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THE DIRECT EFFECTS OF AEROSOLS AND DECADAL VARIATION OF GLOBAL SEA SURFACE TEMPERATURE ON THE EAST ASIAN SUMMER PRECIPITATION IN CAM3.0

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Abstract: Using the CAM3.0 model, we investigated the respective effects of aerosol concentration increasing and decadal variation of global sea surface temperature (SST) around year 1976/77 on the East Asian precipitation in boreal summer. By doubling the concentration of the sulfate aerosol and black carbon aerosol separately and synchronously in East Asia (100–150 °E, 20–50 °N), the climate effects of these aerosols are specifically investigated. The results show that both the decadal SST changing and aerosol concentration increasing could lead to rainfall decreasing in the center of East Asia, but increasing in the regions along southeast coast areas of China. However, the different patterns of rainfall over ocean and lower wind field over Asian continent between aerosol experiments and SST experiments in CAM3.0 indicate the presence of different mechanisms. In the increased aerosol concentration experiments, scattering effect is the main climate effect for both sulfate and black carbon aerosols in the Eastern Asian summer. Especially in the increased sulfate aerosol concentration experiment, the climate scattering effect of aerosol leads to the most significant temperature decreasing, sinking convection anomalies and decreased rainfall in the troposphere over the central part of East Asia. However, in an increased black carbon aerosol concentration experiment, weakened sinking convection anomalies exist at the southerly position. This weakened sinking and its compensating rising convection anomalies in the south lead to the heavy rainfall over southeast coast areas of China. When concentrations of both sulfate and black carbon aerosols increase synchronously, the anomalous rainfall distribution is somewhat like that in the increased black carbon concentration aerosol experiment but with less intensity.

Key words: black carbon aerosol; sulfate aerosol; global decadal change of SST; East Asian summer monsoon precipitation; southern flood and northern drought
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1 INTRODUCTION

The change of precipitation is always an important topic in climate research. In recent decades (1955–2000), a rainfall phenomenon with negative rainfall anomalies in North China and positive anomalies over Yangtze River region and southeast coast areas of China often appears during Eastern Asian Summer Monsoon season, which is called the Southern Flood and Northern Drought precipitation pattern. Various observation results and simulation studies focus on this pattern [1–15]. Among them, Jiang et al.[3] showed that the South China Sea Summer Monsoon which formed earlier since 1970s, decreases south wind near the front of the Monsoon and increases the precipitation south of the Yangtze River. In fact, the summer precipitation pattern (Southern Flood and Northern Drought) over East China has a reverse change since 1970s. This precipitation pattern change highly possibly results from the East Asian Summer Monsoon interdecadal variation[1, 2, 6, 9, 10]. However, which factors lead to this interdecadal change of summer monsoon and precipitation?

Since the 1980s, the coastal cities in East China have experienced intensified urbanization and fast-growing industrialization, and the surface land use and properties in these areas have changed greatly. From the nighttime light value distribution, it can be found that the city boundary between 2010 and 1992 expands significantly in most parts of China, especially in East Asian coastal areas (100–150 °E, 20–50 °N). As

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a result, all kinds of observed aerosol emissions rise continually, and lead to the aerosol concentration increasing over East Asia [16 −19]. Aerosols have great radiation effects on Asian climate. Moreover, among all these aerosols, the sulfate aerosol and black carbon aerosol have different radiation characteristics, and may have different direct climate effects. The most obvious direct climate effect for sulfate aerosol is the scattering effect. This effect leads to negative radiation forcing on the land surface, which makes the land surface temperature decreasing and cools the lower layer atmosphere[20]. Sun et al.[21] pointed out that the sulfate aerosol causes reduced precipitation, weakened wind field and inhibited atmosphere convection over China in summer. Xu [12] argued that the summer monsoon rain belt shifts southward because of the increased sulfate aerosol emission in East China.

Compared to other aerosols, the black carbon aerosol has the unique absorbing radiation effect along with the scattering effect. The black carbon aerosol absorbs solar radiation first and then emits it, which also heats the lower atmosphere a little bit [22]. Wu et al.[23] and Zhang et al.[24] further indicated that the radiation effect of black carbon aerosol is positive in the tropopause, while negative on the land surface. Zhang et al. [24] also presented that such radiation effects of black carbon aerosol stabilize the tropospheric atmosphere, inhibit atmosphere convection, and decrease surface evaporation. When it comes to the climate effects of black carbon aerosol in summer, various studies have different conclusions. Mennon et al.[13] suggested that the increase of the black carbon aerosol may be the reason of the recent precipitation pattern changing in China and India. Similar conclusion can be found in Zhang and Yin [14], which suggests the increased black carbon aerosol emission leads to positive rainfall anomalies in central China but negative anomalies in North China [14]. However, reverse results can also be found in terms of the black carbon aerosol radiation scattering effect. For example, Zhang et al. [25] proposed that the increment of the black carbon aerosol concentration leads to increasing rainfall in North China and decreasing one in South China. In their model study, Gu et al.[26] found that the black carbon aerosol and large particle dust aerosol shifted the rainfall belt towards the direction of the Himalaya Mountains in China. Therefore, the sulfate and black carbon aerosols may have different climate effects due to their different radiation characteristics, and disputes exist about the black carbon aerosol climate effects. However, Hu et al.[27] pointed out that both the increased sulfate and black carbon aerosols concentration reduce rainfall in central East Asia and increase it in North China in their CAM3.0 experiments, because of the land surface warming in South China but cooling in North China in spring. However, when two types of aerosol concentrations increase respectively in East Asia in the same atmospheric model in summer, what will be the aerosols direct climate effects? Furthermore, what is the comprehensive direct climate effect when concentration of both aerosols increases synchronously? The study of Sun et al.[22] shows that the comprehensive effect may be very much like the sulfate aerosol direct climate effect, while the direct climate effect is not a simple linear combination among their various aerosol mixing cases. Then how will the East Asia Summer Monsoon and summer precipitation change when considering the increased concentration of sulfate and black carbon aerosols synchronously? Will there be relationship between the aerosol concentration change and the observed summer rainfall anomalies (Southern Flood and Northern Drought) in East Asia?

The studies above mostly discussed the radiation characteristics of the aerosol direct climate effects, while the direct and indirect climate effects of aerosol exist synchronously. The indirect climate effect of aerosol exerts on the cloud cover and cloud life cycle first, and then influences the land surface radiation balance and climate. For comparison of the importance between the aerosol direct and indirect climate effects, different researches have different conclusions. Wang et al.[28] showed that the indirect climate effect of sulfate aerosol is also very important and can cause the reduction of temperature and precipitation in China. Zhuang et al.[29] believed that the black carbon indirect climate effect decreases the lower atmosphere temperature and precipitation in China. Study of Chen et al. [30] described how the aerosol affects cloud microphysical processes, and presented that the increased aerosol concentration is the important reason for the autumn rainfall decrease in central and East China. However, Hu et al.[31] found that the aerosol indirect climate effect is not as obvious as the direct climate effect in influencing large-scale atmospheric circulation in their CAM5.0 experiments which contain the aerosol direct and indirect climate effects. Further more, Xu et al.[32] pointed out that the aerosol direct climate effect is much stronger than the indirect effect in East Asia, after comparing many results of numerical models, especially for sulfate aerosol.

In addition to the climate effect of aerosol on the East Asian summer climate, the sea surface temperature (SST) variation can also be very important. Fu et al.[15] showed that global SST change, regardless of tropical or extra-tropical oceans, has obvious effect on the increased rainfall in Yangtze River Basin. Zhou et al.[33] and Zeng et al.[34] believed that global SST tendency variation, especially the tropical SST variation, leads to the interdecadal change of East Asian climate through affecting the West Pacific Subtropical High (WPSH). Besides, the global SST interdecadal anomalies appeared around 1976/1977, close to the time of appearance of the Southern Flood and Northern Drought precipitation pattern.

The preceding analyses concluded that both the changes of aerosols' concentration and global SST interdecadal variation have important influence on the East Asian summer climate. Nevertheless, previous studies mostly emphasized the climate effect induced by SST interdecadal change or by one kind of aerosol concentration change. How do we correlate and distinguish the impact of aerosol concentration increment from that of SST anomalies? Since the black carbon aerosol has two opposite radiation effects, what will be its climate effect? And what are the specific physical mechanisms of these two types of aerosol climate effect? What is the comprehensive climate effect when considering the two types of aerosol concentration increasing synchronously?

Based on these discussions, the paper introduces the model, data and experimental design in the second part, describes the simulation results about the aerosol concentration increment and global SST anomalies for the East Asian summer climate with possible mechanisms, and gives the conclusion and discussion in the final part.

2 MODEL, DATA AND EXPERIMENT DESIGN

2.1 *Model introduction*

We use the Community Atmosphere Model 3.0 (CAM3.0) to study the influence of black carbon and sulfate aerosol concentration change on the East Asian summer climate. As the latest version of a series of global common atmospheric models developed by the National Center for Atmospheric Research (NCAR), CAM3.0 is also the atmospheric part of the Community Climate System Model 3.0. CAM3.0 can not only simulate atmospheric change as a climate model, but also couple with the ocean, sea ice and ecological model. The CAM3.0 model is a global spectral model, using triangular spectrum truncation, coupled with a relatively mature land surface model CLM3.0 (Community Land Model 3.0). The CAM3.0 model used in this paper has the Sigma-P hybrid coordinate of horizontal T85 spectral resolution (horizontal 128× 256) and 26 vertical layers (model top height at about 2.917 hPa). Sun et al.[21] found that although having certain deviation with satellite data in some areas, the model simulation results can show the main characteristics of the global aerosol concentration distribution, and has a good coincidence with satellite data in East Asia, especially in East China.

2.2 *Data introduction*

The observed data used in this paper includes hourly rainfall from 160 national reference climatological stations, and four-times-daily rainfall from 600 basic meteorological observation stations. The national reference climatological stations and basic meteorological observation stations are referred to as national meteorological stations, 760 in total. After strict quality control, this paper retains daily precipitation data for 594 national meteorological stations from 1955 to 2000, obtaining summer precipitation trend changes in China in 1955-2000.

In this paper, the United States military meteorological satellite program / linear scanning service system (Defense Meteorological Satellite Program/Operational Linescan System, DMSP/OLS) night-light data is also used. The data comes from the America Geophysical Data Center (http://www.ngdc.noaa.gov/ dmsp/downloadV4composites.html), with spatial resolution of 1 km. Low intensity light of city areas can be detected from the dark rural background. Therefore, the DMSP/OLS data can be used as an important information source to represent the human activities[35, 36]. In this paper we use the differences of the DMSP/OLS data between 2010 and 1992 to highlight the rapid growth of urbanization and industrialization in East Asia (100-150 °E, 20-50 °N) in the recent twenty years.

2.3 *Experiment designs*

The summer rainfall trend in China in the recent decades (1955-2000) shows that the precipitation in North China decreases, while that in the middle and lower reaches of Yangtze River Basin and the southeast coastal areas increases (Fig.1), which has been reported as the Southern Flood and Northern Drought precipitation pattern. From the DMSP/OLS nighttime light value distribution (Fig.2), the fastest developing urbanization and industrialization rates are shown in East Asia (100-150 °E, 20-50 °N), which may lead to the sharp increase of all kinds of aerosol emissions and affect the East Asia climate. In addition, the studies of Zheng et al.[16], Luo et al.[17] and quoted observation results from Lamarque et al.[18], Wang et al.[20], Wu et al.[23], Ji et al.[37] show the significant growth of all kinds of aerosol concentration in East Asia (100-150 °E, 20-50 °N). The black carbon and sulfate aerosols are the two representative aerosols, whose concentration increases quickly as the result of the fast-growing urbanization and industrialization in East China. Moreover, the observed data reveals that the East Asia has the maximum of both the aerosol concentration and thickness in climatology [19]. Figs.3B and 3C are the black carbon and sulfate aerosol concentration distribution in summer in East Asia simulated by CAM3.0, and the high-value areas of the aerosol concentration coincide with the research results mentioned above. The concentrated high-value areas are located around 30-35 °N, just as the city areas in the nighttime light-value distribution (Fig.2) in East Asia. In this paper, we will mainly discuss the direct climate effect due to the increase of the aerosol concentration in summer in East Asia (100-150 °E, 20-50 °N), as compared to the climate change caused by SST interdecadal variation. The experiment designs therefore consider the influence on the East Asian Summer Monsoon and precipitation when doubling the concentration of the sulfate aerosol and black carbon aerosol solely and two types of aerosol synchronously (when only the climatological SST forcing is considered in these experiments) in East Asia(100–150 °E,20–50 °N). Besides, another experiment designs climatological concentration of aerosols with continuous change of observed global SST for 40 years (1957–1996) in the same model.

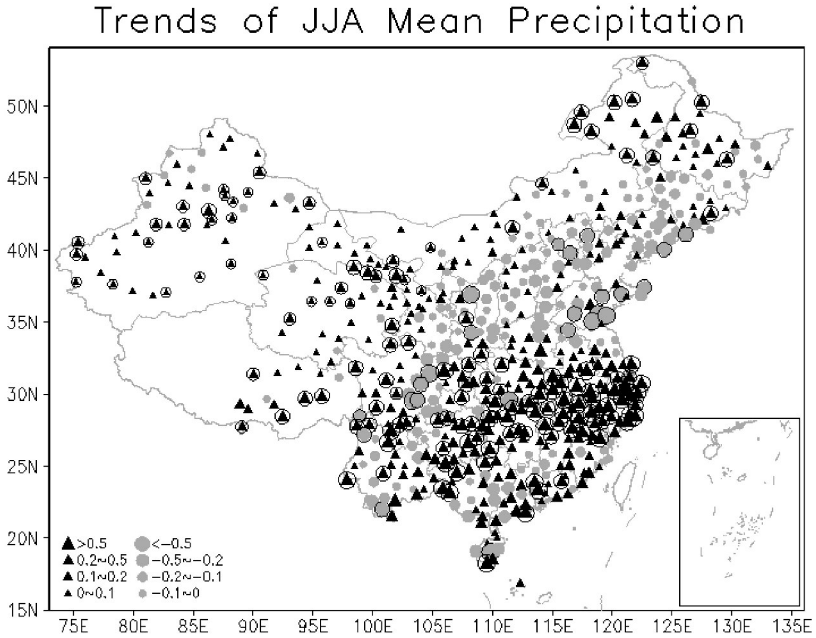

Figure 1. Spatial distribution of summer precipitation trends during 1955–2000 (unit: mm/10 years). The triangles and solid circles denote the value of the trends, while the open circles denote that the trend is significant at the 90% confidence level.

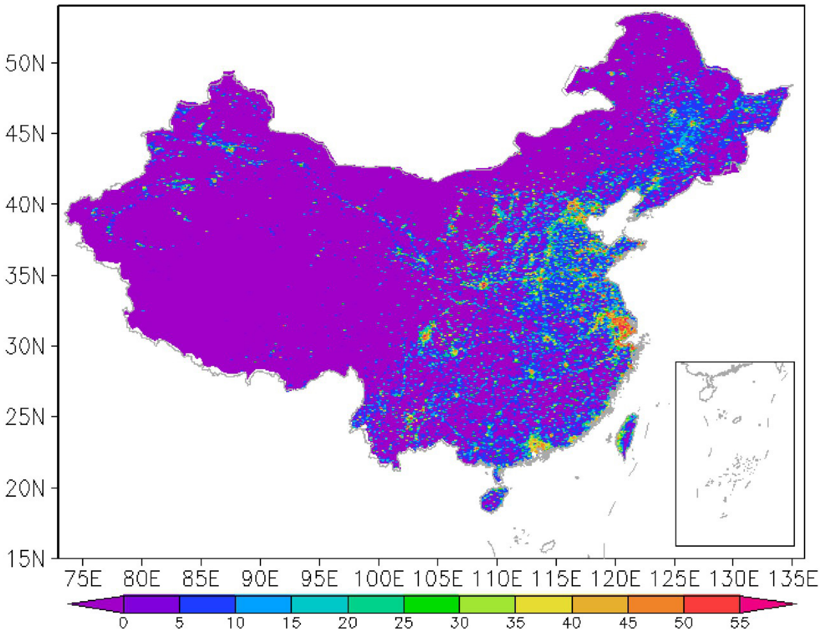

Figure 2. Differences of the DMSP/OLS nighttime light values between 2010 and 1992.

The experiments are divided into five groups. The first one is called CTRL_RUN for reference, which adopts the climatological global monthly SST and post-industrial revolution aerosol concentration as the forcing field. The CTRL_RUN integrates for continuous 20 years to extract the averaged meteorological elements in summer (JJA, the abbreviation for June, July and August). The second one takes into account the influence of SST interdecadal variation on the East Asian climate and uses observed global SST from 1957 to 1996 and the same aerosol concentration in CTRL_RUN. To get the SST interdecadal shift around 1976/77, we subtract the meteorological elements field averaged during 1977–1996 from that averaged during 1957–1976 in summer and note it as the SST experiment result. The third one is about the climate effect of doubling the sulfate aerosol solely, and the forcing filed in this experiment is the same as that of CTRL_RUN, except that the sulfate aerosol concentration in East Asia (100–150 °E, 20–50 °N) is doubled. This experiment integrates continuously for 20 years with climatological global SST, and the averaged meteorological elements in summer minus CTRL_RUN are defined as DSUL. The fourth one is about the climate effect of doubling the black carbon aerosol solely, and the forcing filed in this experiment is also the same as that of CTRL_RUN, except that the black carbon aerosol concentration in East Asia (100–150 °E, 20–50 °N) is doubled. Same as the third experiment, after integrating continuously for 20 years, the averaged meteorological elements minus CTRL_RUN are called DBC. The fifth one is about the climate effect of doubling the sulfate and black carbon aerosol synchronously. Similar to the third and fourth experiments, two types of aerosol concentrations are doubled in East Asia (100–150 °E, 20–50 °N) with 20 years of climatological global SST. The averaged meteorological elements minus CTRL_RUN are then called DTWO. Specific experiment designs can be seen in Table 1.

Table 1. Experiment design.

Groups	1(CTRL_RUN)	2 (SST)	3 (DSUL)	4 (DBC)	5 (DTWO)
Experiment Design	Reference experiment; the climatological field in summer	The averaged climatological field during 1977–1996 minus that during 1957–1976 in summer	The difference between the experiment doubling the sulfate aerosol concentration solely in East Asia and the reference experiment	The difference between the experiment doubling the black carbon aerosol concentration solely in East Asia and the reference experiment	The difference between the experiment doubling the two types of aerosol concentration synchronously in East Asia and the reference experimentt

3 SIMULATION RESULTS AND MECHANISM DISCUSSION

3.1 *Influence of SST interdecadal variation on East Asian summer climate*

The summer rainfall in CTRL_RUN is similar to the observed one, both reflecting significant precipitation in most areas of China, the Indochina Peninsula and the South Asian subcontinent. According to this summer precipitation distribution, the summer monsoon in CTRL_RUN contains significant East Asian Summer Monsoon and South Asian (Indian) Summer Monsoon. In East Asia (boxed region, 100–150 °E, 20–50 °N), the surface prevailing wind field is southeast winds in the south, but southwest winds in the north, with an overall anticyclone circulation (Fig.3a).

As described above, the North Pacific SST has an obvious interdecadal shift around 1976/77. As shown in Fig.3d, the SST anomalies around 1976/77 represent notable warming in North India Ocean, Northwestern Pacific and South China Sea, but striking cooling in North Pacific. Corresponding with this SST anomaly, previous study indicates generally warmer air temperature in China with less rainfall in the middle and lower reaches of Yangtze River Basin, but more precipitation in South China [38]. However, in the SST simulation, it can be seen that under the interdecadal SST anomaly forcing, the precipitation increases in the southeast coast areas of China, over the Indochina Peninsula, Northern Indian and Northwestern Pacific oceans after 1976. When it comes to the abnormal rainfall distribution in China, the results show reduced precipitation in the north of the Yangtze River and increased one in the southeast coastal area, just as the Southern Flood and Northern Drought precipitation pattern (Fig.4d). Then how does such wide range of precipitation interdecadal change correlates with interdecadal SST anomaly? Two main ways of SST anomaly affecting atmospheric circulation, the latent heat flux and the sensible heat flux from the ocean to the atmosphere, are analyzed. The results show that corresponding to the interdecadal precipitation anomaly distribution, the interdecadal difference of latent heat release is positive in Southern China, Northwestern Pacific and tropical Indian Ocean, while negative value is in Northeast China, north of the Indochina Peninsula and northern part of the whole Bengal Bay (Fig.5d). The abnormal interdecadal sensible heat anomaly is mainly negative in the whole Chinese mainland (figure omitted).

The latent heat release increases over the Northwestern Pacific and South China Sea, which enhances local lower atmosphere convergence, resulting in local cyclonic circulation (Fig.5d). This cyclonic circulation transports more water vapor over the Northwestern Pacific and promotes more precipitation there. At the same time, the interdecadal abnormal heating of the lower atmosphere over the Northwestern Pacific weakens the summer land-sea temperature difference in East Asia, and leads to north wind anomaly in the mainland area, especially south of the Yangtze River Valley (Fig.5d). The north wind anomaly reduces summer precipitation in the north of East Asia (Fig.4d), but converges in the Southeastern China coastal area with warm and wet cyclonic anomaly flows from the Northwestern Pacific, resulting in increased local precipitation (Fig.4d). Furthermore, induced by SST anomaly, the lower atmosphere interdecadal warming over the North Indian Ocean leads to intensified equatorial flow over the Indian Ocean, which enhances the South Asian Summer Monsoon under the geostrophic deflection. Stronger Summer Monsoon makes warmer and damper vapor transport northeastward, and eventually brings positive rainfall anomaly over the Indian Peninsula and the East Indian Ocean, as shown in Fig.4d.

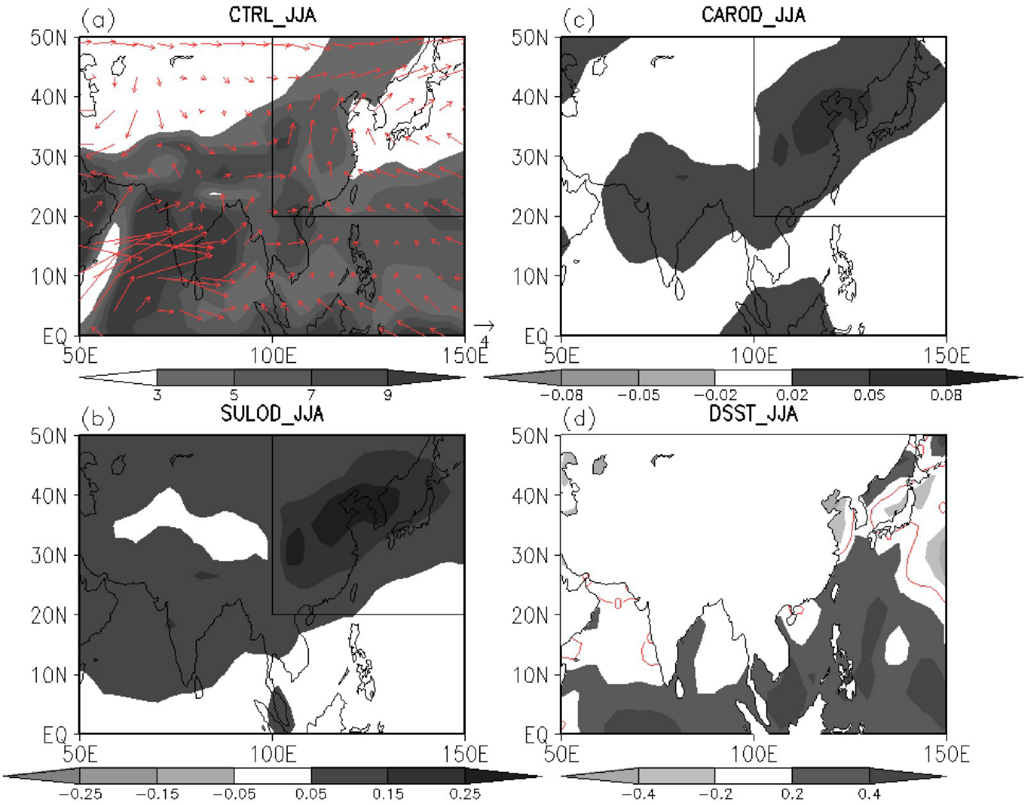

Figure 3. The spatial distribution of (a) summer precipitation (shading, unit: mm/d) and 850 hPa wind field (vector arrow, unit: m/s), (b) the sulfate aerosol thickness in 550 nm of wavelength (unit: optical thickness), (c) the black carbon aerosol thickness in 550 nm of wavelength (unit: optical thickness), (d) SST decadal variation (averaged SST in 1977–1996 minus that in 1957–1976).

3.2 *Influences of aerosol concentration increase on East Asian summer climate*

In addition to the climate effect of SST interdecadal variation on East Asian summer climate, we simultaneously or individually change aerosol concentration in East Asia in the same model, in order to distinguish the aerosol direct climate effect with the impact of interdecadal SST anomaly. Similarly, the impact of the aerosol concentration increment also reduces the rainfall in most of the areas north of the Yangtze River but increases that along the southeast coast areas of China, which is similar to the observed precipitation trend (Fig.1). The dividing line for precipitation with a reverse trend is about 25 °N (the boundary in the DSUL experiment is north of this dividing line, see Fig.4a, 4b, 4c), this precipitation trend happens to be opposite to that in spring[27]. In those three experiments on aerosol climate effect, doubling the sulfate and black carbon aerosol separately or simultaneously can all lead to reduced rainfall in most areas of the central East Asia. However, in the DSUL experiment, precipitation diminishes most obviously in the whole central East Asia. There is much increased precipitation along the southeast coast areas of China but decreased rainfall over the Northwestern Pacific and Indian oceans in all of the three aerosol experiments, distinguishing with that in the SST experiment (Fig.4). In all, the impact of the global SST decadal shift and the direct climate effect of the aerosol concentration increment can both result in the Southern Flood and Northern Drought precipitation pattern, only differentiating with the range and intensity of the rainfall. After the aerosol concentration increment, the latent heat release is corresponding to the precipitation anomaly distribution pattern, with negative release in central East Asia but positive one along the southeast coast areas of China. Bounded by about 30 °N in East Asia (the framed area), there exists northwest wind anomaly in the south but northeast wind in the north. How does the aerosol concentration increment lead to the change of the surface wind field?

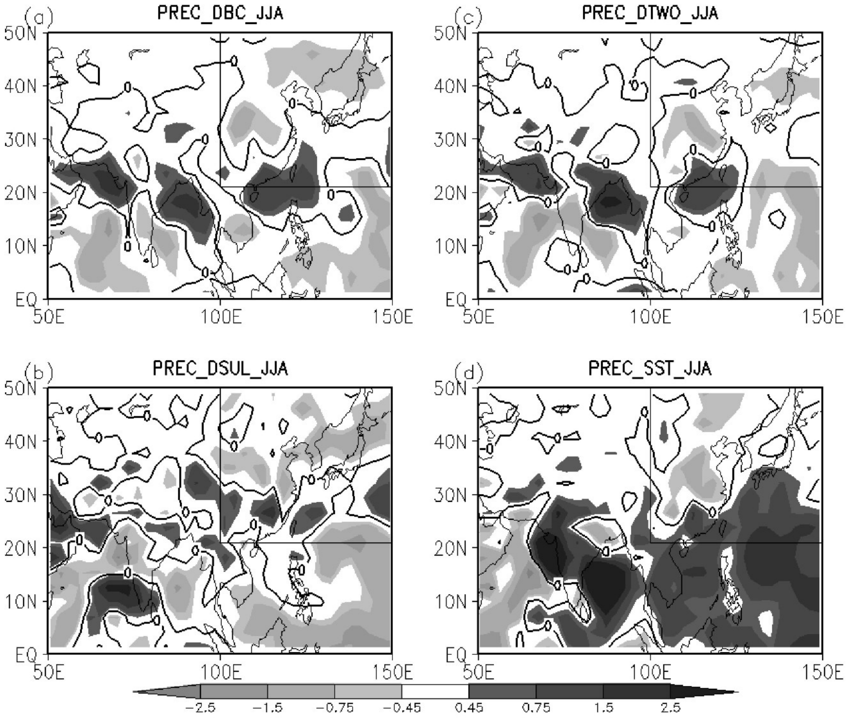

Figure 4. The summertime precipitation change (shading, the zero line in bold black line, unit: mm/d) with (a) doubling black carbon aerosol, (b) doubling sulfate aerosol, (c) doubling both two types of aerosols, (d) the SST decadal shift around 1976/1977. The shadow region is significant at the 90% *t*-test confidence level.

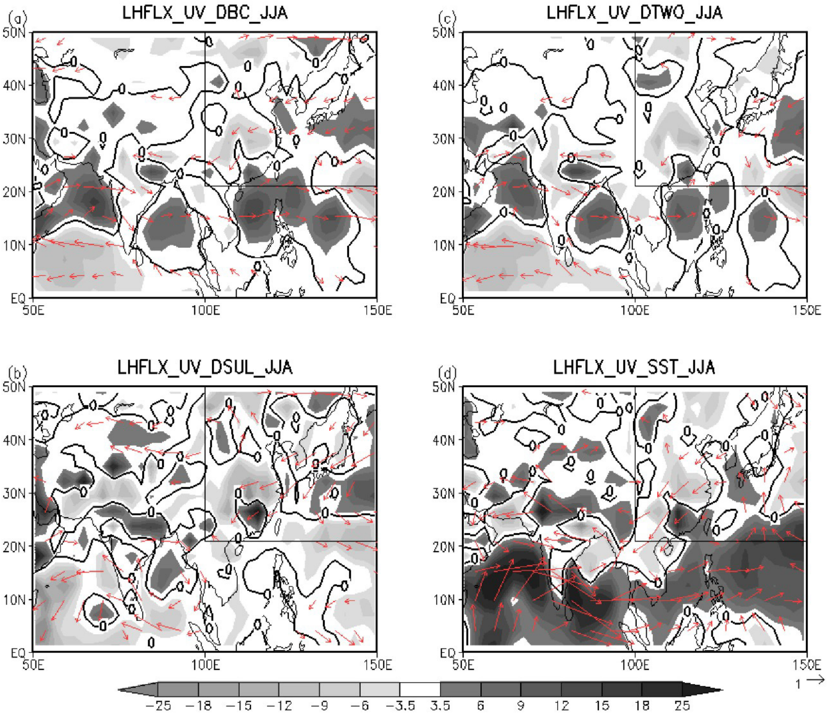

Figure 5. The summertime latent heat change (unit: W/m^2) with (a) doubling black carbon aerosol, (b) doubling sulfate aerosol, (c) doubling two types of aerosols, (d) the SST decadal shift around 1976/1977. The red arrow indicates the change of the 850 hPa wind field (unit: m/s). The shadow region and the anomalous wind arrow are significant at the 90% *t*-test confidence level.

Hu et al. [27] pointed out that the aerosol concentration increment in spring in East Asia cools the lower atmosphere and surface, weakens the westerly in mid-latitude and changes vertical secondary circulation. The sulfate and black carbon aerosols have similar climate effect, although there are great differences in their radiation characteristics [20-24, 37, 39]. Then, what about the mechanism of the climate effects of aerosol concentration increment in summer? Fig.6 gives the differences of lower atmospheric heating rate, the temperature distribution and the meridional circulation along the 110–120 °E after the change of the aerosol concentration in these three experiments. In fact, although the black carbon and sulfate aerosols have distinct characteristics, the summer clear-sky downward solar radiation flux received by the ground in DSUL, DBC and DTWO experiments are all negative (Fig.7), illustrating that any kind of aerosol has radiation shielding effect to cool the surface and lower atmosphere. Therefore, it can generally be inferred from Fig.6 that increasing the sulfate and black carbon aerosol concentration separately or simultaneously can all lead to the temperature change, with 35 °N as the dividing line, with the middle atmosphere warming in the north part of it but the lower atmosphere cooling in the south.

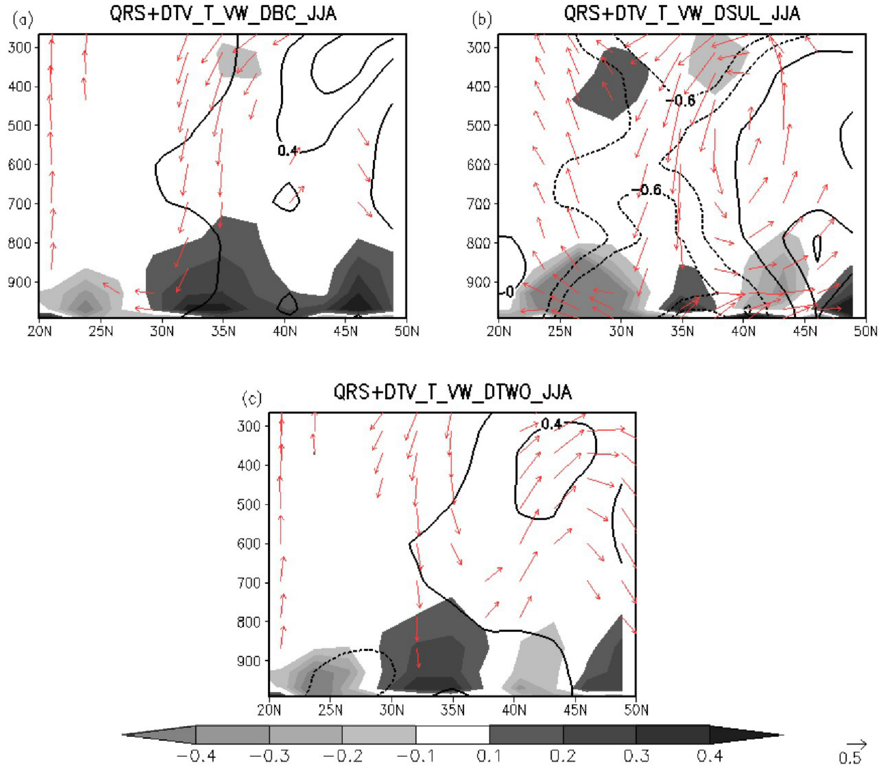

Figure 6. The summertime change of the temperature profile (contour, black bold, interval 0.2, unit: K), the shortwave heating rate adding the turbulent diffusion term (shading, unit: K/d), and the change of the meridional circulation (vector arrow, the wind unit is m/s and the vertical P velocity unit is -10^{-4} hPa/s) when doubling black carbon aerosol (a), doubling sulfate aerosol (b), doubling both two types of aerosols (c) along 110–120 °E,. The shadow region and anomalous wind arrow are significant at the 90% *t*-test confidence level.

However, the black carbon aerosol can also heat the atmosphere when the experiments involve doubling the concentration of the black carbon aerosol (the DBC and DTWO experiments). The calculated whole atmosphere net solar radiation flux shows obvious positive values in East Asia in the two experiments, especially in central East Asia (Fig.8), which illuminates the heating effect of the black carbon aerosol on the middle troposphere. Thus, when the sulfate and black carbon aerosol radiation properties are taken into account separately, it can be inferred from the figures that, the sulfate aerosol concentration increment results in notable negative anomaly in lower atmosphere shortwave heating and surface turbulent heating around 20–45 °N, because of its obvious scattering effect. Moreover, remarkable cooling around 30–40 °N (the range of the maximum sulfate aerosol concentration) can be seen in the DSUL experiment with stronger cooling range and intensity than that in the DBC and DTWO experiments. It is worth noting that significant cooling of the whole lower atmosphere appears after doubling the sulfate aerosol concentration (Fig.6b).

After the black carbon aerosol concentration is doubled, its scattering radiation effect causes less shortwave to be obtained by the ground directly, but its unique absorbing radiation effect warms the middle atmosphere around 30–40 °N where the two types of aerosol concentration reach their maximum. The cooling area in the DBC simulation is south of that in DSUL experiment, with weakened cooling range and intensity (Fig.6a). As a result, the black carbon aerosol concentration increment can also lead to the cooling of the lower atmosphere, but with weaker intensity and the cooling area being south to that in the DSUL experiment. When both of the aerosol concentrations are doubled, the heating rate and temperature distribution in the lower atmosphere are similar to those in the DSUL experiment, while those in the middle atmosphere are determined by the radiation characteristics of the black carbon aerosol (Fig.6c).

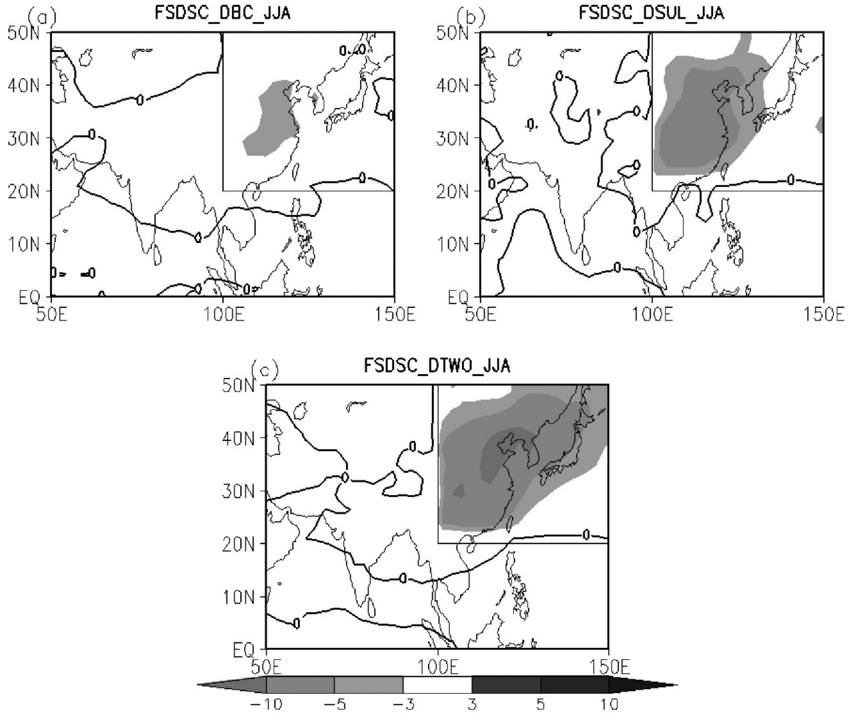

Figure 7. Summertime clear-sky ground-received downward solar radiation flux with (a) doubling black carbon aerosol, (b) doubling sulfate aerosol, (c) doubling both aerosols synchronously in East Area. Unit: W/m^2, the coloring part is significant at the 90% t-test confidence level.

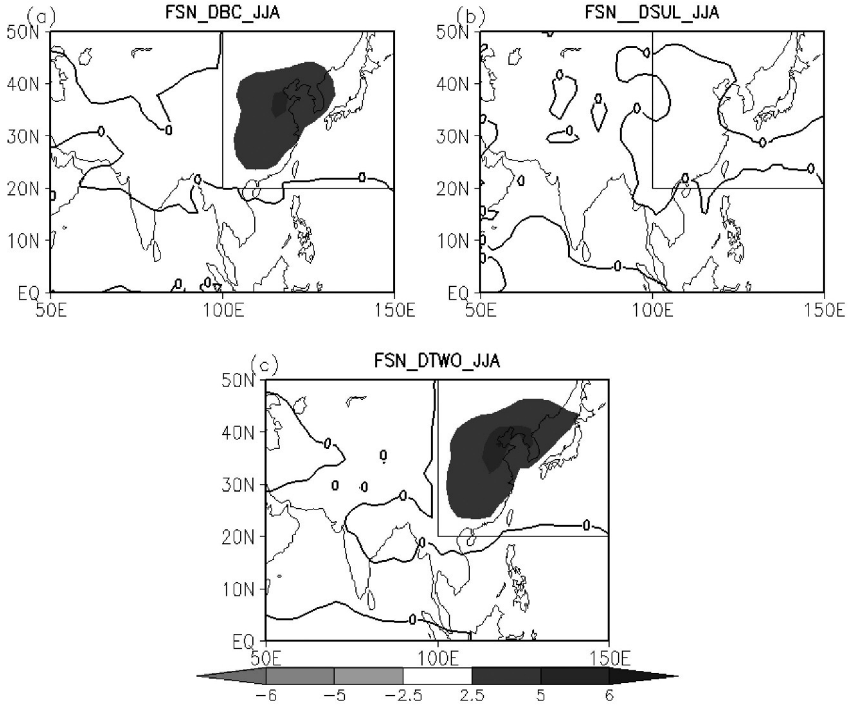

Figure 8. The distribution of the figures and the unit of the variables are the same as that in Fig.7, but for the whole atmosphere net solar radiation flux.

From the above analyses, it is known that similar aerosol radiation shielding effect warms the middle atmosphere north of 35 °N and cools the lower atmosphere south of 35 °N in the DSUL, DBC and DTWO experiments. This temperature change generates abnormal subsidence and induces vertical secondary circulation. Specifically speaking, in the DSUL experiment, the most obvious lower atmosphere cooling due to the doubling of the sulfate aerosol leads to strongest sinking anomaly around 35 °N among the three aerosol doubling concentration experiments, and induces two vertical secondary circulations with the rising branch located around 20 °N and the other one located around 40 °N. While in the DBC experiment, the black carbon aerosol's radiation scattering and absorbing effects result in weakened surface cooling and abnormal sinking south to that in DSUL experiment, with a compensating uprising flow around 20 °N. This southward deflected abnormal rising flow in the DBC experiment results in stronger precipitation anomaly in the southeast coast areas of China (Fig.4a). In the DTWO experiment, the total radiation effect of the sulfate and black carbon aerosol makes the abnormal sinking flow weaker than that in the DSUL experiment. However, there are still two compensating uprising flows, and the southern branch of which is at the same position as that in DBC experiment but with weaker intensity. Therefore, in the DTWO experiment, the rainfall anomaly is at the same position as that in the DBC experiment but with weaker intensity (Fig.4c).

4 SUMMARY AND DISCUSSION

The paper finds that through CAM3.0 simulations, both the global SST interdecadal shift and the aerosol concentration increment can lead to the reduced rainfall in most areas north of the Yangtze River but increased one in southeast coast areas of China, which presents as the Southern Flood and Northern Drought precipitation pattern. The global SST interdecadal variation around 1976/77 shows significant abnormal warming in the North Indian and Northwestern Pacific Oceans but cooling in subtropical North Pacific. The maintaining of this abnormal warming enhances local lower atmosphere convergence, makes more water vapor transport over the North Indian Ocean and Northwestern Pacific, generates abnormal cyclonic circulation locally, and results in significantly more rainfall over there. Because of the background of the interdecadal lower atmosphere heating over the Northwestern Pacific, the summer land-sea temperature differences in East Asia are weakened. Then, north wind anomaly, together with reduced summer precipitation, appears in the north of the East Asian continent. However, in the southeast coast areas of China, the north wind anomaly from the north converges with warm and wet south wind anomaly from Northwestern Pacific, generating heavy rainfall.

The aerosol concentration increment in the three aerosol experiments also has the Southern Flood and Northern Drought precipitation anomaly pattern. However, the precipitation patterns over the oceans, especially over the North Indian Ocean in these experiments, are different from that in the SST experiment. The aerosol concentration increment and the aerosol shielding effect in the model cool the whole atmosphere around 30–35 °N (the area where the aerosol concentrations reach their maximum in the model). Among them, because of the scattering effect of sulfate aerosol, the results of the DSUL experiment show the most significant cooling intensity and range. However, in the DBC experiment, weaker cooling intensity exists in the middle troposphere with a southward deflected compensating rising flow, due to the absorbing radiation effect of black carbon aerosol. When both radiation effects of two aerosols are taken into consideration, the response of the whole atmosphere falls between the two results above. The shielding effect of aerosol concentration increment cools the surface land and lower atmosphere of central East Asia, generates sinking anomaly and decreases precipitation in North China, but induces a compensating rising flow and more precipitation in South China. The most significant lower atmosphere cooling and abnormal sinking low in central East Asia exist in the DSUL experiment. This sinking anomaly leads to two compensating rising flows, with the northern branch of which being stronger. However, in the DBC experiment, the abnormal sinking flow in central East Asia is weakened and southward deflected, which results in a southward compensating rising flow. Although this compensating rising flow has weaker intensity, its location makes the precipitation anomaly more significant compared to that in the DSUL experiment. When the climate effects of two types of aerosol are considered at the same time, the induced sinking anomaly in central East Asia is relatively weak, but there are two compensating rising flows, the southern branch of which is the same as that in the DBC experiment. As a result, the location of the abnormal rainfall in the DTWO experiment is similar to that in the DBC experiment, but with weaker intensity.

The four experiments indicate that both the aerosol concentration increment and the global SST interdecadal variation can lead to increased rainfall in southeast coast areas of China. However, there are little differences between the rainfall trend change and the observed one in the lower reaches of Yangtze River Basin, which may be caused by excluding the indirect climate effects of aerosol in the CAM3.0 numerical model. In fact, the importance of aerosol indirect climatic effects needs further understanding [23-26]. The aerosol indirect climate effects, the influences of other factors such as the Tibetan Plateau, and as well as the interaction between the aerosol concentration distribution and the East Asian

Summer Monsoon intensity [40], are all not discussed in this work. The urbanization and industrialization process in East Asia is with very strong regional heterogeneity, for example, the observed aerosol concentration is increasing significantly in city clusters of the Yangtze River Delta and the Pearl River Delta in China [41], and this uneven regional change may lead to more complicated impacts on East Asian summer precipitation.

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