J. Ocean Univ. China (Oceanic and Coastal Sea Research)
DOI 10.1007/s11802-015-2472-9
ISSN 1672-5182, 2015 14 (4): 585-595
http://www.ouc.edu.cn/xbywb/
E-mail:xbywb@ouc.edu.cn

The Different Effects of Sea Surface Temperature and Aerosols on Climate in East Asia During Spring

HU Haibo[1), *], LIU Chao[1)], ZHANG Yuan[2)], and YANG Xiuqun[1)]

1) *School of Atmospheric Sciences*, *Nanjing University*, *Nanjing* 210093, *P. R. China*
2) *School of Atmospheric Sciences*, *Nanjing University of Information Science and Technology*, *Nanjing* 210044, *P. R. China*

(Received September 3, 2013; revised October 14, 2013; accepted November 6, 2014)

Abstract In this study, we used the NCAR CAM3.0 model to study the climate effects of both decadal global Sea Surface Temperature (SST) changing and the increasing aerosol concentration in East Asia in boreal spring. In the decadal SST changing experiment, a prominent sea surface cyclone anomaly occurred west of the Northwest Pacific warming SST. The cyclone anomaly is conductive to anomalous rising motion and more rainfall over the Northwest Pacific and southeast coast areas of China, but less rainfall in central China. Caused by the only aerosol concentration increasing, the change of climate in East Asia is totally different from that induced by the regime shift of SST around 1976/77 with the same model. The sulfate and black carbon aerosol concentrations were doubled respectively and synchronously in East Asia (20˚–50˚N, 100˚–150˚E) to investigate the climate effects of these two major aerosol types in three experiments. The results show that, in all three aerosol concentration changing experiments, the rainfall during boreal spring increases in North China and decreases in central China. It's worth noting that in the DTWO experiment, the rainfall diminishes in central China while it increases in the north and southeast coast areas of China, which is similar to observations. From the vertical profile between 110˚E and 120˚E, it is found that sulfate and black carbon aerosols first change the temperature of lower troposphere owing to their direct radiative effect, and then induce secondary meridional circulation anomaly through the different dynamic mechanisms involved, and at last generate precipitation and surface temperature anomalous patterns mentioned above.

Key words decadal shift of SST; aerosol; boreal spring; precipitation decrease; central-south China

1 Introduction

In East Asia, the spring rainfall is of great importance for crop's early growing and agriculture water resource control, which extends from South China to the mid-North Pacific. Xin *et al.* (2006) found that there has been a significant decrease of the late spring (21 April–20 May) precipitation over central and South China (26˚–31˚N, 110˚–122˚E) since the late 1970s. Especially in 2011, a major lack of spring rainfall has led to severe drought in central China, which has reduced the important waterway of Huai River to about one-sixth of its normal size. And the water levels of many lakes in central China were also reported to have reduced to the 'dead level'. The trend pattern of the spring observed precipitation from 1960 to 1990 (31 years) is shown in Fig.1.

It can be seen that there are increased rainfalls along the southeastern coast areas of China and North China, while along the Yangtze River in central China, there is a continuous belt of diminished rainfall (Yang and Lau, 2004; Xin *et al.*, 2006; Kim *et al.*, 2007; Endo *et al.*, 2009). Previous studies indicated that the change of sea surface temperature (SST), especially the basin warming trend of SST in the Indian and Northwest Pacific Oceans, may be connected to this precipitation changing (Yang and Lau, 2004). Xin *et al.* (2006) explored the North Atlantic Oscillation (NAO) changing in the preceding winter leading to the obvious upper troposphere cooling and less spring rainfall over East Asia. And Kim *et al.* (2007) showed that the global aerosols increasing can also lead to the precipitation changing over central and Southeast China during the boreal spring. So besides the regime shift of SST (Nakamura *et al.*, 1997; Nathan *et al.*, 1997; Zhang *et al.*, 1997), the change of East Asia aerosol concentration may be also important in rainfall trend of observation over the East Asia (Lee and Kim, 2011), especially considering the express industrialization and urbanization along the Yangtze River in East China in recent years (Fig.2).

Sulfate and black carbon are two of the most important anthropogenic aerosols, which will lead to a direct aerosol radiative forcing, and will change atmosphere circulation and regional water cycle (Ramanathan *et al.*, 2001). The sulfate aerosol is characteristic of radiation scattering

* Corresponding author. Tel: 0086-25-89681197
E-mail: huhaibo@nju.edu.cn

(negative radiative forcing), and then would lead to a cooling surface (Ramanathan *et al.*, 2005). However, the radiative effect of black carbon aerosol is quite different, for it could warm the atmosphere by absorbing the solar radiation (Liu *et al.*, 2009). Liu *et al.* (2009) also recognized that sulfate aerosol reduces surface temperature and precipitation in large parts of China during both summer and winter time, with weakened summer monsoon. Kim *et al.* (2007) showed that the cooling of the land surface and reduction in rainfall over central East Asia is caused by the radiative forcing of sulfate aerosol. Menon *et al.* (2002) suggested that black carbon aerosol can lead to the increased summer rainfall in south China, and drought in North China, but the contrary conclusion is reached by Zhang *et al.* (2009). The results of Lau *et al.* (2006) suggest that the enhancements of rainfall and Indian summer Monsoon over northern India are caused by the increasing of black carbon emission during late spring. Jiang *et al.* (2013) studied the different effects of sulfate and BC on East Asia summer rainfall using CAM5.0 model; they found that the noticeable effect of temperature changes from BC is on reducing the low-level cloud fraction, and they also discussed the circulation and summer precipitation changes induced by the temperature change in East Asia. By using the CAM5.1 model, Hu and Liu (2013) gave the effects of different climate forcing such as aerosols, greenhouse gases and SST on the decadal variation of late spring precipitation in South China. And they found the change of the global total aerosol concentration could lead to the decreasing trend of late spring precipitation in South China from 1950 to 2000. So, considering the climate effect of aerosol on the East Asia summer and winter monsoons, large numbers of experiments have been done, but the conclusion is still uncertain (Chung *et al.*, 2002; Kim *et al.*, 2006; Gu *et al.*, 2006; Meehl *et al.*, 2008; Liu *et al.*, 2009; Lee and Kim, 2011; Liu *et al.*, 2011; Yoon *et al.*, 2010; Zhang *et al.*, 2010; Zhao *et al.*, 2010).

There are already a number of researches on illuminating the trend of East Asia Summer Monsoon, which may be caused by the global sea surface temperature changing or the climate effect of aerosols. However, there are only fewer researches concerning the mechanism of precipitation trend in spring, which is so important for agriculture and water source management in East Asia. In this work, we try to address the following questions: what is the respective and integrative climate effect of East Asia sulfate and black carbon aerosols in spring? Considering the different radiative effects of sulfate and black carbon aerosols, would they produce opposite climate effects? What would happen to the precipitation climate change over East Asia if the global decadal SST shift is the only forcing, and would this induced climate change be similar to that caused by the aerosols changing in the same model?

The Section 1 of this article introduces the model we used and the model experiments. The second part describes the climate changes resulting from aerosols concentration changing and SST regime shift, and the last one tries to give an explanation and conclusion.

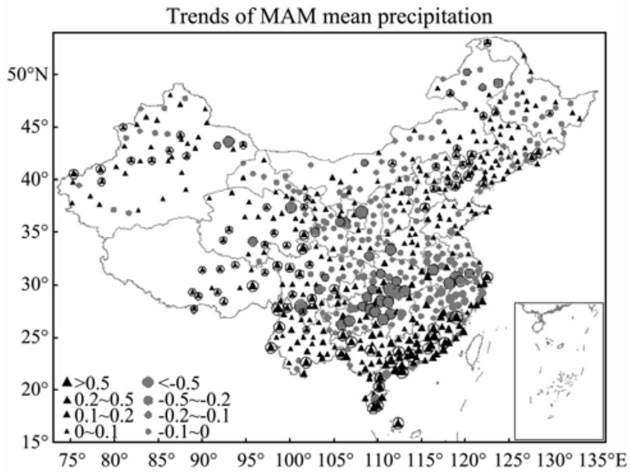

Fig.1 Spatial distribution of spring precipitation trends during 1960–1990. The triangles and solid circles denote the value of the trends, while the open circles denote that trend is significant at 90% confidence level (Unit: mm per decade).

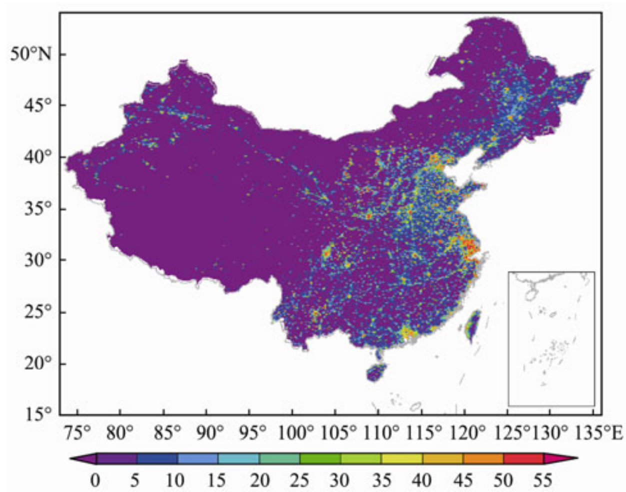

Fig.2 Differences of the DMSP/OLS nighttime light value between 2010 and 1992.

2 Data and Model

2.1 Data and Methods

The observed rainfall data used in this paper include hourly precipitation from 160 national reference climatological stations, and the daily data from 600 basic meteorological observation stations. After strict quality control, we retained the daily precipitation data of 594 National Meteorological Stations from 1960 to 1990. Thus we get the China spring rainfall trend changes in 1960–1990.

We also used the United States military meteorological satellite program/linear scanning service system (Defense Meteorological Satellite Program/Operational Linescan System, DMSP/OLS) night-light data in this paper. The DMSP/OLS data is from the American Geophysical Data Center (http://ngdc.noaa.gov/eog/), the spatial resolution being 1 km. In this dataset the low intensity light of city area can be detected from the dark rural background.

Therefore, the DMSP/OLS data can be used as a representation of human activities (Wang *et al.*, 2012). In this paper, we use the difference of DMSP/OLS image between 2010 and 1992 to highlight the rapid growth of the industrial city in East Asia region (100˚–150˚E, 20˚–50˚N) in recent twenty years.

2.2 Model and Experiments

In this paper, the Community Atmosphere Model (CAM) 3.0 (http://www.cesm.ucar.edu/models/cesm1.0/cam/), which is released by the National Center for Atmospheric Research (NCAR), is used to investigate the impacts of aerosols concentration increase and the SST regime shift on the East Asia climate changing. CAM3.0 itself contains an atmosphere model (Collins *et al.*, 2004, 2006) and a well-developed land surface model (CLM 3.0) described in Oleson *et al.* (2004) and Dickinson *et al.* (2006). Not only can CAM3.0 be operated independently on atmospheric processes, but it can also be coupled with other earth process modules such as ocean, sea ice and ecology. In the model, there are 26 vertical levels using σ–P coordination and T42 horizontal resolution and the top boundary of this model is at 2.917 hPa level. Also, in the model initialization there are 3D five aerosol (sulphate, dust, sea-salt, organic carbon and black carbon) species and the optical parameters from MATCH (Barch *et al.*, 2000; Rasch *et al.*, 2000; Smith *et al.*, 2001; Zender *et al.*, 2003; Mahowald *et al.*, 2003; Liousse *et al.*, 1996; Cooke *et al.*, 1999). From model evaluation of Liu *et al.* (2009), the model is capable of reproducing the global main climatic characteristics. Thus we could use this model to do this study.

Not only the simulations of various studies (Lamarque *et al.*, 2010; Meehl *et al.*, 2008) but the observations (Kim *et al.*, 2006; Chung *et al.*, 2005) proved that aerosols in East Asia (100˚–150˚E, 20˚–50˚N), especially sulfate and black carbon aerosols, have a prominent increase due to human activities (Fig.2). Consequently, we investigate the climate effects resulting from adding aerosols in this area (100˚–150˚E, 20˚–50˚N). To understand the climate effect of aerosol, previous studies always made a comparison between the results with and without one certain specific aerosol. In this paper, we think over the concentration increasing of the sulfate and black carbon aerosols in East Asia (100˚–150˚E, 20˚–50˚N), with the influence of anthropogenic emissions taken into account.

The model experiments are divided into five groups (as in Table 1): the first one is called CTRL, which is integrated for 20 years with climatological monthly mean global sea temperature and the climatological global aerosols concentration after the industrial revolution, and the 20-years mean MAM (March, April, and May) state is used for comparing. The second one is also integrated for 20 years using the same forcing but doubling the sulfate aerosol concentration in East Asia, the group called DSUL. Differing from the second one, the third experiment (DBC) doubles the black carbon aerosol concentration in the same region. In the fourth experiment, both the sulfate and black carbon aerosols are doubled synchronously, and the experiment is named DTWO, The last experiment is integrated for 20 years twice, with two 10-year means climatological global SST (1977–1986 and 1967–1976) and climatological aerosol concentration as in CTRL. The difference state (1977–1986 minus 1967–1976) of two 10-year mean MAM is called SST experiment. In many studies, the detailed trend and variability of SST in global ocean have been documented. Just as the description in Zhang *et al.* (1997) and Xue *et al.* (2003), the SST differences between the mean values of 1977–1986 and 1967–1976 show that warming SST anomalies exist over the western tropical Pacific and tropical Indian Ocean, while cooling SST anomalies occupy the central North Pacific.

Table 1 Model experiments for MAM (March, April, and May)

Group	Experiment design
1 (CTRL)	Mean MAM state with climatological SST and aerosols concentration
2 (DSUL)	Mean MAM state of doubling East Asia sulfate aerosol concentration minus CTRL
3 (DBC)	Mean MAM state of doubling East Asia black carbon aerosol concentration minus CTRL
4 (DTWO)	Mean MAM state of doubling two kinds of aerosol synchronously in East Asia minus CTRL
5 (SST)	The MAM state difference between two different climatological SST (1977–1986 and 1967–1976) forcing experiment

3 Simulation Results

3.1 Climatological Features

As proved by Liu *et al.* (2009), CAM3.0 is capable of simulating the spring rainfall in East Asia, and the simulated spring rainfall in CTRL mostly appears in central China and along the eastern coast of China as observed. When the concentration of aerosol is doubled, the results of group 2, 3 and 4 (Figs.3a, b, c) all reveal that the precipitation in East Asia diminishes in the south but increases in the north, with 38˚–39˚N as the demarcation line. Comparing these results, we also found that the precipitation variation caused by the concentration changing of sulfate aerosol (DSUL) is more significant than that caused by black carbon aerosol (DBC). Especially in the experiment with both two aerosol concentrations doubled synchronously (DTWO), the rainfall decreases in central China but increases over the southeast of China, being just the same as the observations (Xin *et al.*, 2006; Kim *et al.*, 2007). When it comes to the 850 hPa wind field changing, anomaly induced by the sulfate aerosols is also stronger than that induced by black carbon aerosols. And the prevailing convergence exists north of 38˚N over mainland China, while divergence is in the south. Detailed explanation concerning the wind change would be given in Part 2.2. For the surface temperature, a demarcation line always exists around 35˚–36˚N in the aerosol experiments (Figs.4a, b, c), and opposite temperature anomalies are present on the both sides of this demarcation line (the demarcation line of black carbon aerosol doubling experiment exists a little south). In the DSUL experiment, the strongest and widest temperature changing appears, and obvious surface warming exists in the Yangtze River Basin and South China, while cooling in Inner-Mongolia and northeastern China. Similar distribution characteristics also can be found in the distribution of low cloud amount anomalies. But to the contrary, the warming surface temperature anomalies exist in the region with decreased low cloud cover, and cooling anomalies are consistent with the increased low cloud amount.

Wang *et al.* (2000) proposed a teleconnection mechanism to explain the effect of ENSO like SST anomalies on East Asian climate. This mechanism indicates the importance of the strength of the anticyclonic anomaly over Northwest Pacific. In addition to the SST anomaly in the tropical Pacific, SST anomalies in other oceanic regions, especially the South China Sea and the Indian Ocean, are also found to be very important to the East Asian Summer Monsoon variation (Huang and Lu, 1989; Shen and Lau, 1995; Nitta and Hu, 1996; Wu *et al.*, 2003). The regime shift of SST around 1976/77 can also affect the spring rainfall over East Asia (Fig.3d). The figure shows that the precipitation reduces over almost the whole Chinese Mainland, while increasing over the Arabian Sea, South China Sea and southeast coast of China. And a cyclone anomaly appears in the lower altitude west of the northwest Pacific and South China Sea warming SST (Yang and Lau, 2004). In the SST experiment, warm surface temperature anomaly appears in the northeastern China and Inner-Mongolia, while a weak cooling appears over the central-west China (Fig.4d).

Previous studies convince us that the most important direct effect of aerosols is on the clear sky downward solar radiation when the concentration of aerosols alters. For the three groups of aerosol experiments, the reduction of the clear sky net solar flux at surface (Fig.5) could be seen easily, especially when the two aerosols concentration doubled synchronously (DTWO).

Thus, both sulfate and black carbon aerosol can cut down the clear sky downward solar radiation. From the clear sky net solar flux in the atmosphere (Fig.6), a notable heating effect is procured after doubling black carbon aerosol concentration, while almost no alteration is observed in the sulfate aerosol changing experiment, which tells us that only the black carbon aerosol contributes to heating the atmosphere.

The surface latent heat flux anomalies (Fig.7) agree well with the precipitation anomalies (the total precipitation of convective, large-scale and shallow convection) in DBC experiment. This indicates that the variation of precipitation in DBC is mainly caused by the surface latent heat release, and then warms atmosphere in the mid-altitude. For the DSUL, DTWO and SST experiments, the

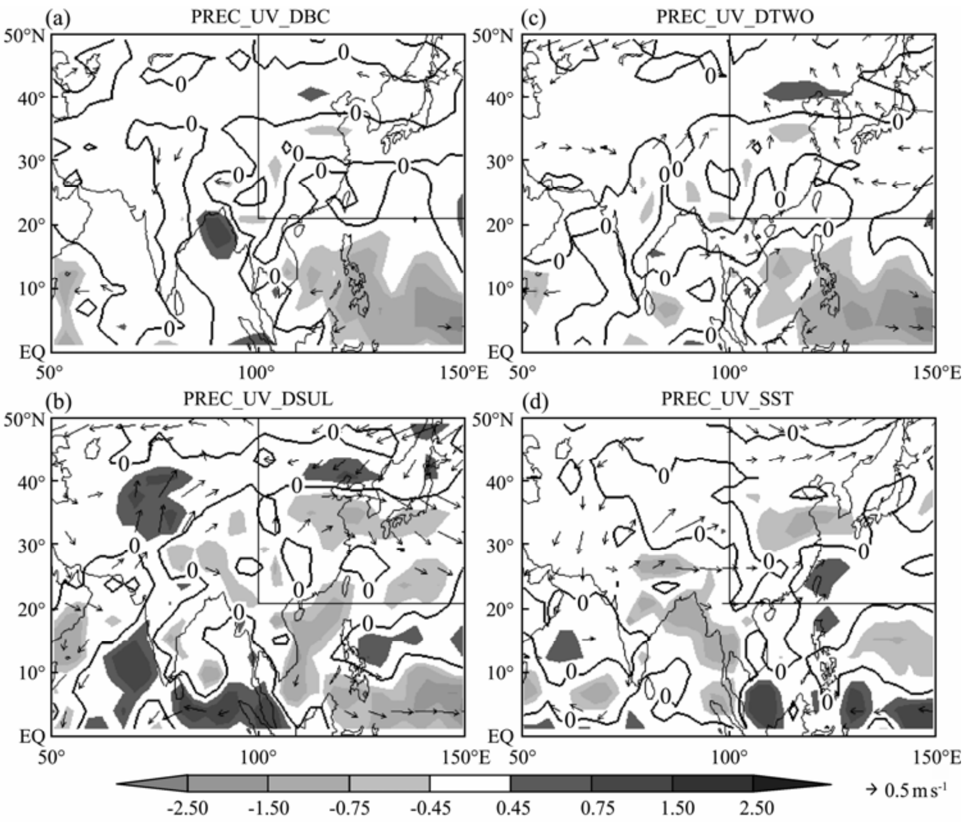

Fig.3 The precipitation (shaded, Units: mm d^{-1}) and 850 hPa wind (vector, Units: m s^{-1}) differences in spring compared with those in CTRL. The experiments are designed as in the East Asia area; (a) doubling of black carbon (b) doubling of sulfate aerosol (c) doubling of both aerosol synchronously, and (d) the experiment with only decadal SST shift around 1976/77. All variables are significant at 90% *t*-test confidence level.

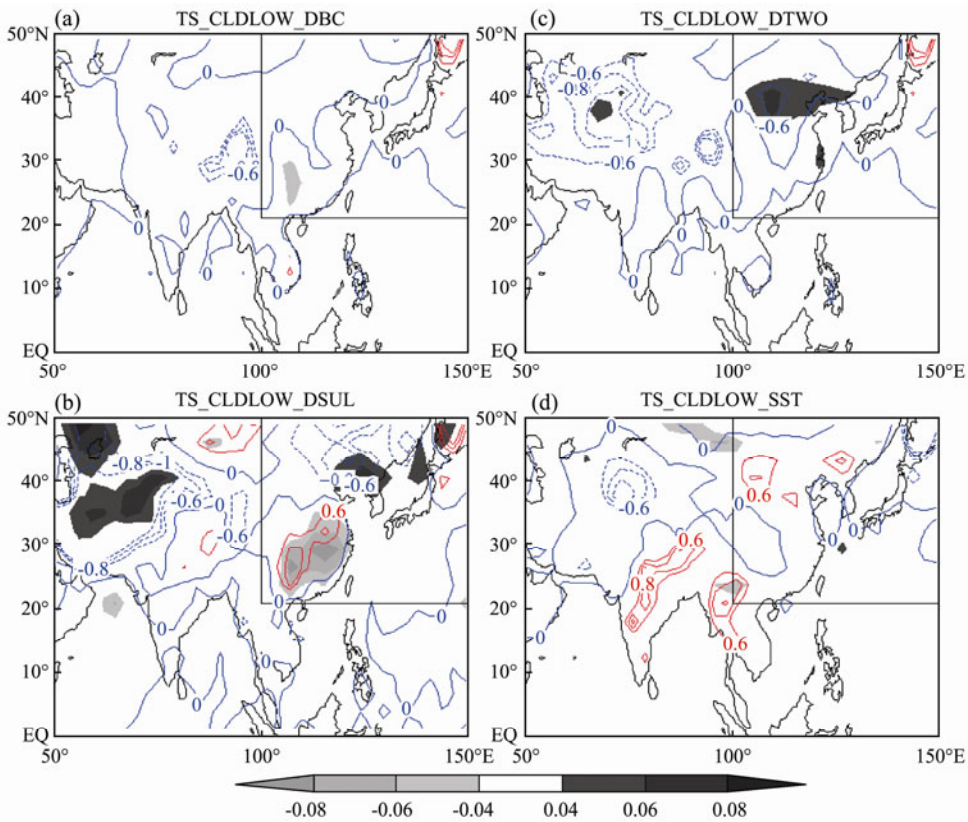

Fig.4 The surface temperature (contour, Units: K) and low cloud amount (shaded, Units: %) differences in spring compared with those in CTRL. The experiments are designed as in the East Asia area (a) doubling of black carbon (b) doubling of sulfate aerosol (c) doubling of both aerosol synchronously, and (d) the experiment with only SST decadal shift around 1976/77. All variables are significant at 90% *t*-test confidence level.

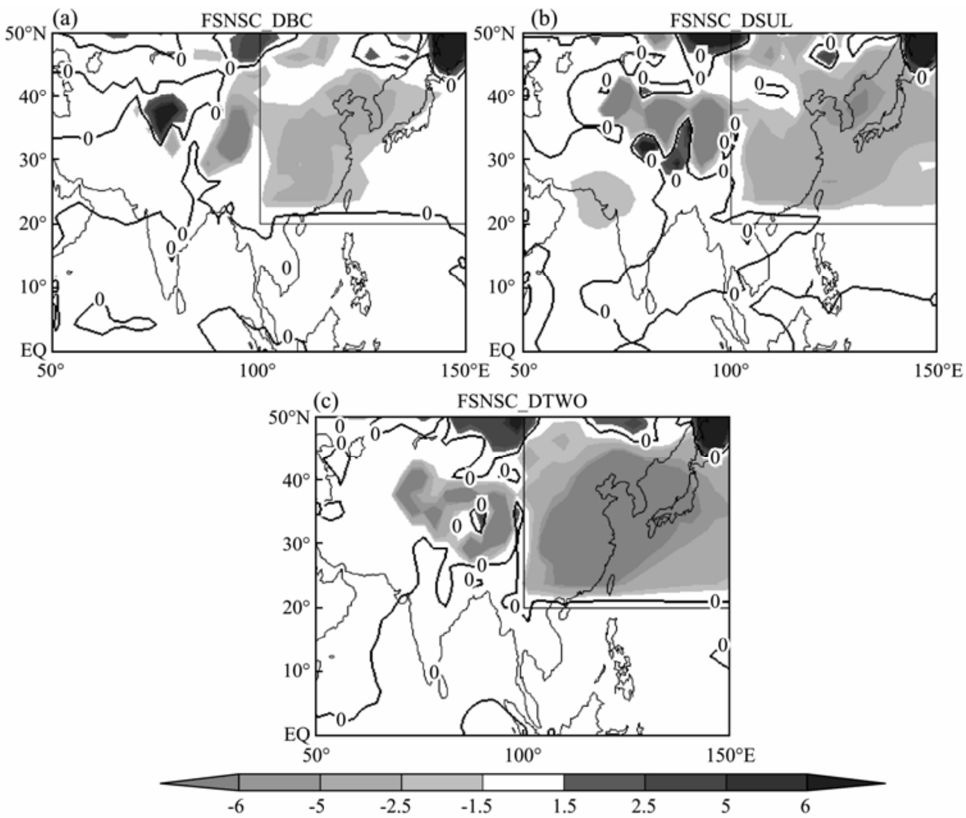

Fig.5 The differences of clear sky net solar flux at the surface in spring for the experiments of (a) doubling of black carbon aerosol (b) doubling of sulfate aerosol (c) doubling of both aerosol synchronously in the East Asia area, respectively. The Units of the flux is W m^{-2}. All variables are significant at 90% *t*-test confidence level.

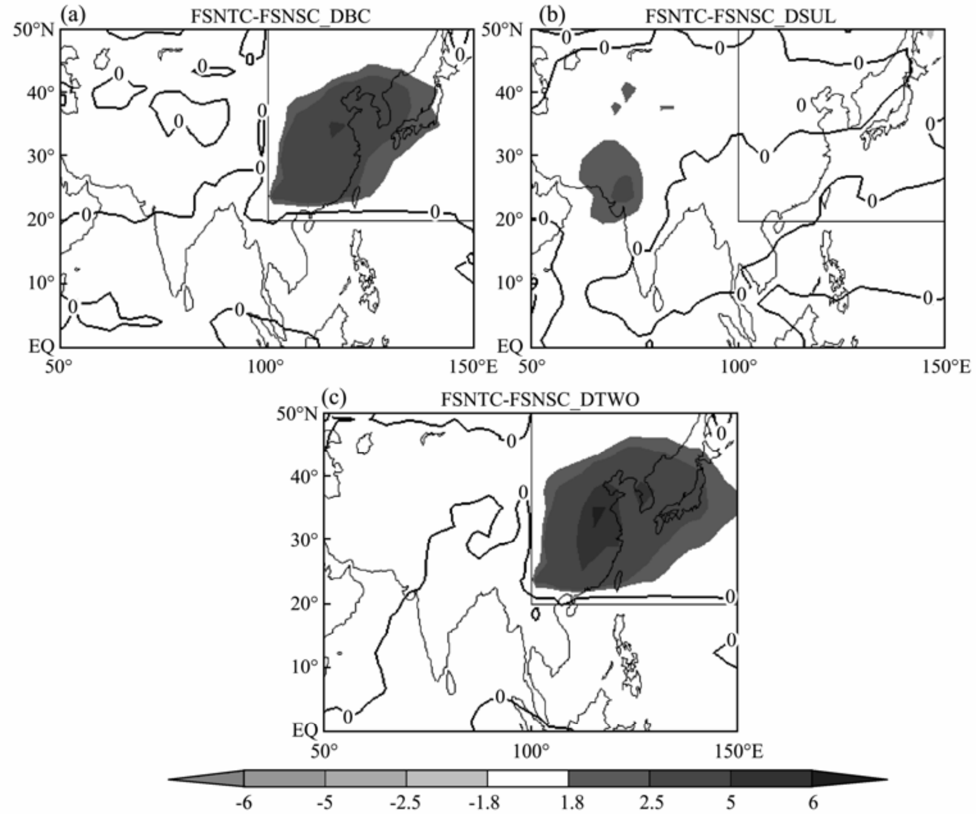

Fig.6 The differences of net solar flux in the atmosphere of clear sky for the experiments of (a) doubling of black carbon aerosol (b) doubling of sulfate aerosol, and (c) doubling of both aerosol synchronously in the East Asia area, respectively. The Units of the flux is W m^{-2}. All variables are significant at 90% *t*-test confidence level.

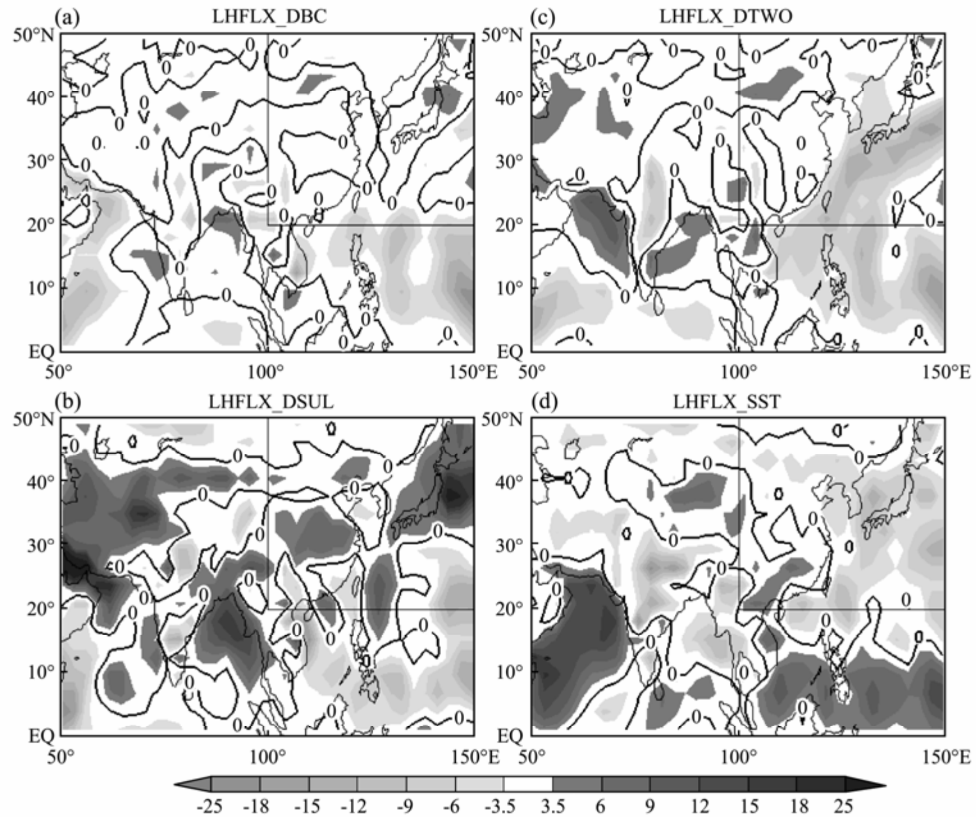

Fig.7 The latent heat flux (shaded, Units: W m^{-2}) differences in spring compared with those in CTRL. The experiments are designed for the East Asia area; (a) doubling of black carbon aerosol (b) doubling of sulfate aerosol (c) doubling of both aerosol synchronously, and (d) the experiment with only SST decadal shift around 1976/77. All variables are significant at 90% *t*-test confidence level.

patterns of surface latent heat flux changing are different from the change of the total precipitation, since we get stronger atmosphere advection anomalies in these experiments. The surface sensible heat flux anomalies (Fig.8) in four experiments are dominated totally by the surface temperature anomalies. The warmer (colder) surface temperature anomaly leads to a positive (negative) upward sensible heat flux anomaly.

On the whole, the three experiments with aerosol concentration changing get the similar pattern of precipitation, surface temperature, and heat flux, while the decadal SST changing leads to quite different patterns in the same model. In the aerosol experiments, the precipitation shows increasing over the north China and southeast coast of China while decreasing over the central-south China; the surface temperature shows warming in South China and cooling in the north China, and the surface sensible heat flux increases in the central-south China and decreases in the north accompanied with the surface temperature (especially in the DSUL experiment). Previous studies have suggested that sulfate aerosol has negative effect on surface temperature, and black carbon aerosol has both negative and positive effect, which can also be seen from Figs.5 and 6. The prominent surface warming in the central-south East Asia in the aerosols experiments disagrees with the pattern of aerosol concentration changing. Therefore, at least it is not the aerosol's direct radiative effect that changes the surface temperature. If taking a look at the lower cloud change, we could find that it matches with the alteration of surface temperature closely, and the surface temperature warms (cools) where the lower cloud amount draws down (grows). In the SST experiment, the rainfall decreases over almost the whole Mainland of China but increases over Southeast Asia. The surface temperature cools in the south but warms in the north, respectively. But why is there a similar rainfall pattern in the three different aerosol experiments, especially considering the opposite radiative effects between sulfate and black carbon aerosols? And what is the dynamical process in the SST experiment?

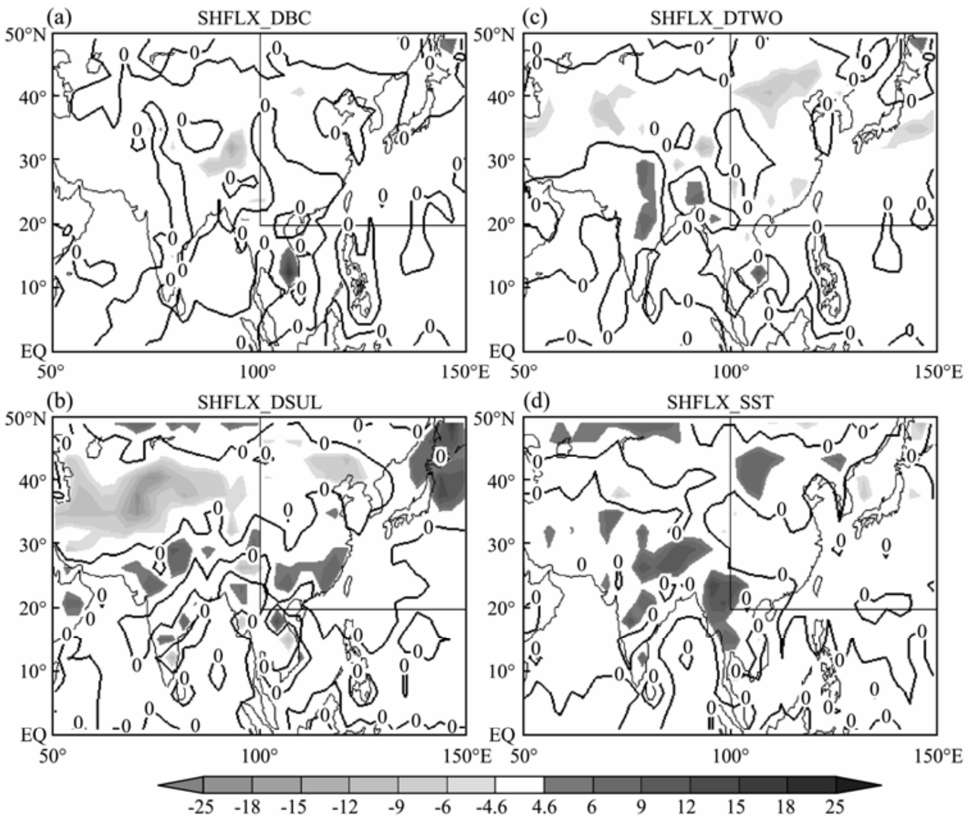

Fig.8 The sensible heat flux (shaded, Units: W m^{-2}) differences in spring compared with those in CTRL. The experiments are designed for the East Asia area; (a) doubling of black carbon aerosol (b) doubling of sulfate aerosol (c) doubling of both aerosol synchronously, and (d) the experiment with only decadal SST decadal shift around 1976/77. All variables are significant at 90% *t*-test confidence level.

3.2 Dynamical Process

To understand the dynamical process of climate effects caused by the aerosol concentration and SST changing, the vertical structure of circulation and temperature anomalies of zonal averaged mean of 110˚–120˚E are given (Fig.9).

According to Figs.9a, b, c, the atmosphere temperature between 20˚–50˚N has a noticeable changing with cooling anomalies to the south of 35˚N but warming to the north in the lower-troposphere (below 700 hPa but not the surface) and mid-troposphere. The contrary temperature anomalies appear near the land surface (below 900 hPa). The sum of the vertical diffusion and solar heating rate near the surface is the determinant of the surface temperature anomalies. For the lower-troposphere, the position of cooling anomalies are just associated with that of the high aerosol concentration in the model initial condition. It means that both sulfate and black carbon aerosols can lead to the lower-troposphere cooling, while for weaker cooling even warming anomalies appear in Figs. 9a, b because of the black carbon warming effect. Because of the positive rainfall anomalies (Fig.3) with positive latent heat flux anomalies, the warming anomalies exist north of 35˚N in the mid-troposphere of the three aerosol experiments. In the decadal SST changing experiment, warming temperature anomalies take up the whole vertical section (Fig.9d). The temperature anomalies in the mid-troposphere are connected with the precipitation anomalies and the atmospheric advection anomalies. For the three aerosol experiments, positive rainfall anomalies appear north of 35˚N and negative anomalies appear in the south part (Fig.3). Connected with these precipitation anomalies (which releases latent heat anomalies), warming (cooling) anomalies appear north (south) of 35˚N in the mid-troposphere. And obvious vertical circulations are found on this section in all the experiments (Fig.9). Around 40˚N, rising motions with heavy rainfall appear in the three aerosol experiments (Figs.3a, b, c and Figs.9a, b, c), while sinking motion exists in the SST experiment. But around 30˚N, obvious sinking movement appears in the DSUL experiment (Fig.9b) around 30˚N, where the sulfate aerosol concentration is high in the model initial condition.

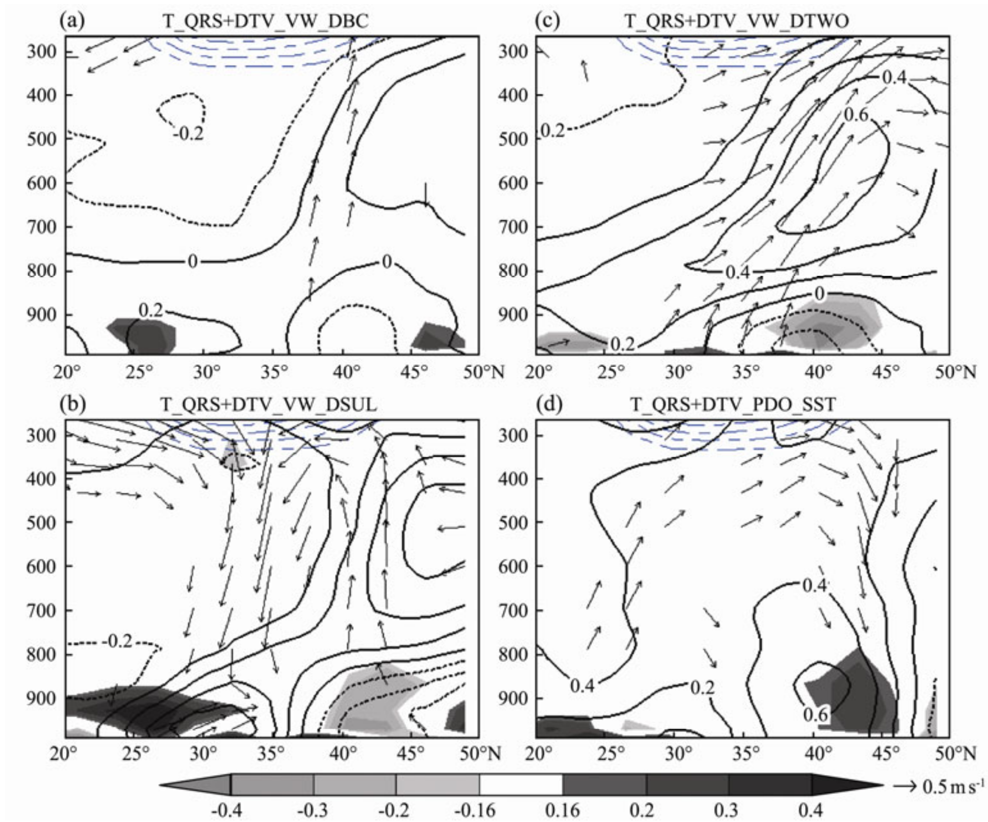

Fig.9 Latitude-altitude distribution (zonal mean of 110˚–120˚E) of the differences about the heating item (sum of short wave heating and vertical diffusion heating, shaded, Units: K d^{-1}), the temperature (contour, Units: K), zonal mean westerly wind (the blue dotted line, units: m s^{-1}) and the meridional wind circulation (vector, unit for the meridional wind: m s^{-1}, unit of the vertical velocity: -10^{-4} hPa s^{-1}) in spring for the experiments of (a) doubling of black carbon (b) doubling of sulfate aerosol (c) doubling of both sulfate and black carbon aerosol synchronously in the East Asia area, and (d) the experiment of only SST decadal shift around 1976/77. All variables are significant at 90% *t*-test confidence level.

Sulfate aerosol only has negative effect to cool the whole lower-troposphere, especially around 30˚N. Then from the equation of thermal wind (Eq. (1)), we know that the meridional temperature gradient is decreased, and the whole zonal wind especially at the upper level is weakened.

$$U_{\mathrm{T}} \approx \frac{g}{f}\frac{z_2 - z_1}{\overline{T}}\boldsymbol{k}\times\nabla_h \overline{T}\ , \qquad (1)$$

In the equation f is the Coriolis parameter, $\overline{T}$ is the averaged temperature in the atmosphere $z_2 - z_1$.

With the geostrophic deviation Eq. (2), north wind anomaly emerges (v_a<0) near the zonal wind jet, and a vertically secondary circulation generates sinking motion around 30˚N with rising motion around 40˚N (Fig.9b).

$$\frac{Du_g}{Dt} = f_0 v_a\ , \qquad (2)$$

where u_g is the geostrophic zonal wind, f_0 is the Coriolis parameter in the f plane, and v_a is the geostrophic deviation meridional wind.

The vertical circulation decreases rainfall and lower cloud amount around 30˚N but increases them around 40˚N. Since the increasing (decreasing) of lower clouds, the downward short wave radiation reduces (strengthens), and the surface temperature cools (warms). The increasing rainfall enhances the latent heat release, heats the mid-altitude atmosphere in the north of East Asia, and then strengthens the local rising motion around 40˚N and forms a positive feedback. With the global changing of total aerosol and precursor emissions from 1950 to 2000, Hu and Liu (2013) also got the obvious drought in the central China by using CAM5.1. In their model result, they found a significant tropospheric warming to the south of 25˚N and cooling around 30˚N in the troposphere. Just because of this significant increased temperature gradient between the lower and middle latitude, accelerated westerly appears with upward motion to the south of 25˚N and downward motion to the north, by using the same dynamical process we mentioned above.

When black carbon aerosol is doubled, the direct difference is that it has both negative and positive effects, which causes weaker temperature cooling and vertical circulation anomalies (Fig.9a). So the sinking motion around 30˚N becomes inconspicuous while the rising motion around 30˚N is still distinct because of the positive feedback with latent heat flux (Fig.9a). If the two aerosol are doubled together, the heating effect of black carbon aerosol plays an inverse role to counteract the negative surface temperature effect of sulfate aerosol south to 30˚N and weakens the sinking motion, while the rising motion is strengthened by both the sulfate and black carbon aerosol (Fig.9c). So the most significant positive precipitation anomaly in the north China appears in this experiment (Fig.3c).

For the SST experiment, the direct impact is on the Indian Ocean and Northwest Pacific warming after 1976/77 (Yang and Lau, 2004). This warming SST anomalies lead to positive surface temperature anomalies overhead (Fig.4d), and a cyclone anomaly (Matsuno-Gill Pattern) (Matsuno, 1966) exists west of the warming Northwest Pacific between 20˚–30˚N in the low troposphere (Fig.3d). This cyclone anomaly leads to a rising motion around 25˚N (Fig.9d). So positive precipitation anomalies appear over west of the Northwest Pacific by this rising motion around 25˚N, and the decreased rainfall with sinking anomaly in the north China is caused. In the result of Wu *et al.* (2005), only the decreased precipitation decadal changing exists over the central and south China with the interannual SST change from 1950 to 2000.

4 Summary and Discussion

As a result of the only negative surface temperature effect of sulfate aerosol, mid-troposphere temperature between 30˚N to 35˚N reduces remarkably after the sulfate aerosol concentration is doubled in DSUL. This temperature decreasing brings about the decrement of meridional temperature gradient, thus leads to a weaker thermal wind and further produces southward wind anomaly according to geostrophic deviation adjustment. Then a secondary vertical circulation is caused by this southward anomaly in the mid-troposphere-rising (sinking) motion north (south) of the zonal wind jet, which leads to precipitation rise in the north and the diminishing in the south. The variation of precipitation promotes the convective latent heat flux, which warms the mid-altitude atmosphere in the north of East Asia. Furthermore, combined with the vertical motion, the lower cloud amount decreases in the south but increases in the north of East Asia, and consequently the surface temperature changes according to the low cloud covering anomaly.

Compared to sulfate aerosol, black carbon aerosol contributes to lessening the sinking motion in the central of East Asia after doubling, because of the warming effect. But the rising motion in the north of East Asia is still obvious because of the reciprocity between the latent heat flux and the atmosphere rising. So the most notable positive precipitation anomaly appears in North China in DTWO, and at the same time the precipitation is suppressed by sulfate aerosol in the central-south China.

Through Matsuno-Gill Pattern, a cyclone anomaly exists over the west of the Northwest Pacific warming SST in the lower troposphere by the 1976/77 SST decadal changing, which increases the northwards water vapor transport and local anomalous rising motion. So, positive precipitation anomalies over the southeast coast of China and the South China Sea are induced in SST experiment.

Clearly, there are still some deficiencies in this paper. Since only the direct effect of sulfate and black carbon aerosols are considered, it is unknown what the climate effect is when the indirect effect and other aerosols are included. Moreover, the increasing of the aerosol concentration is only limited over East Asia by now, while it is unknown what the effect is when global aerosol concentration changes. Our future work might pay attention to these points.

Acknowledgements

This work is supported by the National Key Program for Developing Basic Science (Nos. 2010CB428504, 2012 CB956002); the National Natural Science Foundation of China (Nos. 40906005, 41105059, 41065005, 41176004, GYHY201106017, GYHY201206027); and the National Key Technologies R&D Program of China (No. 2009BAC 51B01).

References

Barth, M., Rasch, P., Kiehl, J., Benkovitz, C., and Schwartz, S., 2000. Sulphur chemistry in the national center for atmospheric research community climate model: Description, evaluation, features and sensitivity to aqueous chemistry. *Journal of Geophysical Research*, **105**: 1387-1415, DOI: 10.1029/1999 JD900773.

Chung, C. E., Ramanathan, V., and Kiehl, J. T., 2002. Effects of the South Asian absorbing haze on the northeast monsoon and surface–air heat exchange. *Journal of Climate*, **15**: 2462-2476, DOI: 101029/2003JD004084.

Chung, C. E., Ramanathan, V., Dohyeong, K., and Podgorny, I. A., 2005. Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations. *Journal of Geophysical Research*, **110**, DOI: 10.1029/2005JD006356.

Collins, W., Cecilia, M., Maurice, L., Gordon, B., Christopher, S., James, A., Chang, P., Scott, C., James, J., Thomas, B., Jeffrey, T., William, G., Daniel, S., Benjamin, D., and Richard, D., 2006. The community climate system model version 3 (CCSM3). *Journal of Climate*, **19**: 2122-2143, DOI: http://dx.doi.org/10.1175/JCLI3761.1.

Collins, W., Rasch, P., Boville, B., Hack, J., McCaa, J., Williamson, D., Kiehl, J., Briegleb, B., Bitz, C., Lin, S., Zhang, M., and Dai, Y., 2004. Description of the NCAR community atmosphere model (CAM 3.0). *NCAR Technical Note NCAR/TN-464+STR*. NCAR, 214pp.

Cooke, W. F., Liousse, C., Cachier, H., and Feichter, J., 1999. Construction of a 1°×1° fossil fuel emission data set for carbonaceous aerosol and implementation and radiative impact in the ECHAM4 model. *Journal of Geophysical Research*, **104** (D18): 22137-22162.

Dickinson, R., Oleson, K., Bonan, G., Hoffman, F., Thornton, P., Vertenstein, M., Yang, Z., and Zeng, X., 2006. The community land model and its climate statistics as a component of the community climate system model. *Journal of Climate*, **19**: 2302-2324, DOI: http://dx.doi.org/10.1175/JCLI3742.1.

Endo, N., Matsumoto, J., and Lwin, T., 2009. Trend in precipitation extremes over Southeast Asia. *SOLA*, **5**, 168e171, DOI: 10.2151/sola.2009-043.

Gu, Y., Liou, K., Xue, Y., Mechoso, C., Li, W., and Luo, Y., 2006. Climatic effects of different aerosol types in China simulated by the UCLA general circulation model. *Journal of Geophysical Research*, **111**, DOI: 10.1029/2005JD006312.

Hu, N., and Liu, X. H., 2013. Modeling study of the effect of anthropogenic aerosols on late spring drought in South China. *Acta Meteorologica Sinica*, **27**: 701-715, DOI: 10.1007/s13351-013-0506-z.

Huang, R., and Lu, L., 1989. Numerical simulation of the relationship between the anomaly of subtropical high in East Asia and the convective activities in the tropical western Pacific. *Advances in Atmospheric Sciences*, **6**: 202-214.

Jiang, Y. Q., Liu, X. H., Yang, X. Q., and Wang, M., 2013. Effects of anthropogenic aerosols on East Asian summer clouds and precipitation with Community Atmospheric Model version 5. *Atmospheric Environment*, **70**: 51-63, DOI: 10.1016/j.atmosenv.2012.12.039.

Kim, M.-K., Lau, W. K. M., Chin, M., Kim, K. M., Sud, Y. C., and Walker, G. K., 2006. Atmospheric teleconnection over Eurasia induced by aerosol radiative forcing during boreal spring. *Journal of Climate*, **19**: 4700-4718, DOI: http://dx.doi.org/10.1175/JCLI3871.1.

Kim, M.-K., Lau, W. K. M., Kim, K. M., and Lee, W. S., 2007. A GCM study of effects of radiative forcing of sulfate aerosol on large scale circulation and rainfall in East Asia during boreal spring. *Geophysical Research Letters*, **34**, L24701, DOI: 10.1029/2007GL031683.

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P., 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. *Atmospheric Chemistry and Physics*, **10**: 7017-7039, DOI: 10.5194/acpd-10-4963-2010.

Lau, K., Kim, M., and Kim, K., 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. *Climate Dynamics*, **26**: 855-864, DOI: 10.1007/s00382-006-0114-z.

Lee, W.-S., and Kim, M. K., 2011. Effects of radiative forcing by black carbon aerosol on spring rainfall decrease over Southeast Asia. *Atmospheric Environment*, **44**: 3739-3744, DOI: 105194/acpd-11-24127-2011.

Liousse, C., Penner, J. E., Chuang, C., Walton, J. J., Eddleman, H., and Cachier, H., 1996. A global three-dimensional model study of carbonaceous aerosols. *Journal of Geophysical Research*, **101**: 19411-19432.

Liu, X., Yan, L., Yang, P., Yin, Z., and North, G. R., 2011. Influence of Indian summer monsoon on aerosol loading in East Asia. *Journal of Applied Meteorology and Climatology*, **50**: 523-533.

Liu, Y., Sun, L., and Yang B., 2009. The effects of black carbon and sulfate aerosols in China regions on East Asia monsoons. *Tellus B*, **61**: 642-656, DOI: http://dx.doi.org/10.1111/j.1600-0889.2009.00427.x.

Mahowald, N., Luo, C., DelCorral, J., and Zender, C., 2003. Interannual variability in atmospheric mineral aerosols from a 22-year model simulation and observational data. *Journal of Geophysical Research*, **108** (D12), 4352, DOI: 10.1029/2002JD002821.

Matsuno, T., 1966. Quasi-geosrtophic motions in the equatorial area. *Journal of the Meteorological Society of Japan*, **44**: 25-43.

Meehl, G. A., Arblaster, J. M., and Collins, W. D., 2008. Effects of black carbon aerosols on the Indian monsoon. *Journal of Climate*, **21**: 2869-2882, DOI: http://dx.doi.org/10.1175/2007JCLI1777.1.

Menon, S., Hansen, J., Nazarenko, L., and Luo, Y., F., 2002. Climate effects of black carbon aerosols in China and India. *Science*, **297** (5590): 2250-2253, DOI: 10.1126/science.1075159.

Nakamura, H., Lin, G., and Yamagata, T., 1997. Decadal climate variability in the North Pacific during recent decades. *Bulletin of the American Meteorological Society*, **78**: 2215-2225, DOI: http://dx.doi.org/10.1175/1520-0477(1997)078<2215:DCVITN>2.0.CO;2.

Nathan, J. M., Steven, R. H., Zhang, Y., John M. W., and Robert, C. F., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meterological Society*, **78**: 1069-1079, DOI: 10.1175/1520-0477.

Nitta, T., and Hu, Z. Z., 1996. Summer climate variability in China and its association with 500 hPa height and tropical convection. *Journal of the Meteorological Society of Japan*, **74**: 425-445.

Oleson, K., Dai, Y., Bonan, G., Bosilovich, M., Dickinson, R., Dirmeyer, P., Hoffman, F., Houser, P., Levis, S., Niu, G.-Y., Thornton, P., Vertenstein, M., Yang, Z.-L., and Zeng, X., 2004. Technical description of the Community Land Model (CLM). *Technical Report NCAR/TN-461+STR*. NCAR, Boulder, CO 80307.

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R., and Wild, M., 2005. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *PNAS*, **102** (15): 5326-5333, DOI: 10.1073/pnas.0500656102.

Ramanathan, V., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D., 2001. Aerosols climate and the hydrological cycle. *Science*, **294**: 2119-2124, DOI: 10.1126/science.

Rasch, P., Barth, M., Kiehl, J., Schwartz, S., and Benkovitz, C., 2000. A description of the global sulfur cycle and its controlling processes in the National Center for Atmospheric Research Community Climate Model, Version 3. *Journal of Geophysical Research*, **105**: 1367-1385, DOI: 10.1029/1999 JD900777.

Shen, S., and Lau, K. M., 1995. Biennial oscillation associated with the East Asian summer monsoon and tropical sea surface temperature. *Journal of the Meteorological Society of Japan*, **73**: 105-124.

Smith, S. J., Pitcher, H., and Wigley, T. M. L., 2001. Global and regional anthropogenic sulfur dioxide emissions. *Global and Planetary Change*, **29** (1-2): 99-119.

Wang, B., Wu, R., and Fu, X., 2000. Pacific–East Asian teleconnection: How does ENSO affect East Asian climate. *Journal of Climate*, **13**: 1517-1536, DOI: 10.1175/1520-0442(2000) 013<1517:peathd>2.0.co;2.

Wang, H., Zheng, X., and Yuan, T., 2012. Overview of researches based on DMSP/OLS nighttime light data. *Progress in Geography*, **31**: 11-18 (in Chinese with English abstract).

Wu, L., Lee, D., and Liu, Z., 2005. The 1976/1977 North Pacific climate regime: The role of subtropical ocean adjustment and coupled ocean-atmosphere feedbacks. *Journal of Climate*, **18**: 5125-5140, DOI: 10.1175/JCLI3583.1.

Wu, R., Hu, Z. Z., and Kirtman, B. P., 2003. Evolution of ENSO-related rainfall anomalies in East Asia. *Journal of Climate*, **16**: 3741-3757, DOI: http://dx.doi.org/10.1175/1520-0442(2003)016<3742:EOERAI>2.0.CO;2.

Xin, X., Yu, R., Zhou, T., and Wang, B., 2006. Drought in late spring of south China in recent decades. *Journal of Climate*, **19**: 3197-3206, DOI: http://dx.doi.org/10.1175/JCLI3794.1.

Xue, Y., Smith, T. M., and Reynolds, R. W., 2003. Interdecadal changes of 30-yr SST normals during 1871–2000. *Journal of Climate*, **16**: 1601-1612, DOI: http://dx.doi.org/10.1175/1520-0442-16.10.1601.

Yang, F., and Lau, K. M., 2004. Trend and variability of China precipitation in spring and summer: Linkage to sea surface temperatures. *International Journal of Climatology*, **24**: 1625-1644, DOI: 10.1002/joc.1094.

Yoon, S.-C., Kim, S., Choi, S., and Choi, I. J., 2010. Regional-scale relationships between aerosol and summer monsoon circulation, and precipitation over northeast Asia. *Asia-Pacific Journal of Atmospheric Sciences*, **46**: 279-286, DOI: 10.1007/s13143-010-1002-3.

Zender, C. S., Bian, H., and Newman, D., 2003. Mineral dust entrainment and deposition (DEAD) model: Description and 1990's dust climatology. *Journal of Geophysical Research*, **108**, 4416, DOI: 10.1029/2002JD002775.

Zhang, H., Wang, Z., and Guo, P., 2009. A modeling study of the effects of direct radiative forcing due to carbonaceous aerosol on the climate in East Asia. *Advance in Atmospheric Sciences*, **26**: 57-66, DOI: 10.1007/s00376-011-0117-5.

Zhang, L., Liao, H., and Li, J., 2010. Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. *Journal of Geophysical Research*, **115**, D00K05, DOI: 10.1029/2009JD012299.

Zhang, Y., Wallace, J. M., and Battisti, D. S., 1997. ENSO-like interdecadal variability: 1900–1993. *Journal of Climate*, **10**: 1004-1020, DOI: http://dx.doi.org/10.1175/1520-0442(1997) 010<1004:ELIV>2.0.CO;2.

Zhao, C., Wang, Y., Yang, Q., Fu, R., Cunnold, D., and Choi, Y., 2010. Impact of East Asian summer monsoon on the air quality over China: View from space. *Journal of Geophysical Research*, **115**, D09301, DOI: 10.1029/2009JD012745.

(Edited by Xie Jun)