eastern and southwest China (left panels in Figure 5) is not consistent with the model

simulation. Our simulation might overestimate the AOD in the three dust source centers; the possible reason comes from the overestimation of giant aerosol ($5.0\text{--}20.0\ \mu\text{m}$) and the uncertainty in characterizing soil property. Meanwhile, the model does not describe the presence of additional aerosol types as well as background aerosols; this may also be

FIGURE 5: MISR-observed aerosol optical depth (a, c) and simulated dust AOD (b, d) averaged in spring (a, b) and summer (c, d) during 2000–2009.

an indication of relatively weak long range dispersal of dust plume by the model [14]. Besides, Sun et al. [15] have detailed and compared the same model (RegCM4) simulated results of control run with various observations on the regional scale of Asia and found that the performance of RegCM4 is basically good. Overall, the control simulated result is reasonable when compared with observations or other model results.

4. Results and Analyses

4.1. Impacts of Topography on the Distribution of Dust in East Asia. The uplifting of the northern TP and its nearby major mountains significantly influences the distribution of dust in East Asia. The dust mixing ratio at 600 hPa is higher in the Taklamakan and Gobi Desert in spring than in summer in HMD – HM, with their center values greater than $150 \mu\text{g kg}^{-1}$ (Figure 6(a)). In summer, the dust mixing ratio is relatively lower than that in spring over the two deserts (Figure 6(b)). However, in LMD – LM, the dust mixing ratio is lower in the above two deserts in both spring and summer

(Figures 6(c) and 6(d)). Besides, uplift of the northern TP causes the dust mixing ratio to increase greatly in the northern TP (Figure 6(e)), and this enhancement is discussed further, in detail, below. The dust mixing ratio only increases markedly in the Taklamakan Desert in summer between HMD – HM and LMD – LM (Figure 6(f)).

The seasonal variation of the regional mean dust column burden averaged in the Taklamakan Desert in the four different experiments is illustrated in Figure 7. The dust source has an important effect on the maintenance of the dust cycle in East Asia. Both HMD and LMD capture the highest dust emissions in spring in the Taklamakan Desert, but the experiments with an absence of deserts all missed this feature. Besides, it is interesting to note that the differences between HMD and HM are greater than the differences between LMD and LM in summer (Figure 7(a)). The formation of cyclonic circulation in the Tarim Basin, induced by uplifting of the northern TP and its nearby major mountains, may be a reason for the higher dust production there in summer. This is discussed further in Section 4.3.

FIGURE 6: Dust mixing ratio changes at 600 hPa ($\mu\text{g kg}^{-1}$) between different numerical experiments in spring (a, c, e) and summer (b, d, f): (a, b) HMD – HM; (c, d) LMD – LM; (e, f) (HMD – HM) minus (LMD – LM).

As mentioned, Figure 6 shows that the topography also significantly influences the dust distribution in the TP in spring. Therefore, we further analyzed the differences in the dust vertical profile between the different experiments, as shown in Figure 8. In HMD – HM (Figure 8(a)), the dust mixing ratio is highest in the western TP and the center values reach $40 \mu\text{g kg}^{-1}$. The values in the central and eastern TP range from 20 to $30 \mu\text{g kg}^{-1}$ and the dust concentration is higher between 400 hPa and the near-surface layer of the TP (Figure 8(a)). In LMD – LM, the dust concentration is lower over the TP and the dust vertical mixing is weak (Figure 8(b)).

The differences between HMD – HM and LMD – LM show that the uplifting of the northern TP and its nearby major mountains enhances the dust load over the TP (Figure 8(c)).

4.2. Dust Effects on the Heat Source over the TP Modulated by Topography. The differences in dust load between HMD and HM are greater than those between LMD and LM over the TP (Figure 8), and dust can directly modify atmosphere-earth radiation [55, 56]. Therefore, the dust effects on the heat source over the TP may differ in the high- and low-mountain experiments. We use 600 hPa atmospheric temperature to

FIGURE 7: Annual cycles of monthly dust column burden (mg m^{-2}) regionally averaged for the Taklamakan Desert ($37^{\circ}\text{--}42^{\circ}\text{N}$, $78^{\circ}\text{--}87^{\circ}\text{E}$) in (a) HMD and HM and (b) LMD and LM.

FIGURE 8: Longitude-height ($32^{\circ}\text{--}37^{\circ}\text{N}$) DMR ($\mu\text{g kg}^{-1}$) changes between different experiments in spring: (a) HMD – HM; (b) LMD – LM; (c) HMD – HM minus LMD – LM.

FIGURE 9: Atmospheric temperature changes at 600 hPa over the TP in spring (units: °C) between different numerical experiments: (a) HMD – HM; (b) LMD – LM.

simply represent the heat source over the TP, following Liu and Wang [57].

The heat source over the TP substantially decreases in the northern TP due to the high dust load between HMD and HM (Figure 9(a)), in which the decrease can exceed 0.6°C. It also decreases between LMD and LM, but the reduction is not significant compared with that between HMD and HM due to the low dust load (Figure 9(b)).

We further analyzed the variation in the heat source over the northern TP (hereafter NTP-HT) during the period of East Asia summer monsoon onset (Figure 10). The NTP-HT greatly decreases due to dust from the 27th to the 48th pentad in both the high- and low-mountain experiments, but the decreasing effect on the NTP-HT in HMD – HM is quite a lot stronger than those in LMD – LM due to the high dust content over the TP with the uplift of the northern TP.

4.3. Dust Effects on the East Asia Summer Monsoon and Its Onset Modulated by Topography. In HMD, north and south China are affected by westerly and southwesterly winds, respectively, and there is strong cyclonic circulation in the Tarim Basin (Figure 11(a)). Without the major deserts of northwest China, the cyclonic circulation and northwesterly winds weaken (Figure 11(b)). In HMD – HM, dust weakens the East Asia summer monsoon and causes strong cyclonic circulation over the Tarim Basin. Therefore, dust emissions are still stronger in summer over the Taklamakan Desert due to the strong updraft induced by the cyclonic activity (Figures 6(e) and 7(a)). Both LMD and LM capture the major features of the East Asia summer monsoon (Figures 11(b) and 11(d)), but there is no cyclonic circulation over the Tarim Basin. Therefore, the dust concentration is lower over the Taklamakan Desert (Figure 7(b)). Both the high- and low-mountain experiments show that dust weakens the East Asia summer monsoon, which is in agreement with previous studies [15, 58].

Because of the close relationship between the heat source of the TP and East Asia summer monsoon onset, we analyzed

FIGURE 10: Regional mean atmospheric temperature (°C) change at 600 hPa averaged in the northern TP (34°–38°E, 90°–105°N).

the dust effects on East Asia summer monsoon onset under the high- and low-mountain settings. The index of East Asia summer monsoon onset that we used followed the definition of Wang and Ho [59], as follows:

$$RR_i = R_i - R_{JAN}, \quad i = 1, 2, \dots, 73, \quad (2)$$

where RR_i is the relative pentad mean rainfall rate. In the Northern Hemisphere, R_i is the pentad mean rainfall rate and R_{JAN} is the pentad mean rainfall rate of January. If RR_i is greater than 6 mm day^{-1} , then the onset of the East Asia summer monsoon begins. Pentad is five days, and there are 6 pentads in one month.

Following Liu and Yin [60], we chose two key monsoon regions of East Asia: a southern monsoon region (22°–30°N, 105°–120°E) and northern monsoon region (34°–42°N, 105°–120°E). Figure 12 shows the variation in East Asia summer monsoon onset index averaged in the southern monsoon region. Onset of the East Asia summer monsoon begins in

FIGURE 11: 700 hPa wind field averaged in summer (June to August) in (a) HMD, (b) HM, (c) LMD, (d) LM, (e) HMD-HM, and (f) LMD-LM. The grey area represents the topography below 700 hPa.

the 29th pentad in HM but is two pentads later in HMD. The onset of the East Asia summer monsoon begins in the 31st pentad in LM but in the 32nd in LMD. The results demonstrate that dust can delay the onset of the East Asia summer monsoon, but the delaying effect of dust in HMD - HM is stronger than that in LMD - LM.

The dust effect on East Asia summer monsoon onset in the northern monsoon region is illustrated in Figure 13. The onset of the East Asia summer monsoon in this region starts in the 36th pentad in both HM and LM, while dust delays the monsoon onset by one pentad in both HMD and LMD compared with HM and LM. The sensitivity of

the dust-induced East Asia summer monsoon onset anomalies to the topography change in the northern monsoon region is lower than that in the southern monsoon region.

4.4. Impacts of the Effects of Dust on Precipitation Induced by Topography Changes. The regional monthly mean of precipitation averaged in north and south China in the four experiments is illustrated in Figure 14. Dust hinders precipitation over north and south China due to the delaying effect of dust on the onset of monsoon in both the high- and low-mountain experiments. The suppression effects in HMD - HM are much stronger than in LMD - LM in

FIGURE 12: East Asia summer monsoon onset index averaged in the southern monsoon region (22°–30°N, 105°–120°E) in (a) HMD and HM and (b) LMD and LM.

FIGURE 13: As in Figure 10 but for the northern monsoon region (34°–42°N, 105°–120°E).

FIGURE 14: Regional mean precipitation rate (mm day⁻¹) averaged in the rainy season (May to August) in north China (a) (38°–42°N, 110°–120°E) and south China (25°–30°N, 110°–115°E) in the four different experiments.

FIGURE 15: Regional mean water vapor mixing ratio (g kg^{-1}) at 850 hPa averaged in the rainy season (May to August) in north China ($38^{\circ}\text{--}42^{\circ}\text{N}$, $110^{\circ}\text{--}120^{\circ}\text{E}$) and south China ($25^{\circ}\text{--}30^{\circ}\text{N}$, $110^{\circ}\text{--}115^{\circ}\text{E}$) in the four different experiments.

both north and south China. The differences in precipitation in north China are substantially in July in HMD – HM, while for south China the differences are markedly from spring to summer (March to July). The influences of dust on the precipitation induced by the modified topography in south China are stronger than those in north China, because the delaying effects on the onset of the East Asia summer monsoon in south China are stronger than those in north China.

Our simulation did not include the dust indirect effect, but it is interesting to note that the previous research demonstrated that the indirect effect of aerosols from central eastern China also reduces Asian monsoon strength and precipitation [58]. The main reason for the reduction of the precipitation in East Asia is that dust cooling effect created cyclone-anticyclone-cyclone flow pattern emanating from the dust source region to the East China Sea and weakened the East Asia summer monsoon [15]. Besides, we analyzed the water vapor mixing ratio and found that the change characteristic of water mixing ration in the above two regions also decreased (Figure 15). The reduction of the water vapor mixing ratio induced by dust between the modern terrain experiments is more than that between the low terrain experiments, which is consistent with the changes in precipitation.

5. Discussion and Conclusions

In this study, the latest version of RegCM4.1/Dust was used to study how the northern TP and its nearby major mountains modulate the dust distribution in East Asia. The dust effects on the heat source over the TP and, ultimately, the related onset of the East Asia summer monsoon under different terrain settings were then analyzed. The simulations showed that the dust load in northwest China during spring increases

greatly in the Taklamakan Desert in HMD – HM compared to LMD – LM. The increase can exceed $150 \mu\text{g kg}^{-1}$ in spring. Interestingly, the dust concentration is higher in the Taklamakan Desert during summer in HMD–HM compared to LMD – LM. The formation of cyclonic circulation in summer, induced by the uplifting of the northern TP and its nearby major mountains, is the reason for this higher dust production in the Taklamakan Desert (Figure 11(e)). Due to the absence of uplifting of the northern TP and its nearby major mountains, there is no mechanism for dust emission in summer over the Tarim Basin (Figure 11(f)). Additionally, the dust loading over the TP is sensitive to the northern TP changes. It is higher in HMD – HM and lower in LMD – LM, over the TP.

The uplift of the northern TP causes the dust loading over the TP to increase, and dust cooling effect causes the radiation absorbed by the TP to reduce. Therefore, dust aerosol causes the heat source over the TP to decrease in both the high- and low-mountain experiments. The reduction in HMD – HM is much larger than in LMD – LM, reaching -0.6°C in the northern TP. Due to the weakening of the heat source over the TP induced by dust, the onset of the East Asia summer monsoon is delayed in both the high- and low-mountain experiments. The effect of dust on East Asia summer monsoon onset is stronger in HMD – HM than in LMD – LM. Dust delays the onset of the East Asia summer monsoon over the northern and southern monsoon region in East Asia by two pentads and one pentad, respectively, in HMD – HM, while in LMD – LM the delay is one pentad in both the northern and southern monsoon region. It also weakens the East Asia summer monsoon in both the high- and low-mountain experiments, which is consistent with previous research [15, 58].

Furthermore, dust suppresses precipitation in both the high- and low-mountain experiments, but the suppression

effects are stronger in HMD – HM than in LMD – LM. In north China, the suppression effect is markedly in July in HMD – HM, while in south China it is markedly from March to July. The dust effects on precipitation in south China are more sensitive to the topography change than in north China.

Most previous studies have focused on the dust cycle and its radiative effects on temperature, precipitation, and the East Asia summer monsoon. A recent modeling work using RegCM4.1/Dust studied the relationships among topography, inland deserts, and regional climate evolution in East Asia and found that the topography is closely related to dust change in East Asia [33]. Besides, to date, simulation work using high-resolution regional climate modeling, in the context of dust effects on the heat source over the TP and its effect on East Asia summer monsoon onset, is rare. Dust can influence the climate through direct and indirect effects, and the uplift of the TP is proved to have great effects on the global and regional climate [31]. However, most previous researches only focus on one of the above two factors. On the one hand, this study helps to figure out combined effects of dust and the TP uplifting on the East Asia summer climate, while, on the other hand, it has a certain referential significance for the quantification of the topography-modulated dust distribution and its effects on the onset of the East Asia summer monsoon, as well as understanding the aeolian dust effects on the East Asian climate.

However, the analysis about the interactions between dust aerosols and meteorological factors in the simulation has some deficiencies. First, RegCM4.1/Dust only includes the direct radiative effect of dust aerosol. Thus, we acknowledge that these preliminary results on the effects of dust on the heat source over the TP and the related onset of the East Asia summer monsoon are uncertain. The findings need to be evaluated using models that include both direct and indirect dust effects. Second, dust effects are sensitive to aerosol optical properties assumed in the model, and the value of single scattering albedo in Asia desert is still uncertain [61]. The results in this study also need to be validated by sensitivity experiments with different aerosol properties. Third, the simulation only includes dust aerosol, but there are other kinds of aerosols in the atmosphere. Accordingly, we plan to carry out experiments with all major types of aerosols in the future to further evaluate the results. Finally, the uncertainty from the model cumulus parameterization schemes should also be considered in future work.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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