Possible contribution of heavy pollution to the decadal change of rainfall over eastern China during the summer monsoon season

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Received 8 September 2013
Accepted for publication 10 October 2013
Published 30 October 2013
Online at stacks.iop.org/ERL/8/044024

Abstract

A regional climate model (RegCM4.1) is used to conduct two sets of sensitivity experiments. There are 20-year runs in each set of experiments. The experiments in each set include the variation of anthropogenic SO\textsubscript{2} emissions during 1989–2008 but exclude natural variations of the atmosphere and sea surface temperature. The model results suggest that the high-speed emission of SO\textsubscript{2} and its uneven distribution over eastern China can contribute to the change in May–August rainfall over eastern China between the two decades of 1999–2008 and 1989–1998, especially to the decrease (increase) of rainfall in the Yangtze River valley (Huang-Huai River region). Furthermore, the areas of decreasing (increasing) rainfall correspond to the downward (upward) currents of the anomalous atmospheric circulation, which is caused by the two humps of the difference in sulfate concentration between the two decades.

Keywords: regional climate model, sulfate, rainfall decadal change, eastern China, simulation

1. Introduction

Rainfall in eastern China during May to August is an important water resource for the local residential, agricultural, and industrial activities. Mostly, this rainfall relates to the East Asian summer monsoon (EASM), which possesses a significant inter-decadal variability (Ding and Chan 2005). In the 1990s, the major pattern of summer precipitation over China is droughts over northern China but floods over the Yangtze River valley and southern China (Ding et al 2008, 2009, Dai et al 2012, Ye and Lu 2012). Recently, this pattern seems changed, and Zhu et al (2011) found that during 2000–2008, in contrast to 1979–1999, rainfall has increased over the Huang-Huai River region but decreased over the Yangtze River valley. They suggested that this is caused by the significant change in sea surface temperature (SST) associated with the Pacific decadal oscillation. Duan et al (2013) suggested that the variation of summer rainfall in China during 1980–2008 is related to the spring sensible
heat and snow depth over the Tibetan Plateau. Cheng et al (2005) found that the SST in the South China Sea and aerosols over China both contributed to the drought trend in some parts of southern China during 1961–2002. Lei et al (2011) indicated that the change in summer rainfall over China during 1958–2008 was partially caused by human activities, such as increased greenhouse gases as well as increased aerosols. During the last two decades, a high-speed emission of anthropogenic aerosols has occurred in China (Street et al 2003, Ohara et al 2007). Thus, a question is raised of whether the heavy pollution is contributing to the decadal change of rainfall over eastern China during the summer monsoon season.

Anthropogenic aerosols reduce the solar radiation reaching the ground and alter the regional climate (Qian et al 2001, Giorgi et al 2002a, 2002b, 2003, Li et al 2011). During 1960–2000, through analyzing the observations in China, it was found that the aerosol optical depth has significantly increased (Yunfeng et al 2001), and the solar radiation reaching the ground has decreased at a speed of about 3.0 W m\(^{-2}\) per decade (Liang and Xia 2005, Qian et al 2006, 2007). Zerefos et al (2009) found that, due to aerosols, China has experienced a dimming period during 1984–2006. Zhao et al (2012) pointed out that the variability of the solar radiation has a significant influence on the decadal variability of the summer rainfall over East Asia. In this area, sulfate, which scatters solar radiation, is a major type of anthropogenic aerosol (Street et al 2003, Li et al 2011). Therefore, this study is going to reveal the contribution of the radiative forcing of anthropogenic sulfate to the decadal change of rainfall over eastern China during the summer monsoon season. Only the direct effect of sulfate in a regional climate model is analyzed in this study. The structure of this paper is as follows. Section 2 describes the data and the model experiment. Section 3 presents the model results. The conclusions are provided in section 4.

2. Data and model experiment

In early May the pre-summer rainy season begins in southern China, and after proceeding stepwise to the north, the rain belt of the EASM retreats to the ocean in August (Ding and Sun 2002, Ding and Chan 2005). Thus, we define May–August as the summer monsoon season over eastern China. The observed daily precipitation in China during May to August of 1989–2008 has been obtained from the 598 stations of the China Meteorological Administration. The precipitation data are processed to 0.5° × 0.5° grid data using the Cressman (1959) objective analysis. Besides the observed rainfall, we also use the six-hourly atmospheric data of 2.5° × 2.5° resolution reanalysis during 1970–2008 (Kalnay et al 1996) of the US National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), the monthly 2° × 2° resolution extended reconstructed SST during 1970–2008 (Reynolds et al 2002) of the US National Oceanic and Atmospheric Administration (NOAA), and the annual emission inventory of anthropogenic SO\(_2\) during 1989–2008 obtained from the European Emission Database for Global Atmospheric Research (EDGAR). The atmospheric data includes surface air pressure, air temperature, geopotential height, relative humidity, and horizontal wind; except for the surface air pressure, the data are at 17 pressure levels.

The NCEP data and NOAA SST during 1970–2008 are averaged at each time interval of a calendar year, which is six hourly and monthly for atmosphere and SST respectively. During the averaging, we discard the last day of February in a leap year, which has no influence on the model results. A regional climate model (RegCM4.1, http://gforge.ictp.it) that contains a simple chemistry module is used to conduct 20 experiments that are driven by the same atmosphere and SST, which are the mean conditions of 1970–2008 mentioned above. The model is an atmosphere–chemistry online coupled model. Each experiment contains only one run that is integrated from 1 March to 31 August, taking the first two months as spin-up time. However, each experiment uses the SO\(_2\) emission inventory of one year in 1989–2008 respectively. Therefore, the 20 experiments, like a 20-year simulation, do not contain any annual and decadal variations caused by the atmosphere and SST but only by the SO\(_2\) emission. We denote these 20 runs by RMEAN. In the following, we denote each experiment in RMEAN by the year number that relates to the SO\(_2\) emission. Using this design, we can explore the direct effect of anthropogenic sulfate on the decadal change of rainfall without the natural variability of the atmosphere and SST being included. The details of the sulfur model in RegCM4.1 can be referred to in the study by Qian et al (2001).

Besides the 20 runs in RMEAN, we also conducted another 20 runs, denoted by R1997. The differences between RMEAN and R1997 are in the lateral and boundary conditions. In R1997, we use the same SO\(_2\) emission as used in RMEAN but the atmospheric and oceanic conditions of 1997. R1997 is conducted to test if the results from RMEAN depend on the atmospheric and oceanic conditions of any single year. The year 1997 is chosen because the rainfall in 1997 is the heaviest over 110°E–120°E/20°N–50°N during May–August of 1989–2008 (figure not shown). This means that in 1997 the activities of the synoptic disturbances are strong over eastern China. This may potentially alter the results from RMEAN. In the following, we mainly present the results from RMEAN, except for the rainfall of R1997 in figure 1. The remaining results of R1997 are discussed in section 4.

RMEAN and R1997 share the same configurations as follows. RegCM4.1 is configured with the rotated Mercator projection (shaded area in figure 2(b)), horizontal resolution of 60 km × 60 km, and 18 sigma levels. The lateral boundary scheme of linear relaxation, cumulus convection scheme of Emanuel (1991), boundary layer scheme of Holtslag et al (1990), and land model of the biosphere–atmosphere transfer scheme are used. The model results at 18 sigma levels are interpolated to 20 pressure levels and saved in daily intervals for analysis.
Figure 1 shows the differences of rainfall during May–August in the observation, RMEAN, and R1997 between the two decades of 1999–2008 and 1989–1998. In figure 1(a), which shows the observed rainfall, it is found that during 1999–2008 compared to 1989–1998 the rainfall is decreased along the Yangtze River valley (about 30°N) and increased over the Huang-Huai River region (about 35°N). This agrees with the finding by Zhu et al. (2011). Additionally, in southern China (around 24°N), rainfall during 1999–2008 is more than that during 1989–1998, and in northern China (to the north of 40°N) it is the opposite. This is consistent with the finding by Liu et al. (2011) that there is an abrupt shift of the decadal rainfall in summer near 1999, which exhibits a significant decrease in rainfall over northern China.

Figure 1(b), which presents the rainfall in RMEAN, shows a quite similar pattern to that in the observation. Although the decadal changes of rainfall are smaller than those of the observation, rainfall significantly (10%) decreases or increases over eastern China (figure 1(b)). We also conducted a 5% significance test. The 5% significance areas are smaller than the 10% ones. The changes of the modeled rainfall in the Yangtze River valley and Huang-Huai River region closely resemble those in the observation. In northern China, model results also suggest a decrease in rainfall around 42°N in a small area, which is different from the observation that has a large area of decreased rainfall. In southern China, the increase of rainfall in the simulation is 2° further north than that in the observation. Rainfall around 105°E is quite different between the observation and simulation. Overall, although the 20 experiments share the same boundary forcing and initial fields, the variation of SO$_2$ emission causes a decadal change of rainfall over eastern China in the model. The change is significant and quite similar to the observation, especially over the Yangtze River valley and Huang-Huai River region. Figure 1(c) shows rainfall in R1997. It is found that there is a significant (10%) decrease of rainfall over the Yangtze River valley. Rainfall increases over the Huang-Huai River region. Moreover, rainfall decreases over northeast China at about 40°N, and increases over

3. Model results

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Figure 2. (a) Time series of the annual emission of anthropogenic SO$_2$ (in 10$^4$ Gg) in China. The red and blue dashed lines mark the averages of the emission in the two decades of 1999–2008 and 1989–1998 respectively. (b) Differences of SO$_2$ emission (in mg m$^{-2}$ d$^{-1}$) between the two decades of 1999–2008 and 1989–1998. The shaded area also indicates the model area.

During the last two decades, there is a high-speed emission of anthropogenic SO$_2$ in China (the data are obtained from EDGAR, figure 2(a)). The emission increases mostly in eastern China, and is higher around 30$^\circ$N and 40$^\circ$N as well as the coastline in southern China in 1999–2008 than in 1989–1999 (figure 2(b)). However, some areas show a decrease in emission in 1999–2008, such as the Huang-Huai River region. These differences in emission between the two decades cause a difference in the sulfate concentration in the atmosphere and an anomaly in atmospheric circulation. Figure 3 shows the latitude–height plot of the differences of the modeled mixing ratio of sulfate and meridional circulation over eastern China (averaged between 110$^\circ$E and 120$^\circ$E) during May–August between the two decades. Sulfate has three centers of large concentration at low levels at 25$^\circ$N, 30$^\circ$N, and 40$^\circ$N respectively. Those centers are consistent with the large emission areas in eastern China shown in figure 2(b). Varying with increasing height, the sulfate concentration becomes a pattern of two humps, and the centers at 25$^\circ$N and 30$^\circ$N merge together. This merger is caused by the prevailing southwest wind at low levels over southern China during May–August (figure not shown), which transports the sulfate to the north.

Over the two humps of sulfate, there are two downward currents respectively (figure 3). Due to the compensation effect, an upward current between the two humps and another upward current at about 26$^\circ$N are formed. The downward (upward) currents correspond to the decrease (increase) in rainfall shown in figure 1(b). In figure 4, it is found that southern China at about 24$^\circ$N. Generally, the pattern of rainfall changes in figure 1(c) agrees with the results found in figures 1(a) and (b).

However, there are some differences in rainfall changes between R1997 and RMEAN. The changes of rainfall are smaller in R1997 than those in RMEAN over the Yangtze River valley and Huang-Hai River region. The significance of the increase of rainfall over the Huang-Huai River region almost disappears in R1997. Over southeast China, the increase of rainfall in R1997 is not significant. Therefore, R1997 underestimates the changes of the rainfall. This is because in R1997, strong synoptic disturbances and rainfall damp the effect of sulfate. Over northeast China, the decrease of rainfall in R1997 is at about 40$^\circ$N, which is to the south of that in RMEAN. Rainfall change around 105$^\circ$E in R1997 is more similar to the observation than that in RMEAN. Rainfall changes over northeast China and around 105$^\circ$E are different between R1997 and RMEAN. This relates to the differences of the atmospheric circulation and the weather systems between RMEAN and R1997. Thus, the interaction between sulfate and the atmosphere is different. We are not going to further explore the interaction between the atmosphere and sulfate, which is out of the scope of this study. In the following, we only show the results from RMEAN, but will further discuss the results of R1997 in section 4.

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figure 3. latitude–height plot of the differences of the mixing ratio of the anthropogenic sulfate (shaded, in 10^{-3} mg kg^{-1}) and meridional circulation of the atmosphere (vectors) during may–august between the two decades of 1999–2008 and 1989–1998 in rmean. the horizontal meridian wind (in m s^{-1}), vertical wind (in 10^{-4} pa s^{-1}), and mixing ratio are averaged between 110°n and 120°e.

the whole of eastern china has stronger negative radiative forcing at the top of the atmosphere in 1999–2008 than in 1989–1999, with the maximum difference value of about -3.0 w m^{-2}. the two humps of sulfate cause stronger negative radiative forcing on the atmosphere around 30°n and 40°n in 1999–2008 than in 1989–1998 (figure 4). these two negative radiative forcing centers induce air sinking, which results in the formation of the two downward currents in the corresponding areas (figure 3). it is noted that the amount of sulfate is higher at 40°n than at 30°n, but the heights of the humps of sulfate are about the same (figure 3); the difference of the radiative forcing between 30°n and 40°n is small (figure 4), and then the downward currents over those two areas are about the same (figure 3). overall, through analyzing the model results, we find that the heavy pollution contributes to rainfall change over the past two decades.

4. conclusions

two sets of sensitivity experiments are conducted with different sulfate forcings by employing different annual emissions of anthropogenic so_{2} during 1989–2008. rmean uses the same climatological atmospheric and oceanic data, and r1997 uses the atmospheric and oceanic data of 1997. under such an experimental design, the contribution of the variation of anthropogenic sulfate to the decadal change of rainfall over eastern china during may–august can be explored without the natural variations of the atmosphere and sst being included. the model results show that due to the high-speed emission of anthropogenic sulfate and its uneven distribution over eastern china, the heavy pollution decreases rainfall over the yangtze river valley and part of northeastern china but increases rainfall over southern china and the huan-huai river region in 1999–2008 compared to 1989–1998.

the uneven distribution of the emission forms two humps of the differences of the sulfate concentration over eastern china. the two humps cause two downward currents and consequently upward currents, which relate to the decrease and increase of the rainfall respectively. the uneven emission of anthropogenic sulfate is probably associated with the speed of the economic development in different areas in eastern china. the areas of 30°n (the yangtze river delta) and 40°n (the beijing–tianjin–hebei area) are more developed than the area between them. so, to summarize, through altering the solar radiation, the anthropogenic sulfate could have contributed to the decadal change of rainfall over eastern china during the summer monsoon season of the last two decades.

it is noted that there are some limitations to the results of the present study. firstly, we used the averaged initial and boundary conditions in rmean. this has smoothed out the synoptic disturbances at the lateral boundary, and then decreased rainfall and sulfate wet deposition. therefore, the effects of sulfate are overestimated in rmean. for example, comparing r1997 with rmean, the signal of the decadal changes of rainfall in r1997 is weaker due to the strong wet deposition. the significance of increasing rainfall in the huang-huai river region is almost gone in r1997. if a 5% significance test is conducted, the significance disappears over this region in r1997. furthermore, the downward currents of the anomalous circulation around 30°n and 40°n in r1997 (figure not shown) are weaker than those in rmean (figure 3). the upward current between the two downward currents of the anomalous circulation weakens a lot in r1997.

secondly, only the direct effect is simulated in this study. previous studies (e.g. qian and giorgi 1999, giorgi et al 2003) have pointed out that the indirect effect of sulfate can also affect summer rainfall, and dominates the cooling over east asia in the summer. furthermore, the indirect effect and its interaction with rainfall are complicated and nonlinear. thus, this study only reveals a fragment of the climate effects of sulfate on the decadal change of rainfall in eastern china.
Acknowledgments

This research is supported by the Chinese National Key Basic Research Program (grant No 2011CB403406) and a project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions. AH acknowledges the support from the Special Program for China Meteorology Trade (grant No GYHY201306046). We thank the anonymous reviewers for their insightful and instructive comments.

References

Cheng Y, Lohmann U, Zhang J, Luo Y, Liu Z and Lesins G 2005 Contribution of changes in sea surface temperature and aerosol loading to the decreasing precipitation trend in southern China J. Clim. 18 1381–90
Cressman G P 1959 An operational objective analysis system Mon. Weather Rev. 87 367–74
Dai X-G, Wang P and Zhang K-J 2012 A decomposition study of moisture transport divergence for inter-decadal change in East Asia summer rainfall during 1958–2001 Chin. Phys. B 21 119201
Ding Y and Chan J C L 2005 The East Asia summer monsoon: an overview Meteorol. Atmos. Phys. 89 117–42
Ding Y and Sun Y 2002 Seasonal march of the East Asian summer monsoon and related moisture transport Weather Clim. 1 18–23
Ding Y, Sun Y, Wang Z, Zhu Y and Song Y-F 2009 Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon. Part II: possible causes Int. J. Climatol. 28 1926–44
Ding Y, Wang Z and Sun Y 2008 Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences Int. J. Climatol. 28 1139–61
Duan A, Wang M, Lei Y and Cui Y 2013 Trends in summer rainfall over China associated with the Tibetan Plateau sensible heat source during 1980–2008 J. Clim. 26 261–75
Emanuel K A 1991 A scheme for representing cumulus convection in large-scale models J. Atmos. Sci. 48 2313–35
Giorgi F, Bi X and Qian Y 2002a Direct radiative forcing and regional climatic effects of anthropogenic aerosols over East Asia: a regional coupled climate-chemistry/aerosol model study J. Geophys. Res. 107 4439
Giorgi F, Bi X and Qian Y 2002b Indirect versus direct effects of anthropogenic sulfate on the climate of East Asia as simulated with a regional coupled climate-chemistry/aerosol model Clim. Change 58 345–76
Giorgi F, Bi X and Qian Y 2003 Indirect versus direct effects of anthropogenic sulfur on the climate of East Asia as simulated with a regional coupled climate-chemistry/aerosol model Clim. Change 58 345–76
Holtslag A A M, de Bruijn E I F and Pan H-L 1990 A high resolution air mass transformation model for short-range weather forecasting Mon. Weather Rev. 118 1561–75
Kalnay E et al 1996 The NCEP/NCAR 40-year reanalysis project Bull. Am. Meteorol. Soc. 77 437–70
Lei Y, Hoskins B and Slingo J 2011 Exploring the interplay between natural decadal variability and anthropogenic climate change in summer rainfall over China. Part I: observational evidence J. Clim. 24 4584–99
Li Z et al 2011 East Asian studies of tropospheric aerosols and their impact on regional climate (EAST-AIRC): an overview J. Geophys. Res. 116 D00K34
Liang F and Xia X 2005 Long-term trends in solar radiation and the associated climatic factors over China for 1961–2000 Ann. Geophys. 23 2425–32
Liu Y, Huang G and Huang R 2011 Inter-decadal variability of summer rainfall in eastern China detected by the leafage test Theor. Appl. Climatol. 106 481–8
Ohara T et al 2007 An Asian emission inventory of anthropogenic emission sources for the period 1980–2020 Atmos. Chem. Phys. 7 4419–44
Qian Y and Giorgi F 1999 Interactive coupling of regional climate and sulfate aerosol models over eastern Asia J. Geophys. Res. 104 6477–99
Qian Y, Kaiser D P, Leung L R and Xu M 2006 More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000 Geophys. Res. Lett. 33 L01812
Qian Y, Wang W, Leung L R and Kaiser D P 2007 Variability of solar radiation under cloud-free skies in China: the role of aerosols Geophys. Res. Lett. 34 L12804
Qian Y et al 2001 Regional simulation of anthropogenic sulfur over East Asia and its sensitivity to model parameters Tellus B 53 171–91
Reynolds R W, Rayner N A, Smith T M, Stokes D C and Wang W 2002 An improved in situ and satellite SST analysis for climate J. Clim. 15 1609–25
Street D G et al 2003 An inventory of gaseous and primary aerosol emissions in Asia in the year 2000 J. Geophys. Res. 108 8809
Ye H and Lu R 2012 Dominant patterns of summer rainfall anomalies in east China during 1951–2006 Adv. Atmos. Sci. 29 695–704
Yunfeng L, Daren L, Xiuxi Z, Weiliang L and Qing H 2001 Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years J. Geophys. Res. 106 14501–13
Zerefos C S, Eleftheratos K, Meleti C, Kazadzis S, Romanou A, Ichoku C, Tsililoudis G and Bais A 2009 Solar dimming and brightening over Thessaloniki, Greece, and Beijing, China Tellus B 61 657–65
Zhao L, Wang J and Zhao H 2012 Solar cycle signature in decadal variability of monsoon precipitation in China J. Meteorol. Soc. Japan 90 1–9
Zhu Y, Wang H, Zhou W and Ma J 2011 Recent changes in the summer precipitation pattern in East China and the back ground circulation Clim. Dyn. 36 1463–73