Article ID: 1006-8775(2017) 04-0357-11

# THE ANALYSIS OF MECHANISM OF IMPACT OF AEROSOLS ON EAST ASIAN SUMMER MONSOON INDEX AND ONSET

SHEN Xin-yong (沈新勇)[1, 2], HUANG Wen-yan (黄文彦)[3], CHEN Hong-bo (陈宏波)[3]

(1. Key Laboratory of Meteorological Disaster, Ministry of Education/ Joint International Research Laboratory of Climate and Environment Change/ Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044 China; 2. Key Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029 China; 3. Changzhou Meteorological Bureau, Changzhou, Jiangsu 213022 China)

**Abstract:** RegCM4.3, a high-resolution regional climate model, which includes five kinds of aerosols (dust, sea salt, sulfate, black carbon and organic carbon), is employed to simulate the East Asian summer monsoon (EASM) from 1995 to 2010 and the simulation data are used to study the possible impact of natural and anthropogenic aerosols on EASM. The results show that the regional climate model can well simulate the EASM and the spatial and temporal distribution of aerosols. The EASM index is reduced by about 5% by the natural and anthropogenic aerosols and the monsoon onset time is also delayed by about a pentad except for Southeast China. The aerosols heat the middle atmosphere through absorbing solar radiation and the air column expands in Southeast China and its offshore areas. As a result, the geopotential height decreases and a cyclonic circulation anomaly is generated in the lower atmosphere. Northerly wind located in the west of cyclonic circulation weakens the low-level southerly wind in the EASM region. Negative surface radiative forcing due to aerosols causes downward motion and an indirect meridional circulation is formed with the low-level northerly wind and high-level southerly wind anomaly in the north of 25°N in the monsoon area, which weakens the vertical circulation of EASM. The summer precipitation of the monsoon region is significantly reduced, especially in North and Southwest China where the value of moisture flux divergence increases.

**Key words:** aerosol climate effect; regional climate model; East Asian summer monsoon; monsoon index; onset time; indirect circulation; mechanism analysis

**CLC number:** X16 **Document code:** A

doi: 10.16555/j.1006-8775.2017.04.002

## 1 INTRODUCTION

Aerosols in the atmosphere mainly refer to the solid and liquid particles suspended in the air. Aerosols can be natural or artificial based on their sources. First, China penetrates deep into Eurasia in its west and faces the Pacific on the east; therefore, formation of natural aerosols, including dust and sea salt, occurs naturally. Second, accompanied by rapid social and economic development in China, industrial and agricultural production and transportation discharge abundant sulfates, black carbon, organic carbon, and other types of aerosols into the atmosphere (Ohara et al.[1]). The existence of natural and artificial aerosols in abundance inevitably changes the radiative transfer process (direct effect) and the cloud properties (indirect effect), thus significantly influencing the climate of a region (Zhang[2]; Zhang et al.[3]).

East Asian Summer Monsoon (EASM) is an important circulation system influencing China, and its strength directly determines the spatiotemporal distribution pattern of summer precipitation in China. The summer monsoon and aerosols mutually influence each other. On the one hand, the strength of the summer monsoon leads to changes in the distribution of aerosols (Zhang et al.[4]; Zhu et al.[5]). For instance, Yan et al.[6] claimed that the aerosol optical depth (AOD) of Southern China was higher in years with a weak EASM than in years with a strong one; however, opposite trend was observed in Northern China. On the other hand, aerosols also change the strength of the summer monsoon, and this proposition constitutes an active hotspot of current studies. Using the RegCM4.1 model, Zhou et al.[7] studied the relationship between sulfate aerosols and EASM, and showed that sulfates strengthened the summer monsoon in the early stage (June) and weakened it in the late stage (July and August). Wang et al.[8] and Chen et al.[9] used the

**Received** 2016-06-13; **Revised** 2017-10-16; **Accepted** 2017-11-15

**Foundation item:** National Key Project of Ministry of Science and Technology of China (2016YFC0203301); National Key Basic Research and Development Project of China (2015CB453201, 2013CB430103); National Natural Science Foundation of China (41375058, 41530427); Jiangsu Natural Science Key Project of China (BK20150062)

**Biography:** SHEN Xin-yong, Ph.D., Professor, primarily undertaking research on typhoon and mesoscale meteorology.

**Corresponding author:** SHEN Xin-yong, e-mail: shenxy@nuist.edu.cn

RegCM3 model to study the relationship between artificial aerosols (sulfates, black carbon, organic carbon) and EASM. The results indicated that the introduction of aerosols led to the emergence of cyclonic circulation anomaly over the ocean surface of Eastern China, and the strengthening of northerly winds weakened EASM. Shen et al. [10] adopted the RegCM3 model to simulate the influence of artifical aerosols on South Asian summer monsoon (SASM) in South Asia, and the results indicated that aerosols could simultaneously weaken the low-level westerly flow and the high-level easterly flow, thus weakening SASM.

Besides regional climate models, the global atmospheric circulation model is also an important tool for studying the relationship between aerosols and the summer monsoon. Wan et al. [11] used the global circulation model developed by the Geophysical Fluid Dynamics laboratory to discuss the influence of black carbon aerosols on EASM in Europe, and found that black carbon aerosols strengthened EASM through intensifying the sea—land thermal contrast. Moreover, the summer monsoon precipitation of the Eastern China monsoon region increased as well. Wang et al. [12] used the CAM3 model in their study and found that black carbon aerosols in South Asia strengthened SASM but weakened EASM. Deng et al. [13, 14] adopted the CAM5 model to study the influence of artificial aerosols on EASM in Eastern China, and the results indicated that they could bring forward the onset time of South China Sea summer monsoon and weaken the EASM. Wang et al. [15] utilized the CAM5 global model, and the results indicated that the direct radiative forcing due to sulfate aerosols could reduce the surface temperature of East Asian continent, weaken the sea—land thermal contrast in East Asia, and thus delay the onset time of East Asian subtropical summer monsoon. Moreover, it could also bring forward the ending time of the summer monsoon. Jiang et al. [16] also used the CAM5 model in their study and found that sulfate and organic carbon aerosols could weaken the sea—land thermal contrast, thus leading to the weakening of EASM. Liu et al. [17] adopted the CAM3 model to study the influence of different types of aerosols on the summer monsoon, and the results indicated that EASM could be weakened by sulfate aerosols alone, by black carbon aerosols alone, and also by both of them in combination. Zhang et al. [18] employed a global circulation model developed by the National Climate Center and found that sulfate, black carbon, and organic carbon aerosols could reduce the sea—land temperature and air pressure differences in East Asia, and thus obviously leading to weak the EASM. Liu et al. [19] studied the relationship between aerosols and the summer monsoon precipitation and found that aerosols increased the precipitation in the coastal regions of Southeastern China and reduced the precipitation in regions north of the Yangtze River.

The studies described above mostly focus on the relationship between artificial aerosols and EASM; however, the combined influence of natural and artificial aerosols on EASM has rarely been investigated. Therefore, further studies and extensive research efforts are required to be devoted in this field. Some existing studies show that regional climate models have a relatively good simulative effect toward the spatiotemporal distribution of Asian monsoons and aerosols (Shen et al. [20]; Shen et al. [21]). Thus, in this study, RegCM4.3, a high-version and high-resolution regional climate model, was adopted to discuss the influence of natural and artificial aerosols on EASM indices and onset time through introducing dust, sea salt, sulfate, black carbon and organic carbon. Further, the mechanism of such influence was explained from the perspective of circulation.

## 2 MODEL AND EXPERIMENT DESIGN

### 2.1 *Numerical model*

The earliest version of the regional climate model system, RegCM1 (Dickinson et al. [22]; Giorgi [23]), first emerged in the 1980s, and it has improved and perfected for more than 20 years. It has currently been developed into the latest RegCM4 (Giorgi et al. [24]). Compared to the version RegCM3 (Pal et al. [25]), RegCM4 has been significantly improved in many aspects. New land surface, boundary layer, air—sea flux, and other parameterization schemes have been introduced in the latest model. Furthermore, the model has been perfected in terms of existing radiative transfer and boundary layer schemes.

RegCM4.3 provides two aerosol modules, i.e., the simple aerosol scheme (Solmon et al. [26]) and the gaseous chemical module (CBM-Z) (Shalaby et al.[27]). Limited by calculation conditions, in this study, the simple aerosol scheme was selected that consumed less machine-hours. In its early stage, the scheme included only three types of artificial aerosols (Solmon et al.[26]), i.e., sulfate, black carbon, and organic carbon aerosols, and later Zakey et al. included other two types of natural aerosols also, i.e., dust (Zakey et al.[28]) and sea salt (Zakey et al.[29]).

The emission intensities of the three types of artificial aerosols in this model are determined according to the historical emission list provided by CMIP5; however, those of the other two types of natural aerosols are calculated by using specific formulas (Zakey et al. [28]; Zakey et al. [29]). The aerosol data obtained through simulation by the global model provide the lateral boundary conditions of aerosols for the model. The absorption and scattering of solar radiation by aerosols are determined by the optical properties of aerosols (Solmon et al. [26]). However, the versions preceding RegCM4 consider only the influence of aerosols on shortwave spectra. RegCM4.3 also takes into account the absorption and scattering of infrared spectra by large-size aerosol particles, including dust particles and sea salt particles (Solmon et al.[30]).

2.2 *Experiment design and data*

In order to study the influence of aerosols on the summer monsoon, herein two types of experiment were conducted, i.e., control experiment and sensitivity experiment. The control experiment opened the aerosol module in the model, and considered completely the radiative effect of the five types of natural and artificial aerosols (i.e., dust, sea salt, sulfate, black carbon, and organic carbon aerosols). Compared to the case in which the influence of aerosols was left out, it conformed more to the actual situations. In the sensitivity experiment, the aerosol module was completely closed, and the influence of aerosols on the climate was not taken into account. The differences between the results of the two experiments represented the possible influence of aerosols on the monsoon. Similar to all the previous versions, RegCM4.3 also considered only the direct radiative forcing of aerosols; nonetheless, neglected the indirect cloud-related effect.

The central point of the simulation region in the two experiments was (110°E, 28°N). The number of grid points in the east—west direction was 220, the number of grid points in the north—south direction was 150, and the distance between two adjacent grid points was 60 km. The entire simulation region basically covered the Asian monsoon region. The physical parameterization schemes used in the model included biosphere—atmosphere transfer land surface scheme, Holtslag boundary layer scheme, Grell cumulus convective scheme, and Zeng ocean flux scheme. NCEP/DOE reanalysis data provided the initial field and boundary conditions for the model. The sea surface temperature (SST) forcing field was derived from the weekly mean data of OISST. The entire simulation period ranged from December 1, 1994 to December 31, 2010. To be specific, the first month of simulation served as the spin-up time of the model, and mainly the data of 16 years (1995—2010), obtained through simulation, were analyzed.

The 2.5°× 2.5° global monthly mean precipitation data provided by GPCP and the 2.5° × 2.5° monthly mean reanalysis data provided by NCEP/NCAR were used to test the meteorological element field simulated by the model, respectively, starting from 1979 and 1948. The monthly mean data of AOD at wavelengths 550 and 555 nm, obtained through retrieval respectively by MODIS and MISR on NASA's Terra satellite, were used to evaluate the model's ability to simulate aerosols. To be specific, the resolutions of MODIS and MISR data were respectively 1°× 1° and 0.5°× 0.5°, and they both were started in 2000.

## 3 ANALYSIS OF RESULTS

3.1 *Model simulation testing*

To study the relationship between aerosols and the summer monsoon, the first step was to test the simulative effect of the model for both of them. The model simulation results provided in this section were solely the results of the control expriment. Fig.1 shows the observed and simulated summer wind fields, indicating that in the Eastern China monsoon region, both observed and simulated 850 hPa winds were warm and wet southwesterly flows from the Indian and Pacific Oceans. The simulated 850 hPa wind field basically approximated the observed one; however, its numerical value was slightly greater than the observed value.

The summer meridional circulation of the East Asian monsoon region is the ascending branch of the direct meridional circulation cell. Fig.1c shows that in regions south of 35°N, the observed meridional circulation was southerly wind at low level and northerly wind at high level, and its vertical motion field manifested as obvious ascending motion. In regions north of 35°N, the vertical wind field manifested weak descending motion below the height of 500 hPa. The simulated field of RegCM4.3 was basically similar to the observed field; however, its simulated low-level southerly wind and high-level northerly wind were slightly stronger than the observed ones, and the ascending motion at relatively low latitude was weaker than that observed.

The warm and wet wind in summer from the ocean brings significant precipitation to the monsoon region. Figs.2a and 2b show the observed and simulated total summer precipitations, respectively, revealing that their overall distribution trends were completely consistent. That is, they both progressively declined from the southeastern coastal regions to the northwestern inland regions, and the precipitation of the eastern monsoon region was obviously higher than that of non-monsoon regions in both cases. The simulation error mainly occurred in Southern China. The simulated precipitation in regions east of 110°E was lower but higher in regions west of it. This error was probably caused by the weaker low-level southeasterly wind and the stronger southwesterly wind (Fig.1b) simulated by the model.

In addition to satisfactory simulation of the spatial distribution pattern of precipitation, the model must also have a certain ability to simulate the inter-annual variations of precipitation. Fig.2c exhibits the inter-annual variation curves of the observed and simulated regional mean summer precipitations in the monsoon region. The results indicated that the difference between simulated and observed values was relatively small in each year, in particular, after 1999, the inter-annual variation trend of the simulated summer precipitation basically tallied with that of the observed one. Nonetheless, the simulation error was greater before 1999.

The aerosol module-coupled regional climate model, besides satisfactorily simulating the basic climate state, must also have a sound simulative effect for the spatiotemporal distribution of natural and artificial aerosols. Figs.3a and 3b show the AOD obtained through retrieval, respectively, by MODIS and MISR. The results were basically similar, indicating that the high-value regions of AOD were mostly located in China's eastern industrial districts, Sichuan Basin and Southern Xinjiang Basin, and in the north of India Peninsula. Further, the retrieval values of MISR were slightly lower than those of MODIS. The AOD spatial distribution simulated by RegCM4.3 was completely consistent with the ovreall trend of the satallite retrieval value, and could satisfactorily reflect the high and low-value centers of AOD. The simulation error mainly occurred in the Southern Xinjiang Basin and in the north of India Peninsula, where the simulated value was lower than the satellite retrieval value.

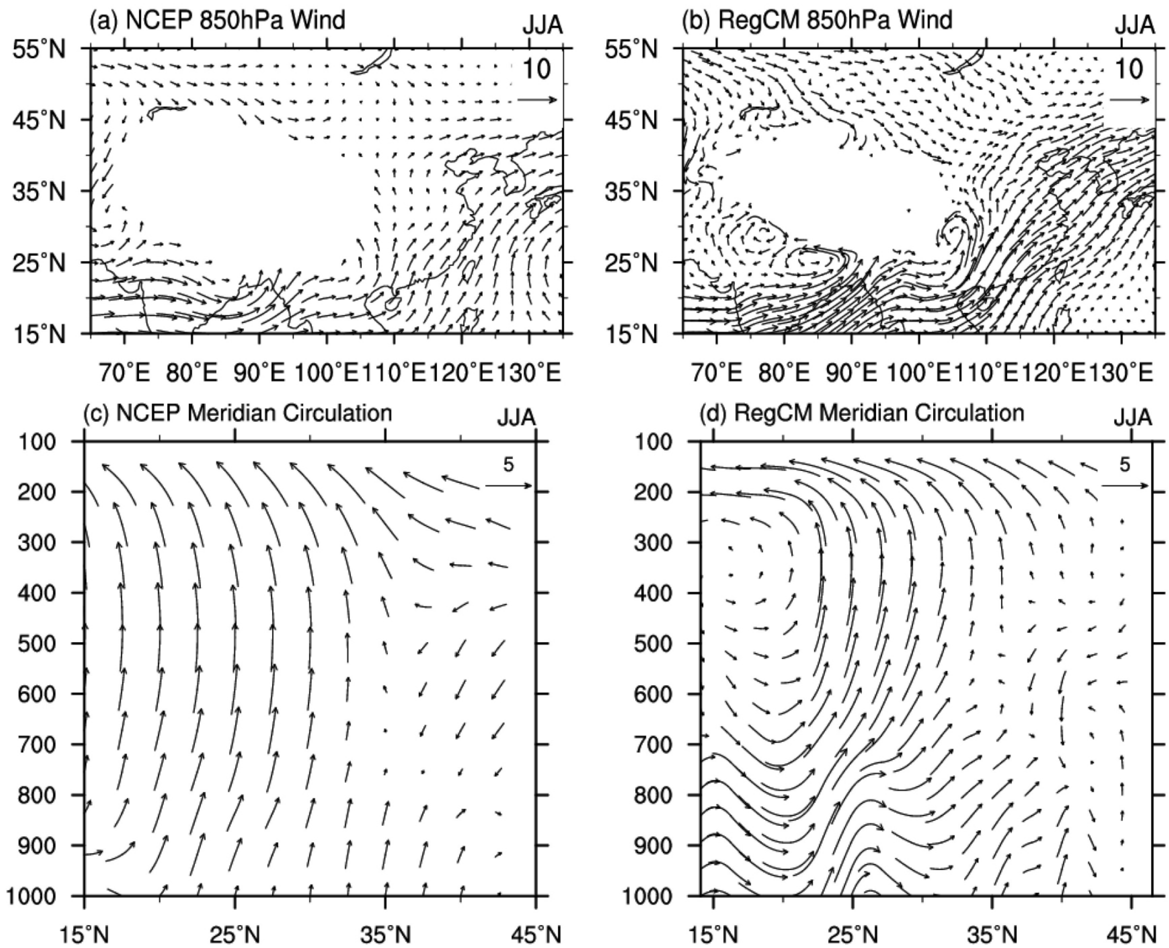
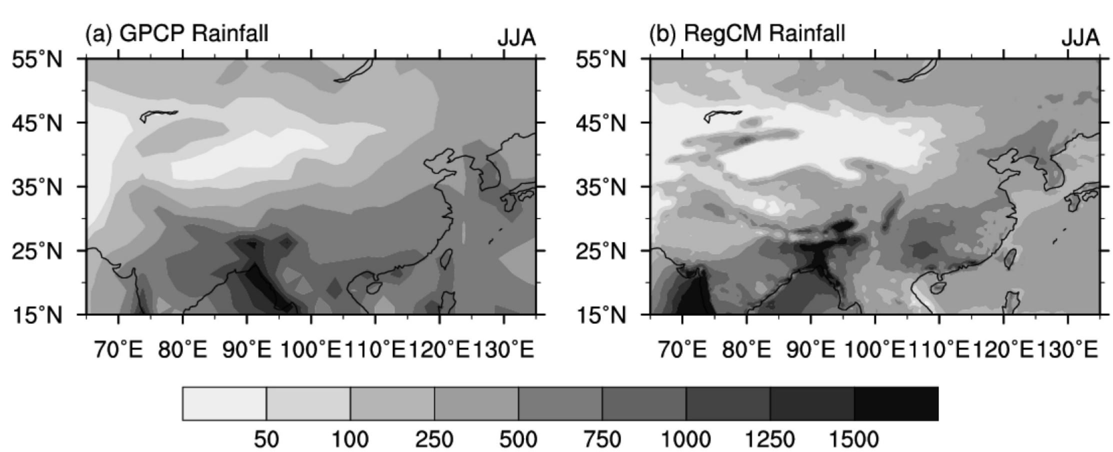



**Figure 1.** Observed (a, c), simulated (b, d) 850 hPa wind (a, b, units: m/s) and meridional circulation averaged over 105° to 120°E (c, d, $V$, units: m/s; $W$, units: $-10^{-2}$ Pa/s) in summer.



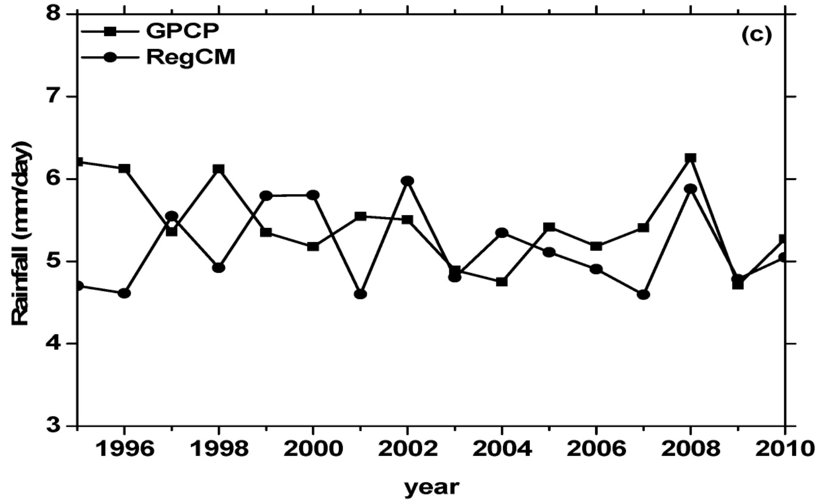



**Figure 2.** Observed (a) and simulated (b) precipitation (units: mm) in summer; inter-annual variability series of regional averaged (105°—120°E, 20—45°N) summer precipitation (c).

Similar to the precipitation, in this study, the simulative effect of the model for the inter-annual variations of aerosols was also comprehensively investigated. Fig.3c exhibits the inter-annual variation curves of the satellite-derived and simulated regional mean summer AOD in aerosol-concentrated regions. Clearly, both the inter-annual variation curves of the retrieval value and simulated value of AOD manifested obvious fluctuations. To be specific, the simulated values of each year mostly ranged between the retrieval values of MODIS and those of MISR, and the overall variation trend of simulated AOD was roughly consistent with that of retrieval values. Thus, the model successfully simulated the two high-AOD value years, i. e., 2003 and 2007.

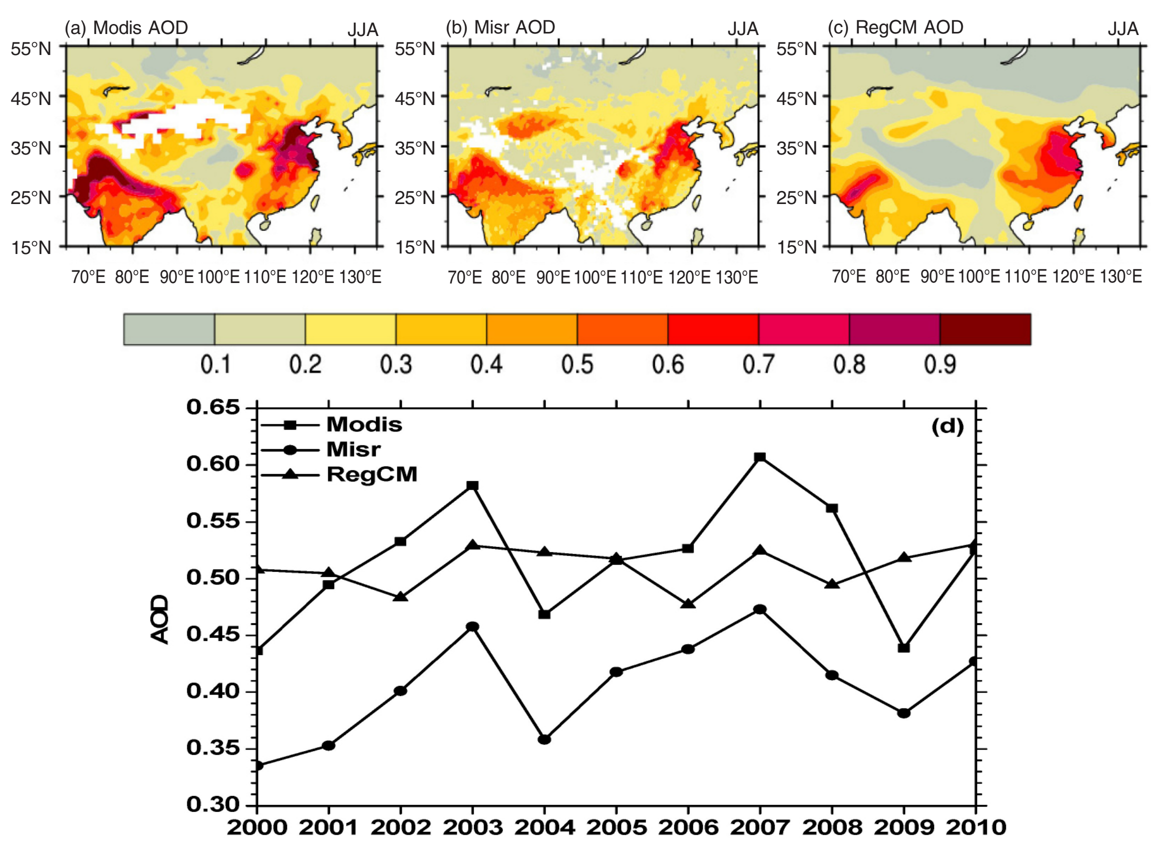



**Figure 3.** MODIS (a), MISR (b) and simulated (c) AOD in summer; inter-annual variability series of regional averaged (105°—120°E, 25°—40°N) summer AOD (d).

Overall, RegCM4.3 presented a relatively good simulative effect for the spatiotemporal distribution of EASM and aerosols, and thus laid a significant and potential basis for studying the influence of aerosols on the summer monsoon.

3.2 *Influence of aerosols on EASM indices and onset and analysis of its mechanism*

The magnitude of EASM indices can basically reflect the strength of the summer monsoon, and the relationship between aerosols and EASM indices can provide the overall trend of the influence of aerosols on the summer monsoon. Currently, there are two dozen widely used EASM indices (Wang et al.[31]), and the primary difference between different EASM indices mainly lies in the adoption of a different physical variable or calculation formula used in the calculation process. Herein, two relatively simple EASM indices were selected to study the relationship between aerosols and the summer monsoon, i.e, the WF proposed by Wang and Fan[32] and the WN proposed by Wu and Ni[33] (WF=$U_{850}$ (110°—140°E, 22.5°—32.5°N)−$U_{850}$ (90°—130°E, 5°—15°N); WN=$V_{850}$ (110°—130°E, 20°—30°N). Fig.4 shows the variation curves of EASM indices after introducing natural and artificial aerosols, revealing that the variation trends of the two EASM indices incurred by aerosols were basically consistent and they mainly presented a decreasing trend, testifying to aerosols' ability to weaken the strength of the summer monsoon. However, the specific amplitudes of variation still differed across different years. For instance, in around 2002, the introduction of aerosols slightly increased the EASM indices; however, in 1997, 2004, 2008, and several others years, their introduction witnessed an obvious declining trend of EASM indices. This difference might be attributed to the strength of EASM and the radiative forcing caused by aerosols. Fig.4 clearly exhibits that the increasing of EASM indices in 2002 might have been related to the relatively weak negative radiative forcing caused by aerosols in that year. The mean ratios of the variation amplitudes of the two EASM indices caused by aerosols to the magnitudes of the two EASM indices themselves were both around 5%.

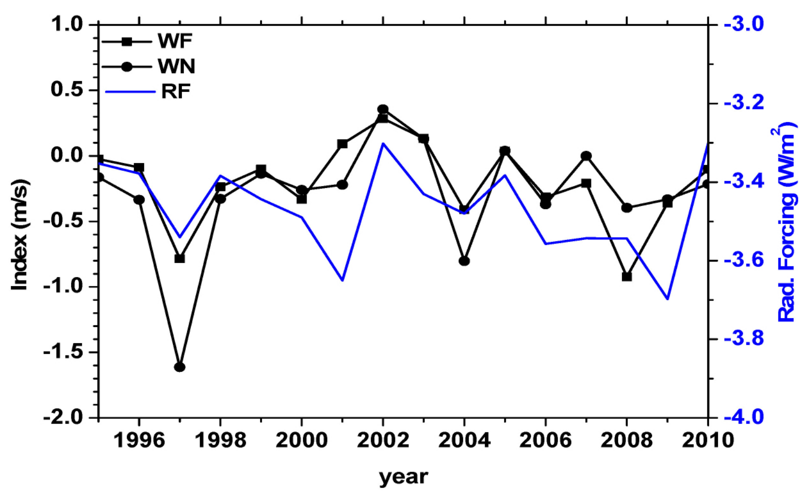



**Figure 4.** Inter-annual variability series of summer monsoon indices differences between control and sensitivity experiment and aerosol radiative forcing.

Similar to EASM indices, EASM onset time is also an important parameter in the quantification of the summer monsoon. In the course of the natural and artificial aerosols reducing EASM indices, it is also necessary to investigate their influence on the change in the EASM onset time. Currently, several methods are available which can be conveniently employed to determine EASM onset time, and many of them have introduced the same two variables, i.e., potential pseudo-equivalent temperature and meridional speed (Wang et al.[34]). In this study, the method proposed by Lian et al.[35] was employed to determine the EASM onset time. The method claims that a monsoon region can be determined as having witnessed EASM onset when its potential pseudo-equivalent temperature has reached 336 K and its meridional speed has reached 4 m/s. Fig.5 shows the variations of EASM onset time incurred by aerosols, indicating that except for Southeastern China, the EASM onset time of the entire monsoon region was delayed by about one pentad, and both Central China and Northeastern China passed the significance test. The delay of EASM onset time by aerosols was mainly attributed to the weakening of the low-level southerly wind. The regions witnessing long-delayed EASM onset time basically corresponded to those regions that had a relatively significant northerly wind anomaly at the level of 850 hPa (Fig.6d).

The above mentioned analysis indicated that aerosols had a weakening effect on the summer monsoon. The specific cause of this weakening effect

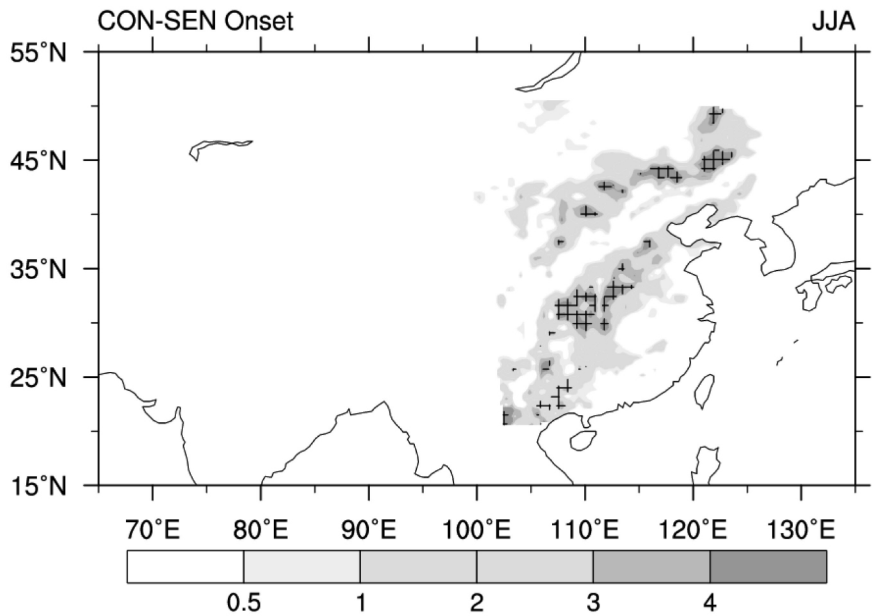
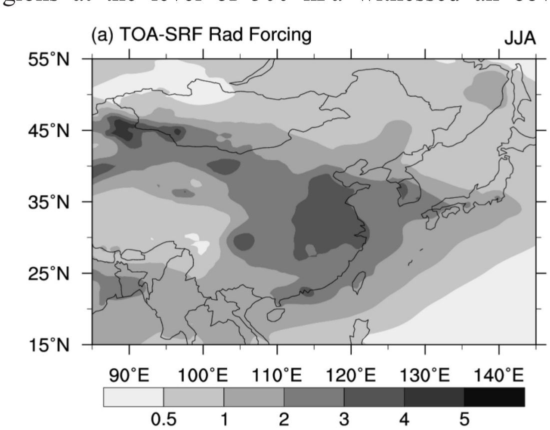



**Figure 5.** Summer monsoon onset differences between control and sensitivity experiment (units: pentad, line-shading indicates the differences are significant at 95% confidence level).

was explained through analyzing the relationship between aerosols and EASM circulation. Aerosols influence atmospheric circulation mainly through changing the radiative transfer process, which may further change the climatic state of a region. Fig.6a demonstrates the differences in the top of atmosphere (TOA) radiative forcing and surface radiative forcing caused by aerosols. The aerosols exert a negative radiative forcing action both on the surface and at the TOA through scattering and absorbing solar radiation. Fig.6a shows that in regions distributed with aerosols, the absolute value of the negative radiative forcing produced by aerosols at the TOA was less than that produced on the land surface. This was attributed to the fact that black carbon and dust aerosols strongly absorbed solar radiation and the portion of solar radiation absorbed by aerosols could not reach the land surface.

After absorbing solar radiation, aerosols heat the middle and upper atmosphere, and may further change the circulation pattern. Fig.6b exhibits the heating rate of solar shortwave radiation by aerosols at the level of 500 hPa and the resultant changes in atmospheric temperature. Clearly, the aerosols absorbed solar shortwave radiation in the Southeastern China and in offshore regions and the atmospheric temperatures of these regions were correspondingly elevated by above 1℃. Comparison of Figs.6a and 6b shows that the high-value regions of heat absorption by aerosols were mainly located in the Yangtze—Huaihe regions. However, the high-value regions of heating rate shifted eastward and southward, possibly because the introduction of aerosols led to changes in cloud cover and further changed the shortwave radiation. Fig.6c exhibits the variations of cloud cover after the introduction of aerosols, indicating that the cloud cover obviously increased in the Yangtze—Huaihe regions, and the increase in cloud cover further increased the reflection of shortwave radiation, thus partially offsetting the heating of shortwave radiation by aerosols. In the east and south of the Yangtze—Huaihe regions, the changes in cloud cover caused by aerosols were relatively small or insignificant; therefore, the heating action of aerosols for the atmosphere was more obvious in these regions. However, when the air columns were heated in the middle atmosphere, they expanded leading to a decrease in the geopotential height of low-level atmosphere, and an increase in the geopotential height of the high-level atmosphere. Figs.6d and 6e show the variations of geopotential height and wind field incurred by aerosols at the levels of 850 and 200 hPa, respectively. Clearly, the heating and temperature-rise regions at the level of 500 hPa witnessed an obvious



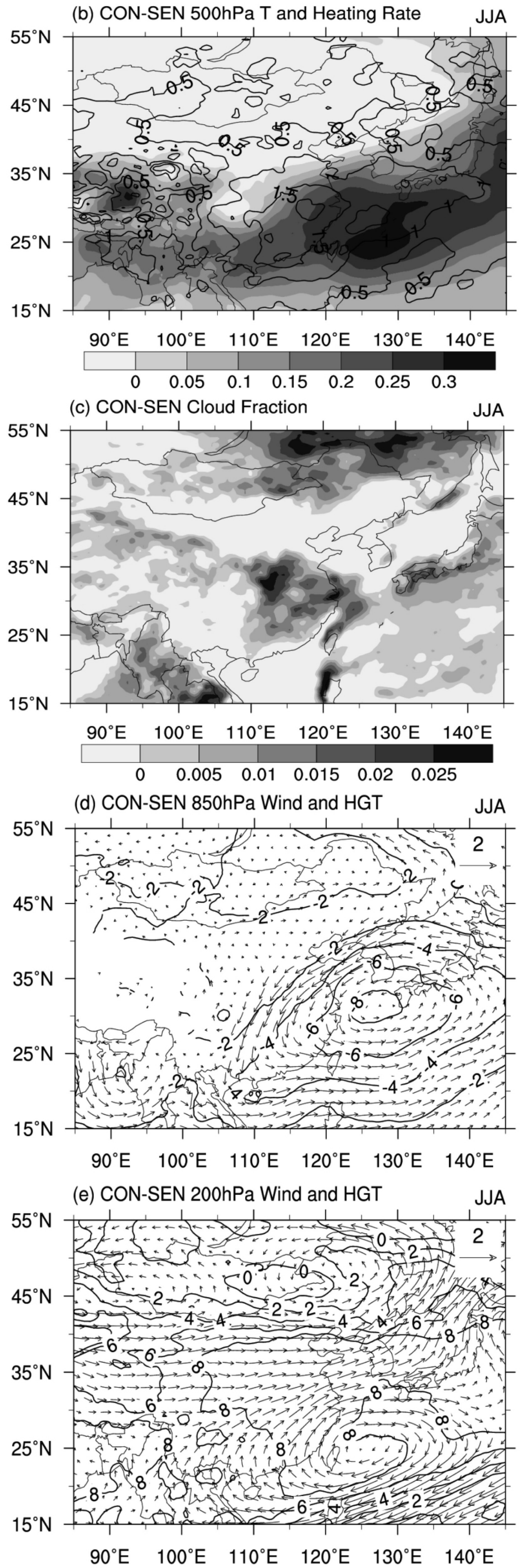



**Figure 6.** Summer radiative forcing differences between the top of atmosphere and surface (units: W/m$^2$) (a); 500 hPa temperature (contour; units: ℃) and shortwave heating rate (shaded; units: $10^{-6}$ K/s) (b), total cloud (c), 850 hPa wind (arrow; units: m/s) and geopotential height (contour; units: gpm) (d), 200 hPa wind (arrow; units: m/s) and geopotential height (contour; units: gpm) (e) differences between control and sensitivity experiment.

decline of geopotential height in the low-level atmosphere (850 hPa), and the negative variations of geopotential height could arouse cyclonic circulation anomaly. China's eastern monsoon region was located exactly on the west side of the circulation, thus it experienced the northerly wind. In contrast to the case in low-level atmosphere, the heating and temperature-rise regions at the level of 500 hPa witnessed an obvious increase of geopotential height in the high-level atmosphere (200 hPa). The positive variations of geopotential height could initiate anticyclonic circulation anomaly, and China's eastern monsoon region was located exactly on the west side of the circulation, thus experiencing the southerly wind. The low-level northerly wind and high-level southerly wind incurred by aerosols were exactly opposite to the low-level southerly wind and high-level northerly wind prevailing in the East Asian monsoon region in the summer. Thus, from the perspective of horizontal circulation, natural and artificial aerosols had an obvious weakening effect on EASM.

Besides changing the horizontal circulation of the East Asian monsoon region, aerosols also influence the vertical circulation of this region to some extent. Fig.7a shows the variations of mean surface radiative forcing with latitude caused by aerosols in the latitudinal domain 105°—120°E, revealing that aerosols exerted a negative radiative forcing action on the surface in the entire simulated region and the high-value centers of the absolute values of negative radiative forcing were mainly located in aerosol-concentrated regions (i.e., 25°—40° N, Fig.3). The negative surface radiative forcing caused by aerosols inevitably leads to the temperature decline of low-level atmosphere. Fig.7b exhibits the latitude-height cross section of the variations of mean temperature and meridional circulation incurred by aerosols in the latitudinal direction 105°—120° E. Notably, corresponding to the high-value centers of the absolute values of negative radiative forcing, the air below the height of 500 hPa experienced obvious temperature decline in regions north of 25° N. However, in regions south of 25° N, aerosols also led to negative radiative forcing but did not result in obvious temperature decline, because the introduction of aerosols in these regions slightly reduced the cloud cover (Fig.6c). Moreover, the reduction of cloud cover further increased shortwave radiation, and thus partially offset the temperature decline caused by the negative radiative forcing of aerosols. In regions north of 25°N, temperature decline resulted in obvious descending motion of the air, and, combined with the low-level northerly wind flow(Fig.6d) and the high-level southerly wind flow (Fig.6e), indirect meridional circulation anomaly was formed in the East Asian monsoon region. It was completely opposite to the summer meridional circulation of this region, as the latter was direct meridional circulation cell. Similar to the case of horizontal circulation, from the perspective of vertical circulation, natural and artificial aerosols also had an obvious weakening effect on EASM.

### 3.3 *Influence of aerosols on EASM precipitation*

Aerosols can weaken the strength of the summer monsoon, thus naturally it can also lead to the variations of summer precipitation. Fig.8a shows the variations of summer precipitation incurred by natural and artificial aerosols. Clearly, summer precipitation mainly presented a declining trend in the Chinese monsoon region, in particular, in Northern China and Southwestern China. The total reduction of summer precipitation was around 100 mm, and most areas of the above mentioned regions passed the significance test. The reduction of precipitation in the monsoon region was related to the change in the divergence of water vapor flux due to aerosols. Fig.8b exhibits the variations of the divergence of water vapor flux incurred by aerosols, indicating that in the eastern monsoon region north of 25°N , the divergence of water vapor flux largely experienced positive variations. Thus, the water vapor flux was in a divergence zone, which reduced the total summer precipitation. Aerosols can intensify the divergence of water vapor flux, because the variations of the divergence of water vapor flux caused by aerosols can be simplified into the sum of $D \times q'$ and $v' \times (\Delta q/\Delta y)$, wherein, $D$ represents the horizontal divergence, $q'$ represents the specific humidity variations caused by aerosols, and $v'$ represents the meridional speed variatiosn caused by aerosols. Aerosols can result in obvious northerly wind anomaly in low-level atmosphere in Eastern China (Fig.6d), that is, $v' < 0$. The weakening of the southerly wind also gives rise to the reduction of the specific humidity $q$, that is, $q' < 0$. For the Chinese mainland monsoon region, generally there are $D < 0$ and $\Delta q/\Delta y < 0$, thus $D \times q' > 0$ and $v' \times (\Delta q/\Delta y) > 0$, that is, aerosols can give rise to positive variations of the divergence of water vapor flux. The reduction of precipitation in the monsoon region was also closely related to the fact that aerosols have weakened the vertical circulation of the summer monsoon. In regions north of 25°N, the introduction of aerosols caused the descending motion of the entire level of atmosphere, and thus inhibited summer precipitation (Fig.7b). The introduction of aerosols did not lead to obvious reduction of summer precipitation in

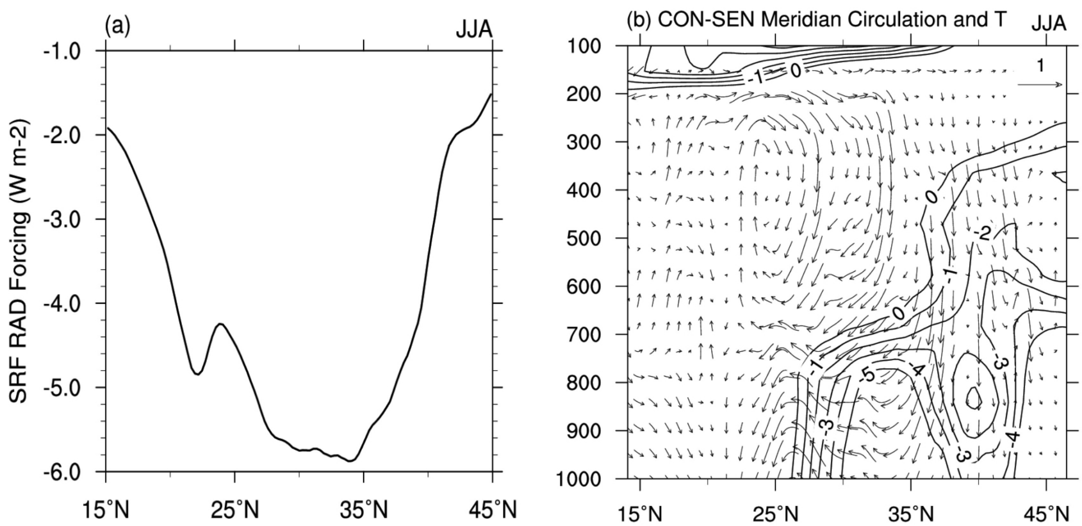



**Figure 7.** Summer radiative forcing (units: W/m$^2$) at surface averaged over 105°—120°E (a); latitude-height cross section of temperature (contour; units: ℃) and meridional circulation (arrow; $V$, units: m/s; $W$, units: $-10^{-2}$ Pa/s) differences between control and sensitivity experiment averaged over 105°—120°E (b).

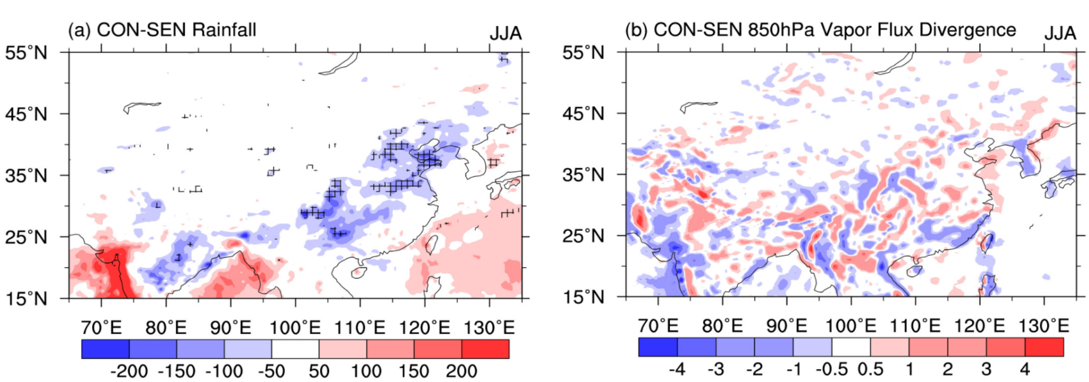



**Figure 8.** Precipitation (a, units: mm, line-shading indicates that the differences are significant at 95% confidence level) and 850 hPa water vapor flux divergence (b, units: $10^{-6}$ g/(cm$^2$·hPa·s)) differences between control and sensitivity experiment in summer.

Southeastern China, because the southerly wind of this region was not weakened (Fig.6d), and the divergence of water vapor flux was in its negative-value center (Fig.8b). This indicated that the water vapor flux was in its convergence zone, which was unfavorable for reducing summer precipitation.

## 4 CONCLUSIONS

In this study, the high-resolution regional climate model RegCM4.3 was adopted, and numerical simulation was conducted on EASM (1995—2010) through introducing dust, sea salt, sulfate, black carbon and organic carbon aerosols. Based on the model having satisfactorily simulated both EASM and aerosols, the possible influence of natural and artificial aerosols on EASM was comprehensively investigated and discussed, and following conclusions were obtained.

(1) Natural and artificial aerosols can reduce EASM indices by about 5%, and, except for the Southeastern China, they can delay the EASM onset time of the entire monsoon region by about one pentad.

(2) Natural and artificial aerosols have an obvious weakening effect on the horizontal circulation of EASM. In the Southeastern China and in offshore regions, aerosols absorb solar radiation, and exert a heating effect on middle-level atmosphere. When heated by aerosols, air columns expand, thus leading to a decrease of the geopotential height of low-level atmosphere and initiation of cyclonic circulation anomaly. They also lead to an increase of the geopotential height of the high-level and initiation of anticyclonic circulation anomaly. The northerly wind on the west side of cyclonic circulation anomaly can weaken the low-level southerly flow of EASM, and the southerly wind on the west side of cyclonic circulation anomaly can weaken the high-level northerly flow of EASM.

(3) Natural and artificial aerosols have a significant weakening effect on the vertical circulation of EASM. In regions north of 25°N, the negative radiative forcing produced by aerosols through scattering solar radiation results in the obvious temperature decline of the air below the height of 500 hPa. This further leads to the obvious descending motion of the air. Combined with the low-level northerly wind flow and the high-level southerly wind flow, indirect meridional circulation anomaly forms in the East Asian monsoon region. It is completely contrary to the summer meridional circulation of this region.

(4) Aerosols can intensify the divergence of water vapor flux in the Chinese monsoon zone, and thus obviously reduce the summer precipitation in this region, in particular, in Northern China and Southwestern China.

**REFERENCES:**

[1] OHARA T, AKIMOTO H, KUROKAWA J, et al. An Asian emission inventory of anthropogenic emission sources for the period 1980—2020 [J]. Atmos Chem Phys, 2007, 7: 4419-4444.

[2] ZHANG Xiao-ye. Aerosol over China and their climate effect [J]. Adv Earth Sci, 2007, 22(1): 12-16 (in Chinese).

[3] ZHANG Xiao-ye, LIAO Hong, WANG Fen-juan. The effects of aerosols and clouds on climate change and their responses [J]. Progressus Inquisitiones De Mutatione Climatis, 2014, 10(1): 37-39 (in Chinese).

[4] ZHANG L, LIAO H, LI J. Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China [J]. J Geophys Res, 2010, 115, D00K05.

[5] ZHU J, LIAO H, LI J. Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon [J]. Geophys Res Lett, 2012, 39, L09809.

[6] YAN L, LIU X, YANG P, et al. Study of the impact of summer monsoon circulation on spatial distribution of aerosols in East Asia based on numerical simulations [J]. J Appl Meteor Climatol, 2011, 50(11): 2270-2282.

[7] ZHOU Y, HUANG A, JIANG J, et al. Modeled interaction between the subseasonal evolving of the East Asian summer monsoon and the direct effect of anthropogenic sulfate [J]. J Geophys Res, 2014, 119 (5), doi: 10.1002/2013JD020612.

[8] WANG Yong, JI Zhen-ming, SHEN Xin-yong, et al. Causation analysis of the direct climate effects of anthropogenic aerosols on East-Asian summer monsoon[J]. J Trop Meteor, 2013, 29(3): 441-448 (in Chinese).

[9] CHEN Ming-cheng, SUN Zhao-bo, SHEN Xin-yong, et al. Simulation of anthropogenic aerosols' effect on East Asian summer monsoon in recent 22 years [J]. Trans Atmos Sci, 2014, 37(4): 395-404 (in Chinese).

[10] SHEN Xin-yong, CHEN Ming-cheng, WANG Yong, et al. Direct climate effect of anthropogenic aerosol on South Asian summer monsoon [J]. Plateau Meteor, 2013, 32(5): 1280-1292 (in Chinese).

[11] WAN J, RASHED M, LI S. Impact of European black carbon on East Asian summer climate [J]. Atmos Oceanic Sci Lett, 2013, 6(5): 375-380.

[12] WANG Zhi-li, ZHANG Hua, GUO Pin-wen. Effects of black carbon aerosol in South Asia on Asian summer monsoon [J]. Plateau Meteor, 2009, 28 (2): 419-424 (in Chinese).

[13] DENG Jie-chun, XU Hai-ming, MA Hong-yun, et al. A numerical study of the effect of anthropogenic aerosols over the Eastern China on East Asian summer monsoon onset and its northward advancement [J]. J Trop Meteor, 2014, 30(5): 952-962 (in Chinese).

[14] DENG Jie-chun, XU Hai-ming, MA Hong-yun, et al. The effects of anthropogenic aerosols over Eastern China on East Asian monsoons: simulation study with a high resolution CAM5.1 model [J]. J Trop Meteor, 2014, 30 (3): 567-576 (in Chinese).

[15] WANG Dong-dong, ZHU Bin, JIANG Zhi-hong, et al. Direct effect of sulfate aerosols on the process of the East Asian subtropical monsoon [J]. Chin J Atmos Sci, 2014, 38(5): 897-908 (in Chinese).

[16] JIANG Y, LIU X, YANG X, et al. A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation [J]. Atmos Environ, 2013, 70: 51-63.

[17] LIU Y, SUN J R, BAI Y. The effects of black carbon and sulphate aerosols in China regions on East Asia monsoons [J]. Tellus B, 2009, 61(4): 642-656.
[18] ZHANG H, WANG Z, WANG Z, et al. Simulation of direct radiative forcing of aerosols and their effects on East Asian climate using an interactive AGCM-aerosol coupled system [J]. Climate Dyn, 2012, 38: 1675-1693.
[19] LIU Chao, HU Hai-bo, ZHANG Yuan, et al. The direct effects of aerosols and decadal variation of global sea surface temperature on East Asia summer precipitation in CAM3.0 [J]. J Trop Meteor, 2014, 30(6): 1048-1060 (in Chinese).
[20] SHEN Xin-yong, HUANG Wen-yan, HUANG Wei, et al. Distributions and direct climate effects of dust and anthropogenic aerosols over Asia [J]. J PLA University Sci Technol, 2013, 14(6): 687-697 (in Chinese).
[21] SHEN Xin-yong, HUANG Wei, CHEN Ming-cheng, et al. Direct radiative effects of anthropogenic aerosols and their effects on the South Asian winter monsoon [J]. Clim Environ Res, 2014, 19(4): 393-406 (in Chinese).
[22] DICKINSON R, ERRICO R, GIORGI F, et al. A regional climate model for the western United States [J]. Clim Change, 1989, 15(3): 383-422.
[23] GIORGI F. Simulation of regional climate using a limited area model nested in a general circulation model [J]. J Climate, 1990, 3: 941-963.
[24] GIORGI F, COPPOLA E, SOLMON F, et al. RegCM4: Model description and preliminary tests over multiple CORDEX domains [J]. Climate Res, 2012, 52: 7-29.
[25] PAL J, GIORGI F, BI X, et al. The ICTP RegCM3 and RegCNET: Regional climate modeling for the developing world [J]. Bull Amer Meteor Soc, 2007, 88: 1395-1409.
[26] SOLMON F, GIORGI F, LIOUSSE C. Aerosol modeling for regional climate studies: application to anthropogenic particles and evaluation over a European/Africa domain [J]. Tellus B, 2006, 58B: 51-72.
[27] SHALABY A, ZAKEY A, TAWFIK A, et al. Implementation and evaluation of online gas-phase chemistry within a regional climate model (RegCM-CHEM4) [J]. Geosci Model Dev, 2012, 5: 741-760.
[28] ZAKEY A, SOLMON F, GIORGI F. Implementation and testing of a desert dust module in a regional climate model [J]. Atmos Chem Phys, 2006, 6(12): 4687-4704.
[29] ZAKEY A, GIORGI F, BI X. Modeling of sea salt in a regional climate model: fluxes and radiative forcing [J]. J Geophys Res, 2008, 113, D14221.
[30] SOLMON F, MALLET M, ELGUINDI N, et al. Dust aerosol impact on regional precipitation over western Africa: mechanisms and sensitivity to absorption properties [J]. Geophys Res Lett, 2008, 35, L24705.
[31] WANG B, WU Z, LI J, et al. How to measure the strength of the East Asian summer monsoon [J]. J Climate, 2008, 21: 4449-4463.
[32] WANG B, FAN Z. Choice of South Asian summer monsoon indices [J]. Bull Amer Meteor Soc, 1999, 80(4): 629-638.
[33] WU A, NI Y. The influence of Tibetan Plateau on the interannual variability of Asian monsoon [J]. Adv Atmos Sci, 1997, 14(4): 491-504.
[34] WANG An-yu, WU Chi-sheng, LIN Wen-shi, et al. The definition of the advance and retreat of the summer monsoon in China [J]. Plateau Meteor, 1999, 18 (3): 400-408 (in Chinese).
[35] LIAN Yi, SHEN Bai-zhu, GAO Zong-ting, et al. A method describing the subtropical summer monsoon active domain in the East Asia Northwest Pacific region [J]. Acta Meteor Sinica, 2007, 65 (4): 503-510 (in Chinese).

**Citation:** SHEN Xin-yong, HUANG Wen-yan and CHEN Hong-bo. The analysis of mechanism of impact of aerosols on East Asian summer monsoon index and onset [J]. J Trop Meteor, 2017, 23(4): 357-367.