Analysis of aerosol climate effects under global warming

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Abstract. Global warming is a global environmental problem that has a profound impact on natural ecosystems, human socio-economic activities and the future fate of the planet. Aerosols, as tiny particles that are widespread in the atmosphere Its climate effects are complex and uncertain, and it is a key factor in global climate change research. This essay first introduces the definition and classification of aerosols, including natural source aerosols and anthropogenic source aerosols. Then it analyzed the interrelationship between global warming and aerosols. Then it explored the differences in aerosol impacts in various regions, using North China, Northeast China and the Qaidam Basin as examples. It was found that the differences in the spatial and temporal distribution of aerosols can be summarized from the seasonal and interannual variations of Aerosol Optical Depth (AOD) as well as the characteristics of the spatial distribution. The higher AOD values in spring and summer are mainly affected by sand and dust aerosols, localized pollution, and the EI Niño-Southern Oscillation (ENSO) phenomenon. The spatial distribution of AOD showed heterogeneity. The research provides an important scientific basis for the development of effective climate policy and response measures.

1 Introduction

In the context of global climate change, global warming has become a serious challenge that cannot be ignored. Global warming has far-reaching influences on natural ecosystems, human socio-economic activities and the future fate of the earth. Global warming is mainly driven by a combination of factors, including increased greenhouse gas emissions, land-use change, deforestation and accelerated industrialization. Among the many factors exploring climate warming, aerosols, as tiny particulate matter widely existing in the atmosphere, have been the most uncertain factor in anthropogenic climate forcing for a long time, and their complex climate effects have gradually received extensive attention from the scientific community [1].

Aerosols are referred to a gaseous dispersion system consisting of solid or liquid particles suspended in a gaseous medium. Aerosols not only directly affect the Earth's energy balance, but also indirectly influence cloud formation, development, and dispersion through a series of complex physical and chemical processes, thus having a significant impact on the

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climate system. In the study of aerosol climate effects, cloud-aerosol interactions have become a hot topic of research for a wide range of scientists due to their large uncertainty factors and their non-negligible moderating effect on the global climate system [2]. The climate effects of aerosols are particularly important in the context of global warming. On the one hand, aerosols can directly cool the atmosphere and the earth's surface by scattering and absorbing solar radiation, which has a certain mitigating effect on global warming, the so-called "aerosol cooling effect". On the other hand, aerosols can also indirectly alter the energy distribution and water cycle of the climate system by affecting the radiative properties of clouds and precipitation efficiency. Such indirect effects are often more complex and difficult to predict than direct effects [3]. Therefore, an in-depth analysis of the climate effects of aerosols in the context of global warming not only helps to understand more comprehensively the driving mechanisms and evolutionary patterns of climate change but also provides an important scientific basis for the formulation of effective climate policies and response measures.

This paper is to study the climate effects of aerosols in the context of global warming, specifically including the classification of aerosols and their characteristics, the interrelationship between global warming and aerosols, and the difference in aerosol impacts in different regions. Analyse the effects of global warming on aerosol generation, propagation and removal, and the direct and indirect radiative feedback of aerosols on global warming by elaborating on the classification of natural and anthropogenic sources of aerosols. Meanwhile, taking North China, Northeast China and Qaidam Basin as examples, this paper will explore the seasonal distribution characteristics, spatial distribution characteristics and influencing factors of aerosol optical thickness in different regions, to provide a scientific basis for comprehensively grasping the driving mechanism and evolutionary law of climate change.

2 Classification of aerosols

2.1 Natural source aerosols

Natural source aerosols, as an important component of atmospheric aerosols, have a wide range of sources and are complex. Natural source aerosols mainly include sea salt aerosols, sand and dust aerosols, biomass burning aerosols, and biogenic aerosols. These aerosols are produced primarily by physical, chemical and biological processes in nature without direct human involvement and are therefore widespread globally [2].

2.2 Anthropogenic source aerosols

Aerosols of anthropogenic origin are aerosol particles produced directly or indirectly by human activities. These particles are widespread in the atmosphere and have significant impacts on air quality, climate change and human health. With accelerated industrialization and urbanization, aerosol emissions from anthropogenic sources are increasing and have become an important part of the global environmental problem. Aerosols of anthropogenic origin come from a variety of sources, including fossil fuel combustion, industrial processes, agricultural activities, urban buildings and road construction. For example, the combustion of fossil fuels in large quantities releases large amounts of sulphur dioxide, which increases the concentration of sulphate aerosols in the atmosphere, thus contributing to global climate change. In the case of China, the direct radiative effect of sulphate aerosols causes a generalized cooling of inland China [4].

3 Interrelationships between global warming and aerosols

3.1 Impact of global warming on aerosols

Global warming affects aerosol generation, propagation and removal processes in a variety of ways. Elevated temperatures act directly on the aerosol generation process. For example, the rates of some chemical reactions may change as temperatures rise. In terrestrial ecosystems, higher temperatures can affect the physiological activity of vegetation. Volatile organic compounds (VOCs) emitted by plants are precursors to secondary aerosol formation, and temperature changes can alter the rate of VOCs emitted by plants. For some biogenic aerosols, elevated temperatures may induce enhanced microbial metabolic activity, which in turn increases the release of microbial aerosols.

In terms of transmission, warmer temperatures may alter the thermal structure and stability of the atmosphere. A warmer air layer may increase the height of the atmospheric boundary layer, which could affect the aerosol propagation range in the vertical direction. Diffusion and mixing of aerosols in the vertical direction can be altered by changes in the height of the atmospheric boundary layer, which may lead to a more complex distribution of aerosols in the atmosphere. In terms of removal processes, temperature affects chemical and physical processes in the atmosphere. For example, increased temperatures may accelerate the evaporation process of aerosols, especially for some semi-volatile aerosol components. In addition, increased temperatures may change the characteristics of precipitation, indirectly affecting the removal efficiency of aerosols by wet deposition.

Changes in source areas due to climate change have a non-negligible indirect impact on aerosol sources. In the case of the oceans, as global warming increases ocean temperatures, sea ice melts, which can alter marine ecosystems. Phytoplankton are affected by the environment in which they grow, and their abundance and distribution change. Phytoplankton are one of the important sources of marine-sourced aerosols, and the dimethyl sulphur (DMS) they release oxidizes in the atmosphere to form sulphate aerosols. Therefore, changes in marine ecosystems indirectly affect the generation of marine-sourced aerosols.

In terrestrial ecosystems, climate change may lead to the expansion of arid and semi-arid areas and a reduction in vegetation cover. This will increase the release of dust from the surface and expand the source area for dust aerosols. At the same time, the frequency and intensity of forest fires may increase as a result of climate change, and forest fires release large amounts of soot and aerosol precursors, thus becoming an important temporary source area for aerosols. These climate change-induced changes in source regions have complex implications for the overall source strength of aerosols, further affecting their role in the global climate system.

3.2 Aerosol feedback to global warming

3.2.1 Direct effect of radiation

Aerosols directly affect solar radiation through scattering and absorbing, altering the radiative balance of the geothermal air system, which affects the regional climate. It has been found that changes in surface albedo affect aerosol radiative effects and the Earth's radiation balance and that aerosols are more susceptible to radiative warming effects when surface albedo is high. Annan Chen et al. combined satellite and ground observation data to study aerosol and surface albedo under different aerosol characteristics and pointed out that the interaction of aerosol direct radiative effect and surface albedo is important for balancing the Earth's energy.

As surface albedo decreases, the aerosol cooling effect at the top boundary of the atmosphere increases and the warming effect decreases [5].

The scattering of solar radiation by aerosol particles is an important radiative process in the atmosphere. Sunlight encountering suspended aerosol particles is scattered and part of the radiation does not reach the surface. Scattering aerosols, such as sulphates, depend on particle size and other factors, such as sulphate and sea salt aerosols can reduce the amount of solar radiation reaching the surface to produce a cooling effect. Some aerosol particles such as black carbon absorb solar radiation directly, and black carbon aerosol is a strong absorbing component of the atmosphere and has a warming effect on the surface. A study by Huijuan Lin et al. in Regional Climate Effects of Black Carbon in Asia showed that the concentration of black carbon had an extremely significant effect on the shortwave heating rate, especially in the region of large values of black carbon concentration (Fig. 1) [6].

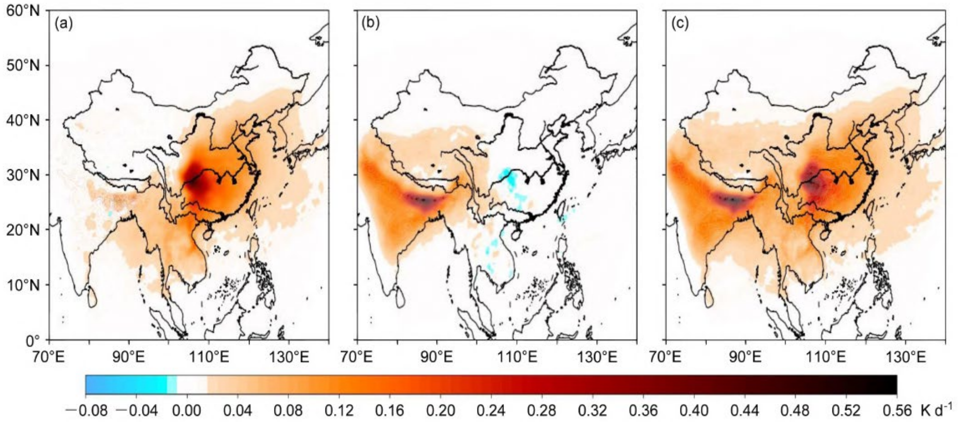


Fig. 1. Changes in shortwave radiation heating rate (SWHR; units: K d-1) near 850 hPa for (a) Chinese black carbon, (b) Indian black carbon, and (c) Chinese and Indian black carbon overwinters (1996 – 2006). The black dots indicate the student's t-test 90% confidence level. [6]

3.2.2 Indirect radiation effect

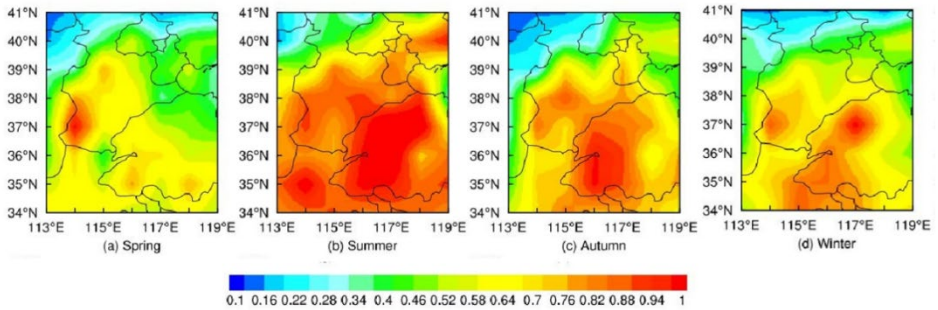
Cloud formation occurs mainly through the process of heterogeneous nucleation that occurs when aerosols are used as cloud condensation nuclei and water vapor accumulates on them. The interaction between aerosols and clouds is an important source of uncertainty in future climate predictions. Graham Simpkins studied how increased aerosol concentrations affect mid-latitude storm clouds by using high-resolution imagery and a global convective licensing model. Studies have shown that aerosols increase the liquid water content of polluted systems, and cloudiness, and thus enhance the albedo of storms, and the outgoing flux of shortwave radiation. These findings help to limit estimates of anthropogenic radiative forcing and improve climate projections [7].

Aerosols have three important types of indirect effects on clouds and the climate system. The first type of indirect effect is the Twomey effect, where an increase in aerosol number concentration leads to an increase in cloud particle number concentration, a decrease in radius, and an increase in cloud albedo [8]. In the oceans, anthropogenic emissions of aerosols increase the concentration of cloud particle numbers, resulting in whiter clouds and increased albedo. The second type of indirect effect, the Albrecht effect or cloud lifecycle effect, is that an increase in anthropogenic aerosols reduces the radius of cloud particles, inhibiting precipitation and altering the cloud lifecycle. In and around large cities, human activities generate aerosols that reduce stratocumulus cloud particle radii, inhibit precipitation, and lengthen cloud duration. Semi-direct effect refers to the absorption of solar energy by light-absorbing aerosols to heat the atmosphere and evaporate clouds, such as soot, black carbon, and other aerosols can heat the atmosphere and clouds to evaporate the cloud droplets, reducing the number of clouds, shortening the cloud lifetime, and reducing the average albedo of the cloud body [9]. In turn, clouds can be cleared of aerosols by precipitation, affecting their effect on clouds. Convective cloud formation begins with the rise of the surface of a heated planet, and the magnitude of the rise depends on the change in temperature with altitude or the rate of descent of the troposphere.

4 Differences in aerosol impacts in different regions

4.1 Impact of aerosols in North China

Aerosol Optical Thickness (AOD) is a physical quantity that describes the light-cutting effect of aerosols. It is a key indicator of the degree of atmospheric turbidity and the most important optical property parameter in determining the climatic effects of aerosols. Spatial averaging of the parameter Column_Optical_Depth_Aerosols_532 in the CALIPSO satellite Level 2 5km aerosol layer product from June 2006-October 2015 by Xingxing Gao et al. Based on multi-source satellite remote sensing data and ground observation data, it is found that the seasonal distribution characteristics of aerosol optical thickness in North China are obvious [10]. As can be seen from Fig. 2, the 532 nm AOD value was the largest in North China in summer, followed by autumn and winter in that order, and the smallest in spring. The corresponding 532 nm AOD values were 0.74, 0.58, 0.55 and 0.49 in that order. The high AOD areas are concentrated in the densely populated and highly urbanized plains of North China, while the low AOD areas are concentrated along the hilly mountains at higher elevations. It can be seen that the spatially varying properties of atmospheric aerosols are strongly influenced by human activities.



(a) Spring (b) Summer (c) Autumn (d) Winter

Fig. 2. Spatial distribution of mean 532 nm AOD values in North China, 2006-2015 (a. spring; b. summer; c. fall; d. winter) [10]

4.2 Impact of aerosols in Northeast China

Li Wan et al. analysed the spatial distribution characteristics and inter-annual trends in Northeast China using MODIS atmospheric aerosol optical thickness data and the China Multiscale Emission Inventory Model (CMEIM) from 2003 to 2022 [11]. It was found that all high values of AOD in Northeast China occurred in spring and summer, with a decreasing trend of AOD in fall and an increase in AOD in winter (Fig. 3) The reason is that the burning of straw in spring and the strong radiation and high humidity in summer favor the acceleration of the air-particle transformation process, which has a greater impact on the atmospheric extinction in the Northeast. Figure 4 shows the regional average values of AOD in the northeast region. As can be seen from the figure, the annual average AOD value is highest in Liaoning. And the AOD values in Liaoning were higher than those in Jilin and Heilongjiang in spring, summer, autumn and winter. The increase of AOD in summer in Northeast China is mainly related to the environmental humidity, and the boundary layer meteorological conditions have some influence on AOD in winter.

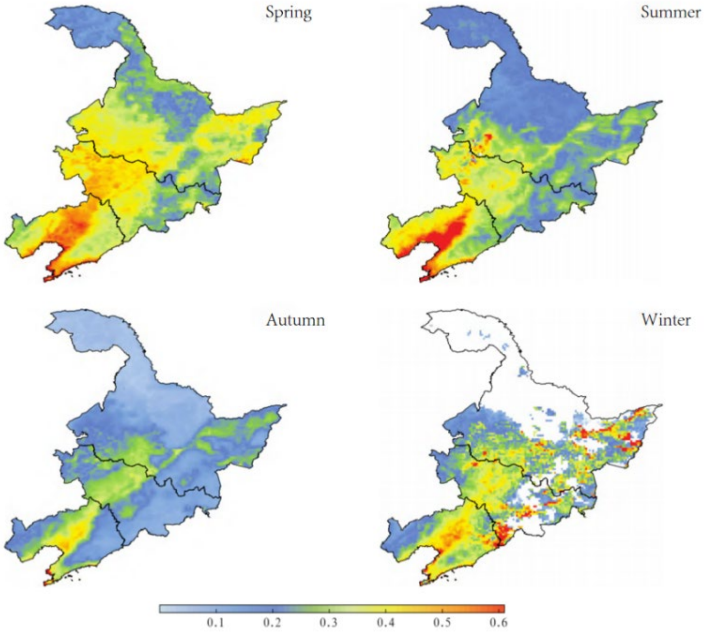


Fig. 3. Seasonal distribution of AOD in Northeast China from Mar 2003 to Feb 2023 [11]

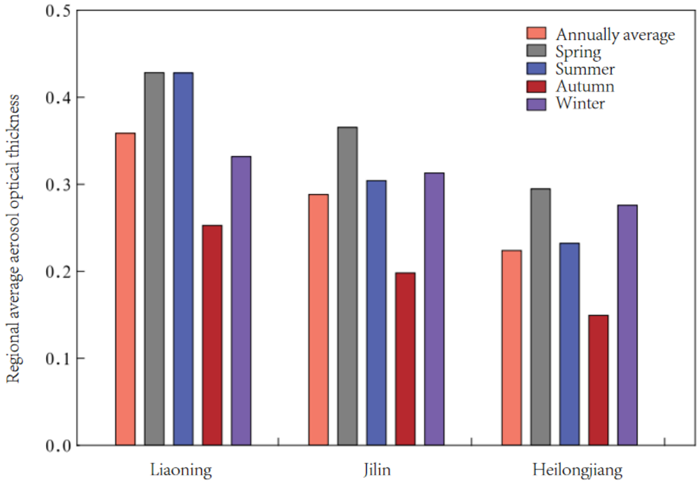


Fig. 4. Regional average of AOD in Northeast China from Mar 2003 to Feb 2023 [11]

4.3 Impact of aerosols in Qaidam basin

Xiao Hongdan et al. explored the spatial and temporal distribution characteristics and influencing factors of AOD in the Qaidam Basin from 2001 to 2021 based on the MODIS MCD19A2 aerosol dataset using linear trend, Spearman's correlation analysis, and Ångström's exponential interpolation method [12]. As can be seen in Figure 5, it indicates that AOD in the Qaidam Basin has obvious seasonal variations, with the area of high AOD values being the largest in the spring, gradually decreasing in the summer, and dissipating in the autumn and winter. Since the basin is mostly desert, dust storms are frequent in the spring and are accompanied by drastic weather changes and the accumulation of large amounts of dust aerosols, resulting in the formation of high-value areas. Figure 6 shows the characteristics of seasonal changes of AOD in the Qaidam region, and it can be seen that the value of AOD is spring > summer > autumn > winter. Due to the topographic constraints of the Qaidam Basin, air convection is poor. The Qaidam Desert is the main source area of sand and dust in the basin, and its AOD reaches its highest level in the spring, which makes it difficult for sand and dust aerosols to diffuse, and thus leads to the emergence of the “Basin Effect”.

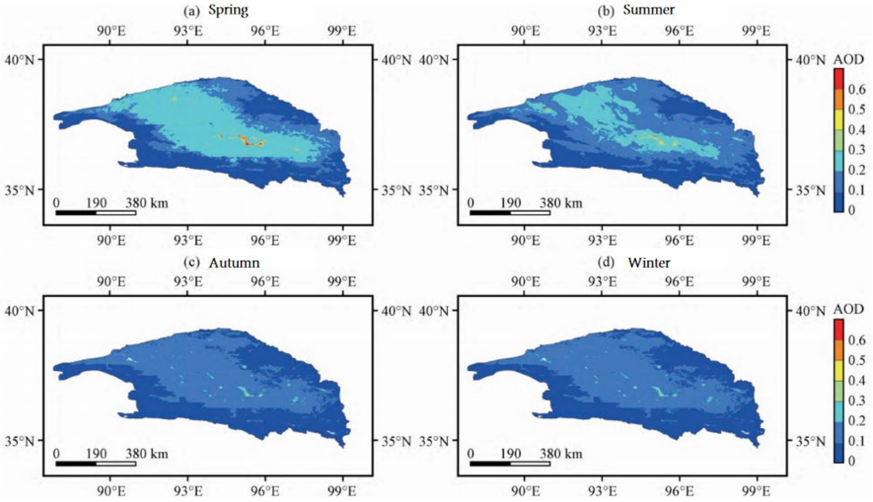


Fig. 5. Seasonal mean spatial distribution of AOD in the Tsaidam Basin during 2001 -2021 [12]

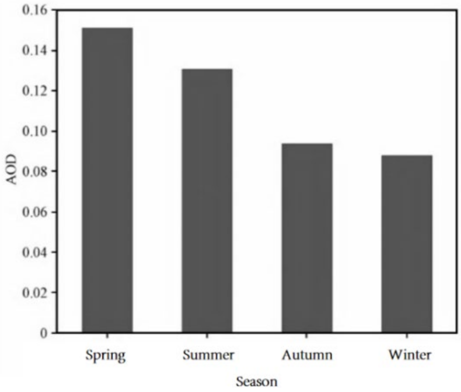


Fig. 6. Characteristics of seasonal changes in AOD in the Qaidam Basin during 2001 -2021 [12]

In terms of seasonal and interannual variations in AOD and spatial distribution characteristics, a case study can summarize the differences in aerosol impacts in different regions found that the differences in the spatial and temporal distribution of aerosols. One reason for the higher AOD values during the spring and summer seasons is the effect of dust aerosols. Dust aerosols are blown up and spread over longer distances in the spring due to dry air and favorable wind conditions, resulting in a greater optical thickness of dust aerosols in the spring. The second is the effect of localized pollution. Emissions due to human activities increase aerosols, which can lead to an increase in the optical thickness of aerosols. Especially during the spring and summer months, when human activities are more frequent due to higher temperatures and increased sunlight hours, the aerosol optical thickness increases. The third is the impact of the El Niño-Southern Oscillation (ENSO) phenomenon. In the spring of the year following El Niño, dry air and low precipitation favor biomass-burning activities in northern continental Southeast Asia, leading to an increase in carbonaceous aerosol emissions, and thus an increase in aerosol optical thickness. On the contrary, the La Niña phenomenon leads to a decrease in the aerosol optical thickness. The spatial distribution of AOD is characterized by inhomogeneity.

5 Conclusion

This paper provides the climatic effects of aerosols in the context of global warming and the differences in impacts in different regions. Global warming and aerosols interact in a complex way, with global warming influencing aerosol production, propagation and removal, and aerosols in turn feeding back on global warming through direct and indirect radiative effects. Aerosol optical thickness in different regions shows distinct seasonal and spatial distribution characteristics. The high AOD areas in North China are concentrated in the densely populated and highly urbanized North China Plain. The high values of AOD in Northeast China were in spring and summer, and the AOD values in Liaoning were higher than those in Jilin and Heilongjiang. The AOD in the Qaidam Basin formed a high-value area in the spring due to the sandstorm weather, and the “basin effect” appeared due to the limitation of the topography. Overall, the differences in the spatial and temporal distribution of aerosols are influenced by several factors, including dust aerosols, localized pollution, and the ENSO phenomenon. The understanding of the climate effects of aerosols and regional differences is of great significance to future climate change research and response efforts and can provide a scientific basis for the formulation of effective climate policies and response measures.

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