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MODELING THE EFFECTS OF ANTHROPOGENIC SULFATE IN CLIMATE CHANGE BY USING A REGIONAL CLIMATE MODEL

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ABSTRACT: Effects of aerosol with focus on the direct climate effect of anthropogenic sulfate aerosol under 2 $\times CO_2$ condition were investigated by introducing aerosol distribution into the latest version of RegCM2. Two experiments, first run ($2\times CO_2$ + 0 aerosol concentration) and second run ($2\times CO_2$ + aerosol distribution), were made for 5 years respectively. Preliminary analysis shows that the direct climate effect of aerosol might cause a decrease of surface air temperature. The decrease might be larger in winter and in South China. The regional-averaged monthly precipitation might also decrease in most of the months due to the effect. The annual mean change of precipitation might be a decrease in East and an increase in West China. But the changes of both temperature and precipitation simulated were much smaller as compared to the greenhouse effect.

Key words: greenhouse effect; regional climate model; region of China; anthropogenic sulfate aerosol

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1 INTRODUCTION

Being an important composition of the atmosphere, aerosol attracts increasing attention from the scientific community in recent years, together with the radiative forcing it causes and effects it imposes on the climate system. The anthropogenic aerosol affects the climate both directly and indirectly. The climate is directly affected when solar shortwave radiation is scattered and absorbed in what is known as the “umbrella effect”, which can be dated back to as early as more than 70 years ago[1]; it is indirectly influenced when optic characteristics and life cycles are altered through the cloud condensation nuclei (CCN), which was first known in the 1970’s[2]. The two effects of the aerosol are just the opposite to that of greenhouse effect, for the radiative forcing value is about one-third or more as powerful as the latter, weakening or even offsetting its effect[3]. It is not affordable, therefore, to ignore aerosol in studying the effect of human activity on climate.

There are quite a number of studies overseas addressing the issue of the aerosol effect — general circulation models are incorporated and effects are estimated on such climate elements as air temperature and precipitation. Reference [4] gives simulated results of some models for the East Asia region.

Domestically, the research on the aerosol effect also began early. The energy equilibrium model was used to estimate the radiative forcing effect of the aerosol and its effect on air temperature[5 - 7]. Recent years witnessed the introduction of aerosol to climate models[8]. Generally speaking, however, more work should be done to introduce aerosol to 3-D atmospheric

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models to probe extensively the effect it may have on climatic elements.

2 DESIGNING OF EXPERIMENTS

Having high resolution and detailed physical processes, regional climate models are widely applied in the study of climate over limited areas. On the basis of previous work[9], anthropogenic sulfate aerosol and its effect on shortwave (known as direct climatic effect, to be called aerosol effect in the rest of the text for brevity) are added to our regional climate model and numerical experiments are conducted on the aerosol effect on regional climate in China with CO_2 doubled in quantity.

The model in question is the latest version of the RegCM2 model released by the ICTP, the Abdus Salam International Center for Theoretical Physics. What is improved over the old version[10, 11] is mainly the radiation process, because the radiation scheme has been replaced as the model changes from CCM2 to CCM3. With additional “background aerosol” (sulfate aerosol), the new scheme follows the calculation method of J.T.Kiehl et al[12] and determines the optic characteristics of the sulfate aerosol for the 18 shortwave sections divided by the model (the extinction per unit, single scattering albedo and asymmetric parameter). Their corresponding values are determined in shortwave calculation. The concentration of aerosol takes a near-constant value which is added at the lowest three layers of the model and is used as the background aerosol. The value is useful for reference in experimenting sensitivity to climate, but differs much from the observation.

Due to the present limitation of conditions, a systematic dataset is presently not available as far as the temporal and spatial distribution of aerosol is concerned. The problem is usually solved by having access to the above dataset through development of a chemical transmission model (CTM) that describes in details temporal and spatial distribution of aerosol on the regional or global scale, based on the observations now available.

The anthropogenic sulfate aerosol data used in the work are obtained using the above technique, which are provided by Feichter et al. [13] from the Max-Planck Institute for Meteorology, Germany. In the original data, the horizontal resolution is 3.75 lat. × 3.75 long. and there are 16 layers in the vertical direction. A detailed analysis was made by Zhang et al[8]. Fig.1 (a & b) gives the distribution of aerosol at the lowest layer of the model-determined domain in January and July. Estimates differ for future variation of aerosol emission. With the assumption that it tends to increase in the region of China, there will be 30% more aerosol when the content of CO_2 is doubled.

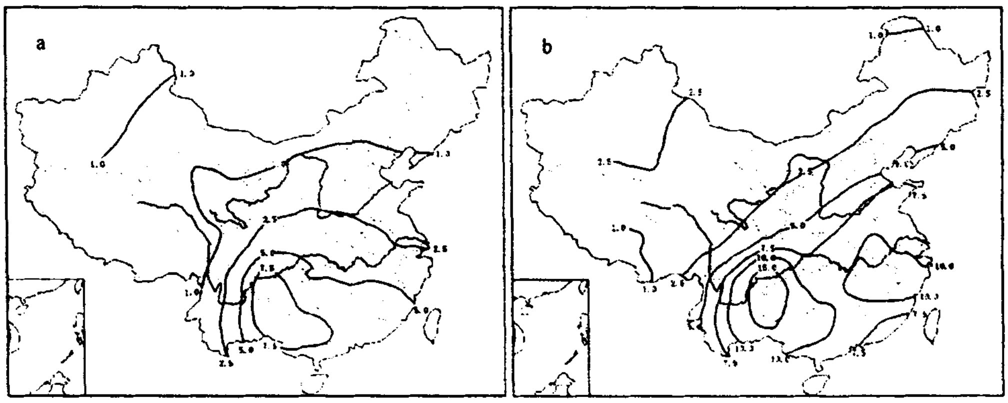

Fig.1 Lowest-model-layer distribution of anthropogenic sulfate aerosol for Jan. (a) and Jul. (b). Unit: μg/m³

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Similar to previous work[9], the initial and lateral fields of the regional climate model are taken from a CO_2 doubling experiment with the CSIRO $R_{21}L_9$ AOGCM of Australia. The first experiment of the model is to double the content of CO_2, which is equivalent to setting the aerosol value zero, i.e. ignoring the effect of aerosol; the second experiment is one that is made with anthropogenic sulfate aerosol when CO_2 is doubled, in which the lately available "observed" aerosol data are added to all gridpoints and layers of the model for climatological integration. For the integrated regional model, the CO_2 is doubled correspondingly. The length of integration is five years in both experiments and two average 5-year differences between the second and first experiments are considered the climatic role of the aerosol. In the sections followed, the results will be used to study briefly the effect of aerosol on surface temperature and precipitation in China with the content doubled for CO_2.

3 EFFECT ON SURFACE AIR TEMPERATURE IN CHINA

Individual climatic elements are interpolated to 160 observation stations across China. First, regional mean surface temperatures are determined on a monthly basis, which reflects the addition of anthropogenic sulfate aerosol and doubling of the CO_2 level (Fig.2). It shows that the aerosol-added model reports widespread reduction of surface temperature though the monthly amount is normally less than –0.2°C and annual mean fall is less than –0.1°C. It indicates that the direct effect of anthropogenic sulfate aerosol causes the temperature to drop in China, but by much smaller amplitude than what the greenhouse effect increases it (with the annual mean of 2.5°C). The figure also tells the seasonal inconsistency in temperature variation caused by the aerosol in the region of China, and slight rises even occur in June. It may be contributed by the fact that the added aerosol results in changes in model-derived physical quantities like clouds (one of indirect climatic effects) to complicate the surface temperature change and cause inconsistent response from temperature from month to month, as well as affecting shortwave radiation. It is an issue that requires more study to confirm.

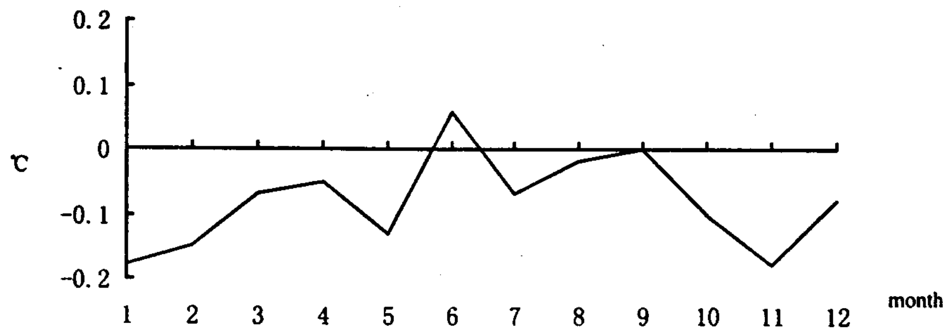

Fig.2 Variations of monthly mean surface temperature over the region of China with aerosol included.

Tab.1 gives the monthly spatial concentration of aerosol for the 160 stations in China and its correlation with the monthly mean surface temperature.

It is seen from the table that the correlation coefficient is –0.29 for the yearly mean, showing the surface temperature in some degree of negative correlation with aerosol concentration, i.e. the higher the concentration of aerosol, the larger the temperature fall it so caused. The correlation is the most obvious in November – April of the wintertime, with the coefficient as high as –0.55 on average; it is much less obvious in May – October of the summertime, with the mean coefficient just a little below zero (–0.04). For the 160 points, the value of spatial correlation is about 0.2 when the level of confidence is 0.99. The wintertime correlation between them is usually above

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the level in the confidence test while it is not most of the time.

Tab.1 Coefficients of the correlation between regional aerosol concentration in China and surface temperature

month	1	2	3	4	5	6	7	8	9	10	11	12	mean
Correlation coefficient	-0.59	-0.69	-0.62	-0.32	0.05	-0.20	0.14	-0.27	0.08	-0.05	-0.51	-0.55	-0.29

Next is a brief discussion of the plane distribution of seasonal surface temperature variation in the region of China with the level of CO_2 doubled and aerosol included.

Temperature variation in China caused by wintertime aerosol (Fig.3a) is generally decreasing nationwide, more pronouncedly so in regions south of the Changjiang R. (Yangtze), the drop being usually below –0.2°C, but less so in Northeast China with the fall less than –0.1°C. In China, precipitation is usually less in winter and so is cloudage, because temperature is directly reduced in most part of the country as a result of the blocking and reflection of shortwave radiation by aerosol. The distribution of temperature fall can also be immediately associated with that of aerosol. In other words, aerosol is higher in content in southern than in northern China (Fig.1a) and thus causes larger reduction of temperature in southern than in northern China. One noteworthy point is that there is also a large-value area of temperature fall in the central and western China, where aerosol is usually small in content. I shows that aerosol can bring about changes in climatological elements in other regions via changes in circulation, in addition to local effect. It needs more study for explanation. Winter is the season in which regionally averaged temperature, –0.14°C, is larger than the other three seasons.

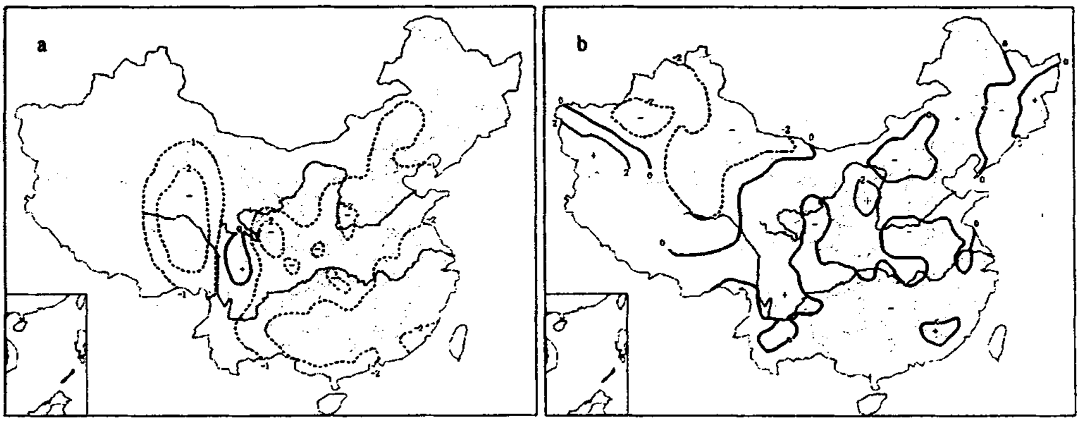

Fig.3 Effect of aerosol on surface temperature in the region of China in winter (a) and summer (b).

The descending trend continues in autumn (figure omitted), though the center has now shifted to areas from the lower reaches of the Changjiang R. To Jiangsu and Shandong provinces while the Northeast China remains a region where the temperature drop is relatively small. Additionally, temperature is relatively low in the southern part of China. One of the characteristics of spring temperature variation is that some sporadic temperature-riding spots begin to appear within the region. The regionally averaged temperature drop becomes smaller for the season, being –0.12°C.

With the increase of cloudage in summer, the effect of aerosol on air temperature in China becomes more complicated as compared with winter and spring. As shown in Fig.3b, the temperature mainly decreases as in the previous seasons, though with much smaller amplitude with the value basically within –0.1°C. Temperature changes alternatively between positive and

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negative in Northern China, though increasing is the main trend. The temperature change is mainly of decrease in Xinjiang and areas around it, probably due to dryer climate and less amount of cloud there. The temperature variation is a weak negative, －0.01, the lowest in all seasons.

With the decrease of cloudage in autumn, temperature mainly decreases in China. The distribution is similar to that of winter, i.e. the drop is larger in southern than in northern China. The temperature change is –0.09°C for regional mean in the season.

Fig.4 gives the distribution of temperature change over the course of the year. Except for a few stations, the basic trend is decreasing, with larger amplitude in the south and northwest parts of the nation, though the magnitude is low, except for the areas south of the Changjiang R. and part of Northwest China where the value is below –0.15°C, which is much smaller than the change induced by greenhouse gases.

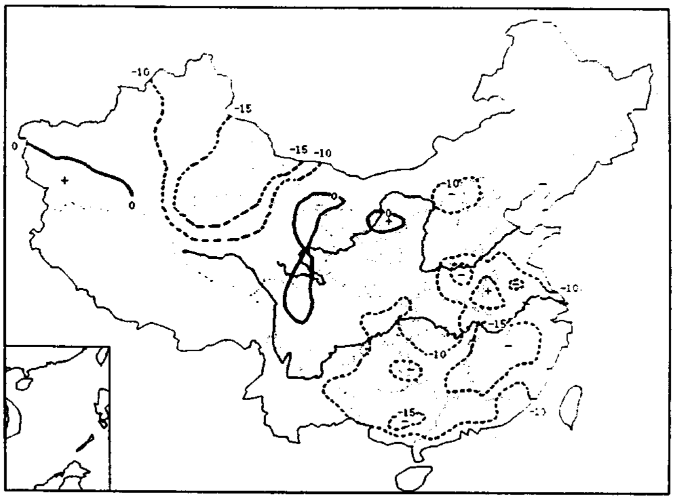

Fig.4 Variations of annual mean temperature over China caused by anthropogenic sulfate. Unit: ×10 °C.

4 EFFECT ON PRECIPITATION IN CHINA

As compared to temperature, anthropogenic sulfate aerosol causes more complicated changes in precipitation.

First of all, with CO_2 doubled, monthly mean precipitation changes (%) are studied for the 160 weather stations in China. From Fig.2, we know that aerosol mainly causes the precipitation to decrease in China, though with the amplitude ranging from –1% to –5%; the variation is only –1% for monthly mean across the year, even with a tendency to increase in June.

Tab.2 Variation of monthly mean precipitation in China with the inclusion of aerosol (unit: %)

Month	1	2	3	4	5	6	7	8	9	10	11	12	Mean
Precipitation changes	–2.5	–2.3	–1.1	-1.6	–0.5	2.0	–1.4	–4.7	–0.1	–0.9	–3.8	–0.6	–1.2

Seasonal changes resulting from aerosol inclusion in the model are as follows. In winter (Fig.5a), it causes the reduction of precipitation over extensive region of China, with the larger center over the Jiaodong Peninsula and surrounding areas and a temperature fall of 10%;

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precipitation increases over some regions but with small values, usually below 5%. The variation is –1.7% for the regional mean.

The variation is more complicated in spring precipitation, which is basically over the Northeast and North China regions and on the decrease mainly, and the drop rate is larger in some parts than in the rest, with the value over 10%; the increasing and decreasing areas have the same distribution south of the Changjiang R. but decreasing is the main trend; large part of central China shows an increasing trend, with some stations as high as 20%. And the variation is –0.9% for the regional mean.

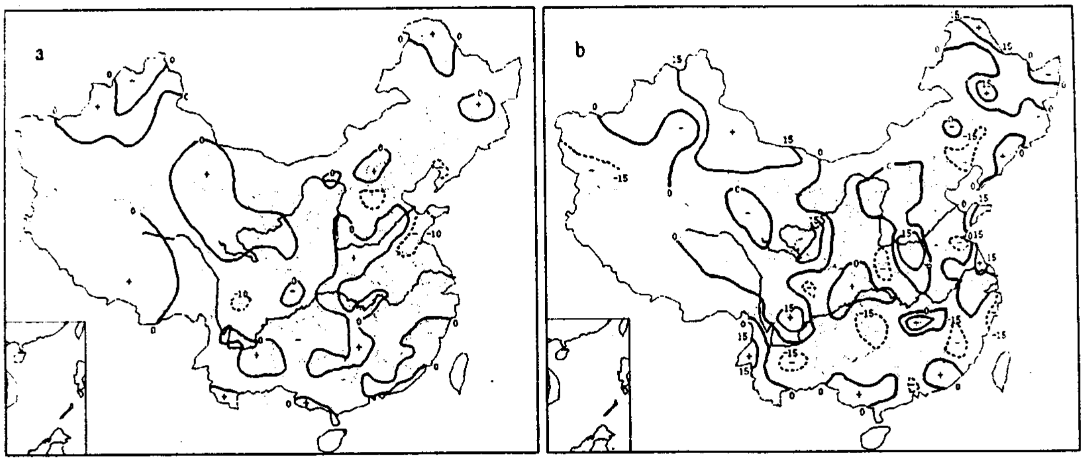

Fig.5 Same as Fig.3 but for precipitation. Unit: %

In summer (Fig.5b), except for a few regions, precipitation decreases over large areas south of the Changjiang R. and eastern part of North China by as much as 15% or more in some locations; precipitation mainly increases in Northwest China. The variation is –1.4% for the regional mean.

For the variation of precipitation in autumn (figure omitted), precipitation mainly decreases in the eastern part of China except for the coastal area in the south. It also decreases in Northwest China. In regions from the Inner Mongolia Autonomous Region to the Great Bend of Yellow R. and from Fujian, Guangdong to Guangxi, precipitation increases. The variation is –1.0% for the regional mean.

The distribution of precipitation change averaged over the year is given in Fig.6. With the doubling of CO_2, the effect of sulfate aerosol is such that it will lead to precipitation decrease over extensive areas south of the Changjiang R. and eastern part of North China but increase over Northwest China; either of the increase or decrease is small, usually within 10%. The variation is only –1.2% for the national mean, which is also much smaller than the change brought about by greenhouse gases.

In general, anthropogenic sulfate aerosol can directly lead to the reduction of precipitation averaged over China, though with small amplitude. The physical relations are complicated for processes from direct radiation effect due to aerosol to precipitation changes, including a number of non-linear effects. Much study is needed before we have physically sound explanation.

5 CONCLUSIONS AND DISCUSSIONS

The latest version of RegCM2 model is fed with aerosol data for experiments on changes in temperature and precipitation in China, which are mainly subject to the direct climatic effect of

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anthropogenic sulfate aerosol and the doubling of CO_2, with or without aerosol.

The latest version of RegCM2 model is fed with aerosol data for experiments on changes in temperature and precipitation in China, which are mainly subject to the direct climatic effect of anthropogenic sulfate aerosol and the doubling of CO_2, with or without aerosol.

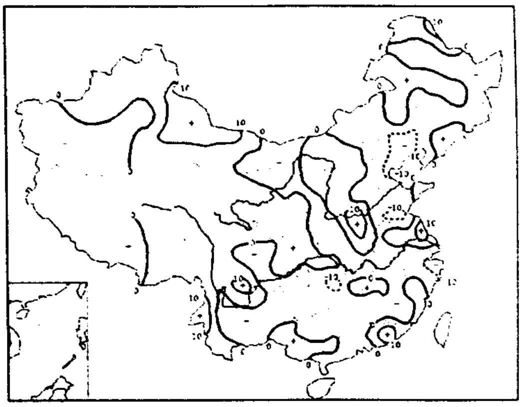

Fig.6 Same as Fig.4 but for annual mean precipitation (%).

As shown the experiments, when only the direct effect of anthropogenic sulfate aerosol is taken into account, the temperature and precipitation will experience some changes in the region of China, though both display decreasing or diminishing tendencies. Specifically, the decrease of temperature is closely linked with the distributing concentration of aerosol in the winter months while being less so in the summer months; annual mean temperature changes are a little larger in the southern and northwest parts of the nation. For the changes in precipitation, however, things are more complicated: the annual mean precipitation is decreasing in areas south of the Changjiang R. and eastern part of North China but decreasing in Northwest China.

The values of the above changes, whether it be temperature or precipitation, are relatively small when compared to those caused by the greenhouse gas CO_2. For the annual mean, the variation of temperature is less than –0.1°C and that of precipitation only –1%. For some overseas models, the variation of temperature simulated is usually between –0.1°C and a few degrees of Celsius[4] while our simulations are near the lower limits of the results without significant effects of the aerosol introduced. One cause is that aerosol needs to be better reflected in the regional model and the other may be resulted from the lack of aerosol effect in the GCM used for driving and forcing lateral boundary fields. Judging from previous experience, the values simulated by the regional model can be a few times or one order of magnitude higher if this kind of model is used in driving.

The effect of aerosol on climate is a very complicated issue. For the aerosol effect on radiation (the so-called direct role) depends on the distribution and physical / chemical properties of the former, like the size, spectral distribution, chemical compositions, mixture between various aerosol particles and optical nature of the underlying surface, etc. They all have large temporal and spatial variability. The indirect effect is more complicated. There has not been a single model that is good enough to calculate the climatic effect of aerosol accurately, which becomes the most uncertain factor in predicting the climatic change caused by anthropogenic activity. In the current, some preliminary conclusions have been achieved in the study of direct aerosol effect. It is necessary to carry out a large number of theoretical analysis and numerical experiments to obtain better-founded and fuller results.

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