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Aerosol Effects on the Atmosphere: Types, Mechanisms and Future Perspectives

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Abstract. Aerosols, composed of solid or liquid particles suspended in the atmosphere, with complex sources and mechanisms of action, are widely present in both natural environments and human activities. Aerosols directly affect the Earth's energy balance by scattering and absorbing solar radiation and indirectly affect climate and precipitation patterns by acting as cloud condensation nuclei, altering cloud formation and microphysical properties. This paper discussed the different types of aerosols, including natural, anthropogenic, and hybrid aerosols, and analyzed their physical and chemical properties. This paper also analyzed the direct and indirect climate effects of aerosols in the atmosphere and explored future research directions, including technological innovations, interdisciplinary collaborations and international policy drivers. Future research on aerosols as an important factor in climate change will contribute to a better understanding of its complexity and to strategies to address global climate change.

1 Introduction

Aerosols are gaseous dispersed systems of solid or liquid particles suspended in a gaseous medium, with particle diameters ranging from a few nanometres to tens of microns, which are widely distributed in the natural environment and human activities. As the problem of climate change becomes more serious, aerosols are appearing more frequently in various articles, giving rise to a wide range of concerns about them.

Atmospheric aerosols have the capacity to directly influence the Earth's energy balance through their scattering and absorption of solar radiation. Additionally, they can indirectly impact the Earth's climate by serving as cloud condensation nuclei and modifying cloud formation as well as microphysical properties.[1]. Therefore, the international community attaches considerable importance to the study of the sources and formation mechanisms of aerosols in the atmosphere. With the development of the national economy, atmospheric particulate pollution has become urban and regional, and organic aerosols have also become a significant challenge for air pollution control [2]. Through long-term atmospheric monitoring, some research teams in the United States have identified in detail the major sources of anthropogenic aerosol (e.g., sulfate and nitrate aerosols) emissions and their concentration distribution patterns in the atmosphere in different regions. In the study of the

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mechanism of action of aerosols on the atmosphere, European scientific research groups have used advanced satellite remote sensing technology and a network of ground-based observatories to investigate in detail the scattering and absorption properties of aerosols in response to solar radiation. The research team discovered that black carbon aerosols significantly contributed to the absorption of solar radiation, with this absorption having a notable impact on regional climate patterns. In the field of aerosol action mechanisms, China has conducted comprehensive research on the physical, chemical and climatic effects of aerosols, utilizing self-developed observational equipment and numerical models. For instance, research into cloud physics has demonstrated that aerosols, acting as water vapor condensation nuclei, exert a considerable influence on precipitation distribution in China, particularly in arid and semi-arid regions, where alterations in aerosol concentration may result in shifts in precipitation patterns. Nevertheless, despite the notable advancements in aerosol research at home and abroad, there remain some challenges and issues that necessitate further experiments and research.

This paper is designed to explore the sources and characteristics of different types of aerosols in the atmosphere and their mechanisms of influence on climate. By classifying and analysing natural aerosols, anthropogenic aerosols and hybrid aerosols, the role of aerosols in radiation, cloud and surface interactions is revealed in conjunction with the findings of international research.

2 Types and characteristics of aerosols

2.1 Natural aerosols

Natural aerosols are defined as aerosols emitted to the atmosphere through a variety of physical, chemical and biological processes occurring in the natural environment [3]. The sources of natural aerosols are numerous and diverse, encompassing volcanic eruptions, forest fires, sea salt particles, wind and sand. The concentration and distribution of these aerosols in the atmosphere are subject to seasonal, geographical and climatic influences. The release of sulfate aerosols into the atmosphere as a result of volcanic eruptions has the potential to exert a significant influence on the global radiation balance. In contrast, sea salt aerosols present in the oceans play a pivotal role in cloud formation. Natural aerosols can accelerate certain chemical processes within the atmosphere, and cause changes in atmospheric colour and a range of other effects.

2.2 Anthropogenic aerosols

Anthropogenic aerosols are aerosols generated through human activities, mainly from industrial emissions, fossil fuel combustion, and agricultural activities. Sulfate, nitrate and organic carbon aerosols are the most common types of anthropogenic aerosols. These aerosols not only influence the climate system by scattering and absorbing solar radiation but also have significant implications for air quality. These include reduced visibility, respiratory diseases, acid rain, and other adverse effects [4].

2.3 Mixed aerosols

Mixed aerosols are a combination of natural and anthropogenic aerosols, and typically possess a complex chemical composition and physical properties [5]. For instance, dust aerosols can adsorb pollutants emitted by anthropogenic activities as they traverse industrial zones, thereby forming mixed aerosols. Such mixing properties contribute to the intricacy and diversity of aerosol climate impacts.

2.4 Physical and chemical properties of aerosols

The physical characteristics of aerosols encompass particle diameter, shape and surface properties, whereas the chemical properties pertain to their composition and chemical reactivity. Particle size is a pivotal factor in regulating the behaviour of aerosols in the atmosphere, influencing their atmospheric residence time, optical properties and settling rate. The physical properties of aerosols encompass particle diameter, shape and surface properties, whereas the chemical properties pertain to their composition and chemical reactivity. Particle size is a pivotal factor in regulating the behaviour of aerosols in the atmosphere, influencing their atmospheric residence time, optical properties and settling rate [6].

3 Mechanisms of aerosol impact on the atmosphere

3.1 Physical effects

3.1.1 Scattering and absorption of solar radiation

The scattering of sunlight by aerosol particles is one of their most significant physical effects [7]. As sunlight traverses the atmosphere, it is subject to scattering by aerosol particles, resulting in the light being dispersed in all directions. This scattering effect not only reduces the intensity of solar radiation reaching the ground but also affects the optical properties and visibility of the atmosphere. The scattering effect of aerosol particles is related to their size, shape, refractive index and other factors. Aerosol particles of small size undergo mainly Rayleigh scattering, resulting in a blue colouration of the sky, while particles of larger size may undergo Mie scattering, causing optical turbidity in the atmosphere. Some aerosol particles are capable of absorbing energy directly from solar radiation, such as black carbon. This absorption increases the heat content of the atmosphere and affects the Earth's energy balance. Concurrently, compounds attached to the surface of aerosols may also absorb solar radiation, thus enhancing the overall absorption effect of aerosols. In East Asia, for example, summer temperatures and pressures are influenced by regional sulphate aerosols in China, with widespread cooling and pressure increases north of about 25°N inland (Fig. 1) [8]. Black carbon aerosols at 500 hPa cause a decrease in temperature north of 45°N and an increase in temperature south of 45°N in China. At 850 hPa, black carbon aerosols cause a significant increase in temperature in the eastern part of China and its coastal areas, and a decrease in temperature in the western and northern parts of the country (Fig. 2) [9].

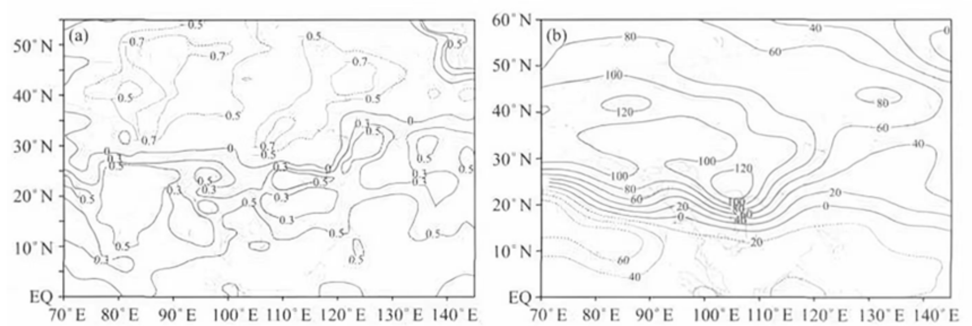

Fig. 1. Sulphate-induced changes in surface temperature and barometric pressure during summer (°C) [8]

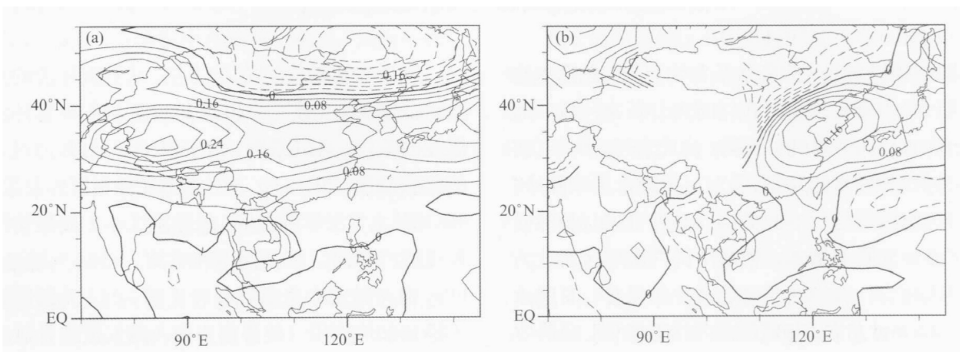

Fig. 2. Summer 500 hPa and 850 hPa temperature changes due to black carbon aerosols [9]

3.1.2 Impact on atmospheric transparency

The presence of aerosol particles reduces the transparency of the atmosphere, making it impossible for light to penetrate the atmosphere [10]. The primary reason for this is the scattering and absorption of light caused by aerosol particle as the concentration of aerosols increases, the transparency of the atmosphere is further reduced, leading to the formation of meteorological hazards such as haze.

3.1.3 Acting as condensation nuclei for water vapor

Aerosol particles can act as condensation nuclei for water vapor, facilitating cloud formation and precipitation processes. When water vapor molecules condense on the surface of aerosol particles, cloud droplets or raindrops are formed. The number, size, and distribution of these cloud droplets and raindrops are influenced by the aerosol particles. The higher the concentration of aerosol particles and the smaller the particle size, the greater the number of cloud droplets and the smaller the droplet size; conversely, a lower concentration of cloud droplets results in larger individual droplet sizes

3.2 Chemical effects

3.2.1 Provision of chemical reaction sites

Aerosol particles, with their large specific surface area and surface energy, are capable of adsorbing gas molecules and chemical reactants in the atmosphere, thereby providing a site for non-homogeneous chemical reactions. These chemical reactions may result in the production of new substances that influence the chemical composition and properties of the atmosphere.

3.2.2 Impact on stratospheric ozone climatic effects

The existence of aerosols in the stratosphere can affect the chemical balance of ozone. For example, volcanic aerosols from volcanic eruptions can reflect sunlight and reduce the intensity of solar radiation reaching the stratosphere, thus slowing down the rate of ozone photolysis [11]. At the same time, some components of volcanic aerosols may also participate in ozone chemistry, further affecting ozone concentrations.

3.3 Climatic effects

3.3.1 Direct climate effect

Aerosols can direct scatter and absorb solar radiation, which can impact the Earth's energy equilibrium and climate system. For instance, sulfate aerosols have a cooling effect by reflecting sunlight and reducing the total amount of solar radiation that reaches the Earth's surface. This effect is particularly pronounced in industrialized regions, where it has a significant impact on the local climate and ecosystem.

3.3.2 Indirect climate effect

Aerosols can also indirectly affect the climate system by influencing the microphysical structure of clouds and precipitation processes. For example, aerosols can increase the number of cloud droplets and reduce the size of individual droplets, making clouds more reflective of sunlight and reducing precipitation. This effect is known as the ‘first indirect effect’ of aerosols. In addition, aerosols may have more complex indirect climate effects by affecting the life cycle of clouds and the efficiency of precipitation.

4 Future prospects for aerosol research

4.1 Technology upgrading and innovation

Future research on aerosols will require some upgrading and innovation of existing technologies, such as the development of new aerosol preparation technologies. With the progress of nanotechnology and material science, the preparation technology of aerosols needs to be more refined and diversified. New preparation techniques such as microfluidic technology, laser induction technology, ultrasonic atomization technology, etc., will be able to prepare aerosol particles with smaller particle sizes, more uniform distribution and more stable performance. At the same time, the monitoring and control system will become more intelligent, and the development of intelligent technology will promote the upgrading of aerosol monitoring and control systems. In the future, there will be more aerosol monitoring equipment based on the Internet of Things, big data and artificial intelligence technology, which will be able to monitor the concentration, distribution and trend of aerosols in the atmosphere in real time and accurately, providing strong support for environmental protection and climate research.

4.2 Expansion of application areas

The application areas of aerosols are expanding with the improvement of related technologies. In the field of healthcare, aerosol inhalation therapy can be used as a new type of drug delivery. With the advantages of fast drug delivery and high bioavailability, this therapy plays an important role in the treatment of respiratory diseases such as asthma and chronic obstructive pulmonary disease. In addition, aerosols can be used for vaccine delivery and drug delivery. In the field of environmental protection, aerosol technology can be used in air treatment, water purification, soil remediation, etc., through adsorption, catalysis, decomposition and other mechanisms to remove pollutants in the atmosphere and water to improve environmental quality. In the field of industrial production, aerosol technology can be used in the preparation of nanomaterials, paint spraying, lubricant spraying and so on. In the future, as the degree of automation and intelligence of industrial production increases, it will play a greater role in improving production efficiency, reducing production costs and improving product quality.

4.3 Interdisciplinary collaboration expansion of application areas

Future research on aerosols requires further understanding of aerosol composition, physicochemical properties, climate system interactions, and aerosol health effects [12]. More accurate modelling of the direct and indirect effects of aerosols in regional and global climate models is an important direction for future research. In addition, interdisciplinary cooperation with each other is key to improving research on aerosols. If aerosols are cross-fertilized between physical chemistry and biology, more in-depth research can be carried out on the biochemical reactions of aerosols and the transport and dispersion of microbial aerosols. This will help to reveal the mechanism of aerosol impacts on ecosystems and human health. For example, cross-collaboration between environmental and atmospheric sciences can help to better understand the complexity and dynamics of the atmospheric environmental system through in-depth studies on the physical and chemical properties, sources and transport mechanisms, and climatic effects of aerosols. The development of environmental and atmospheric sciences will also be promoted.

4.4 International cooperation and policy promotion

Aerosol research requires international cooperation to jointly address global environmental issues. In the future, countries will strengthen cooperation and exchanges in aerosol monitoring, technology research and development, data sharing and other aspects to jointly promote the in-depth development of aerosol research. To strengthen international cooperation, the government can introduce more relevant policies to support aerosol research and technology application. For example, increasing investment in aerosol monitoring network construction, encouraging aerosol technology research and development and innovation, and promoting the application of aerosol technology in areas such as environmental protection and industrial production. These policy measures will provide a strong guarantee for the future development of aerosol research [13].

5 Conclusion

As a significant constituent of the atmosphere, aerosols exert considerable and pervasive influences on the Earth's climate and environment, largely due to their inherent diversity and complexity. First, aerosols have a significant effect on the climate system, both directly and indirectly. The direct effect is reflected in their ability to scatter and absorb solar radiation, thereby affecting the Earth's energy balance. This effect varies among different types of aerosols (e.g., sulfates, black carbon, etc.) and is influenced by some factors such as aerosol particle size, concentration and distribution. Indirect effects are even more complex, as aerosols act as cloud condensation nuclei and can change the microphysical properties of clouds, such as cloud thickness, brightness, and precipitation efficiency, which in turn have a long-term impact on the climate. Secondly, with the advancement of science and technology, aerosol research tools and techniques are also evolving. Breakthroughs in nanotechnology and materials science have made it possible to more precisely prepare and control the particle size, shape and surface properties of aerosol particles, thus enabling in-depth study of their physicochemical properties. Meanwhile, the development of intelligent monitoring technology enables us to monitor the concentration, distribution and trend of aerosols in the atmosphere in real time and accurately, providing important data support for environmental protection and climate research. In addition, the application fields of aerosol technology are expanding, such as environmental protection, medical health and industrial production. Advances in science and technology, such as nanotechnology and intelligent monitoring, have provided strong support for aerosol research and expanded its application areas. By strengthening international cooperation and policy promotion, the in-depth development of aerosol research can be better promoted, contributing more wisdom and strength to the fight against climate change and environmental protection.

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