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REVIEW

A Comprehensive Review of Dust Events: Characteristics, Climate Feedbacks, and Public Health Risks

Lulu Lian[1] · Jianping Huang[1,2] · Siyu Chen[1,2] · Shikang Du[1,3] · Lihui Zhang[1] · Jiabin Yang[1]

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Abstract

Purpose of Review Dust events are global meteorological disasters, affecting approximately 330 million people across 151 countries, from sub-Saharan Africa to northern China and Australia, with profound impacts on ecosystems, human health, and socioeconomics. The WMO airborne dust bulletin 2023 indicates that, dust concentrations in the most severely affected regions worldwide exceeded long-term averages, causing significant impacts on the global environment, economy, and public health.

Recent Findings In recent years, as climate change has led to an increasing frequency and intensity of extreme weather events, research on the interactions between dust aerosols and the climate system, as well as their impacts on human health, has gradually become a hot topic. Studies have revealed the critical role of direct radiative feedback from East Asian dust in exacerbating dust-related air pollution in northern China. Other research highlights the combined effects of Arctic Sea ice anomalies, La Niña events, and a warmer northwestern Atlantic in creating loose, dry surface conditions across Mongolia, along with the formation of the strongest Mongolian cyclone in the past decade, which provided favorable dynamical disturbances and transport conditions for dust events. Furthermore, dust events have been shown to significantly increase the mortality risk from respiratory diseases, particularly chronic lower respiratory diseases and chronic obstructive pulmonary disease (COPD). Circulatory disease mortality risks, including ischemic stroke and hypertensive heart disease, have also risen. These findings underscore the importance of further exploring the interactions between dust aerosols and regional climate, as well as their multidimensional impacts on human health.

Summary Dust events, as a global arid meteorological disaster, affect vast regions worldwide. In China, the severe spring dust storm of 2021 caused significant adverse impacts and economic losses across many northern cities. To enhance global awareness of dust events, strengthen international cooperation, and mitigate their impacts, the United Nations (UN) has designated 2025–2034 as the "UN Decade for Combating Sand and Dust Storms". Implementing effective dust control policies, building climate-resilient health systems, and enhancing efforts in risk mitigation, prevention, response, and recovery can significantly reduce health risks. This review aims to summarize recent advances in research on the impacts of dust on climate and human health. It contributes to expanding our understanding of the climatic effects of dust aerosols and provides crucial scientific evidence for addressing climate change and developing strategies to mitigate health risks associated with dust exposure.

Keywords Dust events · Aerosol · Climate system · Radiative forcing · Health risk

✉ Jianping Huang
hjp@lzu.edu.cn

1 College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, People's Republic of China

2 Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, Lanzhou University, Lanzhou 730000, People's Republic of China

3 College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, People's Republic of China

Introduction

Dust events are major meteorological disasters that frequently occur in arid and semi-arid regions, characterized by their sudden onset, short duration, and wide-ranging impacts [1, 2]. Dust aerosols, lifted from loose surface materials by wind action during dust events, can remain airborne for extended periods and travel great distances [3]. Dust aerosols, categorized into natural and anthropogenic types based on their source regions and mobilization mechanisms, are among the most abundant aerosol types in the atmosphere, with an annual emission of approximately 1514–4313 Tg/yr [4–8], they contribute over 50% to the global aerosol mass [9–13]. Dust events have been shown to directly or indirectly impact agricultural production, human health, ecosystems, and weather and climate systems, thereby influencing various aspects of human life [14–21]. Dust aerosols, in addition to absorbing and scattering atmospheric radiation and serving as cloud condensation nuclei, also influence climate change and precipitation patterns [22, 23]. Furthermore, dust events severely disrupt transportation and daily production activities and pose significant threats to public health [24].

Advances in numerical modeling have improved the accuracy of dust emission simulations, deepening our understanding of the climate impacts of dust aerosols [25–28]. Dust aerosols play a vital role in the climate system. As a significant type of aerosol in the atmosphere, they influence the radiative energy balance of the Earth-atmosphere system. Through shortwave and longwave radiative effects, dust particles alter this energy balance, affecting atmospheric thermodynamic processes and exerting a substantial impact on boundary layer height and thermal structure [29–35]. Additionally, dust serves as an important external source of iron to the oceans, influencing marine biogeochemical cycles and thereby regulating the atmospheric carbon cycle [36–38]. Dust aerosols are closely associated with circulation systems and atmospheric pollution processes on both regional and global scales [39–41], directly influencing regional climate change. For instance, the radiative effects of dust can modify energy distribution, influence local temperature, cloud formation, and precipitation patterns, and ultimately affect feedback processes within the climate system [42, 43].

On the other hand, dust aerosols significantly impact atmospheric environmental quality by influencing boundary layer dynamics, which subsequently affects human health [44]. Exposure to dust aerosols is closely linked to acute and chronic health risks. During their transport, dust aerosols adsorb large amounts of heavy metals, pathogenic microorganisms, and pollutant gases, further enhancing their toxicity and exacerbating their health impacts. Dust aerosols pose threats to the human respiratory, cardiovascular, and immune systems [45–49]. The particulate matter (PM) in dust aerosols, particularly PM_{10} and $PM_{2.5}$, can penetrate deep into the respiratory tract and deposit in the lungs, increasing the incidence of acute respiratory infections, chronic obstructive pulmonary disease (COPD), and asthma [50, 51]. During dust events, the mortality risk from cardiovascular diseases, including ischemic stroke and hypertensive heart disease, rises significantly [52]. Additionally, during long-range transport, dust particles are exposed to various aging processes, carrying and absorbing a significant amount of secondary aerosols, microorganisms, and toxic heavy metals [53]. This further increases the health risks associated with dust particle exposure, particularly for vulnerable groups with weaker immune systems, such as children and the elderly [54]. Studies have shown that exposure to dust aerosols poses significant long-term health impacts on vulnerable populations. For instance, prenatal exposure to dust events has been linked to impaired cognitive function in children, posing a substantial threat to the long-term health and development of human society [55].

This study aims to comprehensively explore the impacts of dust aerosols on weather, climate, and human health, enhancing understanding and response strategies for dust events. Although the effects of dust have been widely studied, significant research gaps and challenges remain regarding the bidirectional feedback mechanisms between dust aerosols and the climate system, as well as the associated health risks. Future research should integrate natural and anthropogenic factors more comprehensively and leverage technological innovation and application to mitigate the multifaceted impacts of dust events. Such efforts will provide valuable solutions for addressing climate change and enhancing disaster prevention and control capabilities.

Method

This literature review was conducted to synthesize current evidence on the chemical concentrations of dust and its associated health and climate effects. The representative references are shown in Table 1, including the authors, year, research content, methods, and the respective fields of study. The review involved a search of several electronic databases, including **PubMed, Web of Science, and Google Scholar**, covering publications from 2000 to now. Search terms included key terms such as **dust events, dust aerosols, radiative forcing, weather and climate, health risks**, and related keywords were used.

Characteristics of Dust

Sources and Drivers of Dust

The sources of dust include both natural and anthropogenic dust emissions [56]. As early as the 1990s, research pointed out that classifying dust aerosols entirely as a natural source was inaccurate [57, 58]. Based on the source regions and emission mechanisms of dust, dust aerosols can be categorized into natural dust (ND) and anthropogenic dust (AD) [7, 56]. ND primarily originates from arid and semi-arid regions (such as the Sahara Desert, Arabian Desert, and Gobi Desert) through wind erosion [59, 60]. Human land cover types (e.g., farmland, pastures, cities) are influenced

Table 1 A list of the representative references in this review

Author	Year	Study area	Findings	Methods	Field of Study
Penner et al	1994	Global	Quantifying the uncertainty of anthropogenic aerosols' climate forcing requires reducing simulation errors	Literature review and model analysis	Source
Tegen & Fung	1995	Global	The contribution of anthropogenic land surface changes to dust emissions is significant	Numerical models and remote sensing	Source
Neff et al	2008	The Western United States	The expansion of farmland in the early twentieth century led to a 500% increase in dust load	Geological records and historical data analysis	Source
Chen et al	2013	The Tibetan Plateau	The impact of Taklamakan dust on the radiative forcing of the Tibetan Plateau is significant in summer	WRF-Chem model simulation and observation comparison	Source
Huang et al	2015	Global	Using CALIPSO lidar to detect anthropogenic dust	Satellite observations and algorithm development	Source
Chen et al	2018	Global	The contribution of natural and anthropogenic dust emissions was quantified	Model simulation and data analysis	Source
Huang et al	2008	Asia	Dust aerosols can be transported to an altitude of 8–10 km over the Pacific, affecting regional climate	CALIPSO and ground-based observations	Transport
Yu et al	2015	North Africa	Approximately 132 Tg of dust is transported across the Atlantic to the Amazon rainforest each year, impacting the ecosystem	CALIPSO observations and MERRA-2 reanalysis data	Transport
Liu et al	2015	The Tibetan Plateau	Anthropogenic aerosols from South Asia are transported to the southern slope of the Tibetan Plateau by the southwest monsoon	Aerosol spectral radiative transfer models and non-hydrostatic models	Transport
Guo et al	2017	East Asia	East Asian dust can be transported across the Pacific to the western United States, affecting local air quality	WRF-Chem model combined with CALIPSO observations	Transport
Proestakis et al	2018	South Asia and East Asia	The Taklamakan and Gobi deserts are the main source regions of dust, with dust activity being strongest in spring and summer	CALIOP satellite observations and spatiotemporal analysis	Transport
Sun et al	2020	Asia	There are significant differences in the dust contribution from different dust source regions in Asia to downstream areas	MERRA-2 reanalysis data and quantitative analysis	Transport
Lau et al	2006	The Tibetan Plateau	Dust aerosols affect the early arrival of the Indian monsoon through their heating effect	Comparison of climate models and observations	Feedback
Shi et al	2019	Northwestern India	Dust acts as ice nuclei, promoting deep convective cloud development and intensifying heavy precipitation events	Meteorological observations and aerosol-cloud interaction models	Feedback
Sarangi et al	2020	High-mountain Asia	Dust deposition accelerates snowmelt at high altitudes, driving the snow-albedo effect in the high-mountain Asia	Satellite remote sensing and ground-based observations	Feedback
Kok et al	2023	Global	Dust influences cloud lifespan and precipitation through radiative effects, intensifying climate feedbacks in arid regions	Multi-model ensemble analysis and literature review	Feedback
Griffin	2007	Global	Microorganisms carried by dust can survive for several days and trigger infectious diseases through long-distance transport	Microbiological analysis and atmospheric transport models	Health effects
Kashima et al	2012	Japan	Dust events are significantly associated with a short-term increase in all-cause mortality	Time series analysis and case–control studies	Health effects

Table 1 (continued)

Author	Year	Study area	Findings	Methods	Field of Study
Giannadaki et al	2014	Global	Dust causes approximately 400,000 premature deaths globally each year, with health risks concentrated in arid regions	Global chemical transport models and health risk assessment	Health effects
Zhang et al	2016	Global	A systematic review of the global health impacts of dust, clarifying the association between dust storms and respiratory diseases, as well as cardiovascular diseases	Systematic literature review and meta-analysis	Health effects
Heft-Neal et al	2020	South Africa	Dust storm exposure is significantly associated with infant mortality	Correlation analysis of satellite data and population health data	Health effects
Zhang et al	2023	China	Dust storms are significantly associated with mortality rates from cardiovascular and respiratory diseases	Epidemiological statistics and case-crossover studies	Health effects

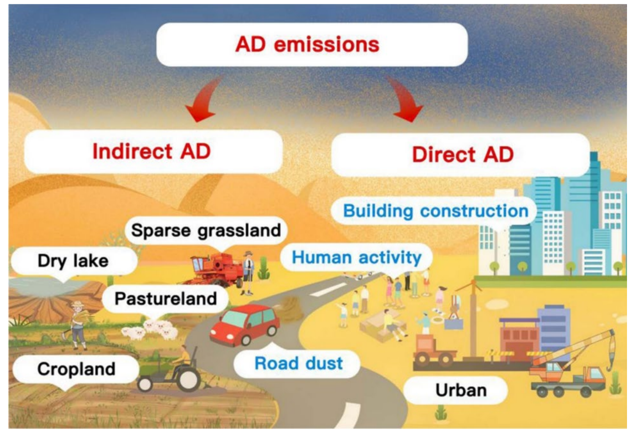

Fig. 1 AD emissions and their sources (from Chen et al. (2023))

by human management practices [61]. AD is indirectly generated by wind erosion of land surfaces disturbed by human activities (human land cover types), typically in semi-arid, semi-humid, and humid regions [56]. AD can be further divided into indirect AD (caused by human activities such as harvesting, farming, grazing, and irrigation practices that lead to desertification or drying up of lakes, making the land more vulnerable to wind erosion) and direct AD (directly emitted dust from human activities like construction, demolition, and vehicle emissions) (shown in Fig. 1) [6, 7, 62]. The Intergovernmental Panel on Climate Change (IPCC) (2017) stated that AD contributes to 30–70% of total dust concentration, which significantly impacts global dust levels. For example, due to agricultural expansion, dust loads in the western United States increased by 500% in the early twentieth century [63]. Studies have shown that the reduction of grasslands exacerbated wind erosion, greatly increasing dust emission fluxes [64]. Chen et al. found that the area of potential AD sources slightly exceeds that of ND sources [56].

Dust emission is a critical step in the dust cycle, influencing the long-range transport and deposition of dust particles, as well as the climate change induced by dust [65, 66]. Researchers continuously strive to improve ND emission schemes under various simplifications and assumptions [4, 25, 67–70]. Overall, ND emission schemes can be categorized into three types: empirical dust emission schemes [58, 71, 72], dust emission schemes with simplified physical processes [73, 74], and dust emission schemes with detailed microphysical processes [68, 75–77]. Furthermore, human activities worldwide also trigger dust emissions [7, 57], which are considered to arise from wind erosion processes that occur when land types are altered or disturbed by human activities [11, 18, 58, 77, 78]. Among these, indirect human dust emissions are driven by wind erosion caused by human-induced changes in land surface types, and their emission mechanism is similar to natural dust emissions [79]. On the other hand, direct human dust emissions result directly from human activities and are highly dependent on the intensity of these activities, which can be modeled using the STIRPAT model [56, 80]. Previous dust emission simulations have often relied on static land cover data, ignoring the dynamic changes in surface bare soil, which can lead to significant uncertainties in simulated dust flux, particularly for human-induced dust emission simulations [81, 82].

Dust storm events are primarily driven by surface and meteorological factors. Shao et al. suggested that global dust concentrations are on a decreasing trend [83], but future climate change and human activities, which alter the surface environment, may exacerbate desertification and expand dust sources, potentially increasing the frequency and intensity of dust events [84]. In the context of global warming, the process of land desertification has influenced dust emissions[85, 86]. Different land surface cover types affect the dust emission process through their impact on wind erosion [87–90]. For instance, the spatial differences in natural factors, such as regional topography, surface sediment composition, soil moisture, and vegetation cover, lead to significant differences in the spatial distribution of dust activities in western Inner Mongolia [91]. In recent years, large-scale vegetation restoration projects in northern China have significantly reduced dust storm occurrences in the region [90]. The increase in surface vegetation cover has been the main reason for the significant reduction in dust activity in the Gobi Desert in recent years [92]. In southern Mongolia and along the China-Mongolia border, reduced vegetation cover and the intense development of Mongolian cyclones are considered the main causes of the severe dust storm events in northern China in March 2021 [93, 94]. Meteorological factors, as the main influences on the occurrence and development of dust storms, reflect the impact of large-scale pressure systems, wind fields, and climate change on dust activities [95–97]. For example, observations based on multiple data sources show that changes in air temperature, precipitation, and soil moisture benefit vegetation cover improvement, which in turn reduces the intensity and frequency of East Asian dust activities. The decreasing trend of strong winds associated with cold air mass intrusion from high latitudes plays a key role in the interannual reduction of dust storm frequency [98]. Climate warming, weakened cold air activity, and reduced frequency have led to a decrease in the frequency and intensity of dust storms in the eastern Hexi Corridor, with seasonal variations in atmospheric circulation being an important factor influencing the seasonal variation of dust activities [99]. Guan et al. analyzed the spatiotemporal distribution characteristics and influencing factors of dust storms in northern China from 1960 to 2007 using station data and vegetation index data, identifying maximum wind speed, average wind speed, and annual average precipitation as the three main factors controlling dust storm frequency [100].

Spatial and Temporal Distribution of Dust

Africa is the largest source of dust globally, followed by Asia. Due to the extensive spatial coverage and occurrence of dust events, research in this area has been challenging. However, recent satellite observations have provided an ideal tool for studying the global distribution of dust aerosols [101]. Previous studies have utilized satellite observations of dust-related phenomena and optical properties to reveal many important aspects of the dust cycle [102–105]. For instance, Proestakis et al. used data from the orthogonal polarization cloud aerosol lidar (CALIOP) to capture seasonal dust event frequencies, dust optical depth (DOD), and particle depolarization ratio (PDR), revealing dust emissions from the deserts of South Asia and East Asia and their potential transmission changes [106]. Kim et al. described the seasonal and vertical distribution of Asian and North Pacific dust aerosols using DOD data from multiple satellites and ground measurements [107]. Song et al. analyzed dust records from CALIOP and the Moderate Resolution Imaging Spectroradiometer (MODIS), observing a decreasing trend in dust emissions from the Gobi Desert (related to increased vegetation cover) and the Northwest Pacific Ocean (NPO) [104]. However, to fully understand dust transmission, researchers need to use satellite-observed DOD to obtain more accurate measurements of dust mass loadings [108], allowing for better estimation of the actual quantity of dust in the atmosphere [109] and its deposition into the oceans [110]. This advancement will improve the predictive capability of regional and global simulation models [111].

Transport of Dust

Studies have identified three major long-distance dust transport belts globally: the transatlantic transport of African dust [108, 112], the transcontinental transport of North African dust across the Arabian Peninsula and the Middle East into Asia [113, 114], and the trans-Pacific transport of Asian dust [115, 116]. Early studies have shown that the dust flux from North Africa is 240 ± 80 Tg/yr, and it is transported across the Atlantic Ocean over long distances, reaching the United States, the Caribbean, and South America under favorable meteorological conditions [108, 117, 118]. Yu et al., using CALIOP observations and MERRA-2 reanalysis data, found that approximately 182 Tg of dust leaves the North African coast each year, with 132 Tg reaching the central Atlantic and 43 Tg being transported to the Amazon rainforest [119]. Observational studies have shown that African dust aerosols are transported northeastward across the Eurasian continent, where they are usually combined with East Asian dust aerosols, affecting the atmospheric environment of East Asia [114, 120]. Since the launch of CALIPSO, the satellite's global observations of cloud and aerosol vertical profiles have further enhanced our understanding of long-distance dust transport [121]. Huang et al. used CALIPSO, ground-based micro-pulse lidar (MPL), and standard ground observations to study the long-range transport and vertical distribution of Asian dust aerosols in the free troposphere during the Pacific Dust Experiment (PACDEX), revealing that dust aerosols from the Taklamakan and Gobi deserts were transported at altitudes of 8–10 km over the Pacific (Fig. 2) [122]. Additionally, dust from South Asia can be uplifted and transported to the Tibetan Plateau, contributing to accelerated glacier retreat [123, 124].

Proestakis et al., revealed the seasonal transport pathways of dust aerosols from the deserts of South Asia and East Asia, with the Taklamakan and Gobi deserts being the primary source regions. Dust activity is strongest during the spring and summer months [106]. Kim et al., analyzed the seasonal variation and vertical distribution of dust in Asia and the North Pacific using multi-source satellite and ground-based observations of dust optical depth, uncovering the vertical gradient during trans-Pacific dust transport [107]. Dust emissions from East Asia can sweep across much of northern and eastern China, South Korea, and Japan, before being deposited into the Pacific Ocean [101, 112, 122, 125–127], and can even be transported to the western United States [128–130].

Model simulations and reanalysis datasets have been widely used to describe the dust cycle. Chen et al. utilized the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) to study the contributions of the Taklamakan and Gobi deserts to East Asian dust loads. Their study found that the Taklamakan Desert has the highest dust emission capacity, approximately 70.54 Tg/yr in spring, but its contribution to East Asian dust loads is smaller than that of the Gobi Desert [66]. This finding is consistent with the results of Sun et al., based on the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) [131]. Numerical models are ideal tools for studying the transport mechanisms of dust and have become essential for understanding the transport processes.

However, relying solely on model simulations introduces significant uncertainty in the results. Therefore, observational dust transport data are needed to reveal the characteristics of Asian dust's trans-Pacific transport and to constrain the model simulations [18, 132]. Guo et al., used CALIPSO, AERONET, backward trajectory models, and the WRF-Chem model to investigate the transport process of East Asian dust. Their study found that East Asian dust can be transported across the Pacific and even reach the western United States [128]. Liu et al., used the Aerosol Species Radiation Transport Model (SPRINTARS) and the Nonhydrostatic Model (NHM) to analyze the transport characteristics and mechanisms of anthropogenic aerosols from South Asia transported to the southern slopes of the Tibetan Plateau via southwest winds [133]. Sun et al., used multi-year MERRA-2 reanalysis data to study the contributions of different Asian source regions to the total dust column and their contributions to downstream dust levels [131]. Based on CALIPSO lidar data, their research quantified the Asian dust cycle and clarified the dominant role of East Asian deserts in contributing to dust in mainland China and adjacent seas [115].

Recent studies show that the record-breaking African dust event of 2020 modulated large-scale circulation through radiative heating, triggering Rossby wave trains, weakening

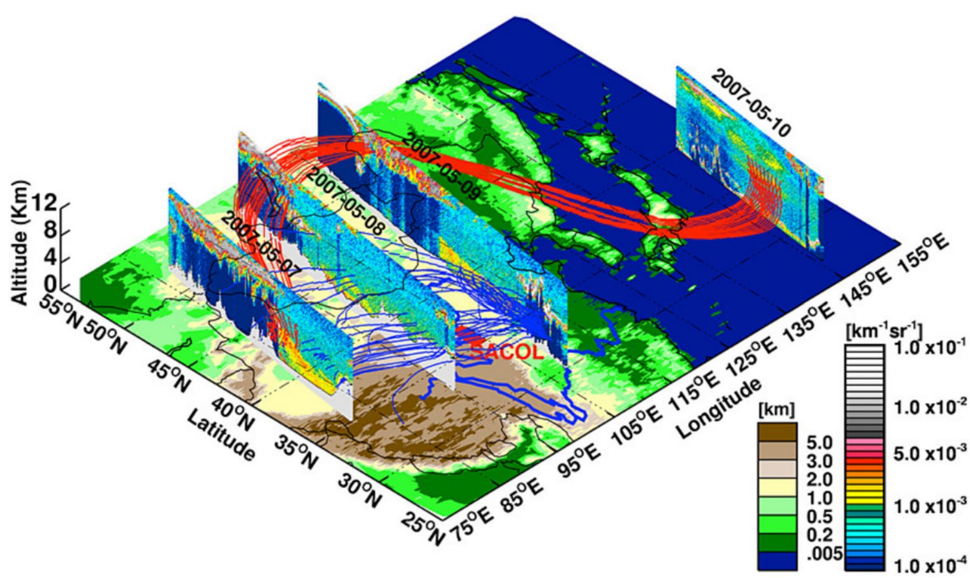

Fig. 2 Dust event originating from the Taklamakan Desert on May 7, 2007, transporting dust to the Pacific (from Huang et al. (2008))

the Indian summer monsoon and North American moist convection, and significantly reducing regional precipitation. This revealed the global transport mechanism of African dust and its widespread role in global climate change (Fig. 3) [134].

Feedback Mechanisms Between Dust and Weather/Climate

Dust aerosols, as a significant absorptive aerosol in the atmosphere, play a pivotal role in regulating the Earth's climate system, particularly its energy balance and dynamic processes. Since the 1990s, the rapid development of dust numerical models has greatly enhanced our understanding of the occurrence, development, transport, and dissipation of dust. Especially after the year 2000, as the volume of research increased, there has been remarkable progress in the quantitative assessment of dust's radiative effects and climate feedback mechanisms [25, 135–137]. These studies have not only deepened our understanding of the impact of dust on the climate system but also provided strong support for predicting the spatiotemporal distribution of dust events and their potential effects on climate change.

The Impact of Dust on Radiation Budget

Dust aerosols significantly impact the atmospheric radiation balance, boundary layer structure, and regional climate patterns through direct, indirect, and semi-direct radiative effects (Fig. 4) [22, 138, 139], with notable consequences for global weather and climate change [2, 140–142]. The direct radiative effect of dust aerosols is primarily through scattering and absorption of shortwave radiation, which reduces surface energy input, while absorption of longwave radiation heats the atmosphere, significantly altering energy transfer between the atmosphere and the surface [122, 143–145]. The particle size and abundance of dust aerosols influence the direct radiative effect. Kok et al. found that the global dust direct radiative effect is constrained between -0.48 and $+0.20$ $W \cdot m^{-2}$, suggesting that dust may lead to net heating of the planet [146]. During the day, dust particles mainly adjust shortwave radiation, whereas at night, they exhibit longwave radiation effects [147, 148]. Specifically, during the day, dust particles lower the surface heat flux through shortwave radiation, suppressing boundary layer development, weakening turbulent mixing, and hindering the downward transport of upper-layer momentum, leading to reduced near-surface wind speeds and decreased dust resuspension and emission [29, 149]. At night, the dust layer creates a longwave radiation surplus at the surface, enhancing the warming effect, which weakens boundary layer stability and promotes the nighttime diffusion of dust aerosols [150–152]. The net shortwave radiative forcing of dust aerosols at the surface may exceed -70 $W \cdot m^{-2}$ in areas with high dust concentrations (Aerosol Optical Depth greater than 0.7) [153]. Since dust scatters and absorbs longwave radiation, which weakens longwave radiation transmission in the atmosphere, the scattering and absorption of longwave radiation at the top of the atmosphere determines the direct radiative effect of dust [154].

The indirect radiative forcing of dust aerosols occurs by altering the macro- and micro-physical properties of clouds, which in turn changes the radiative characteristics of the clouds [155–158], affecting the energy fluxes in the Earth-atmosphere system [159, 160]. For example, dust

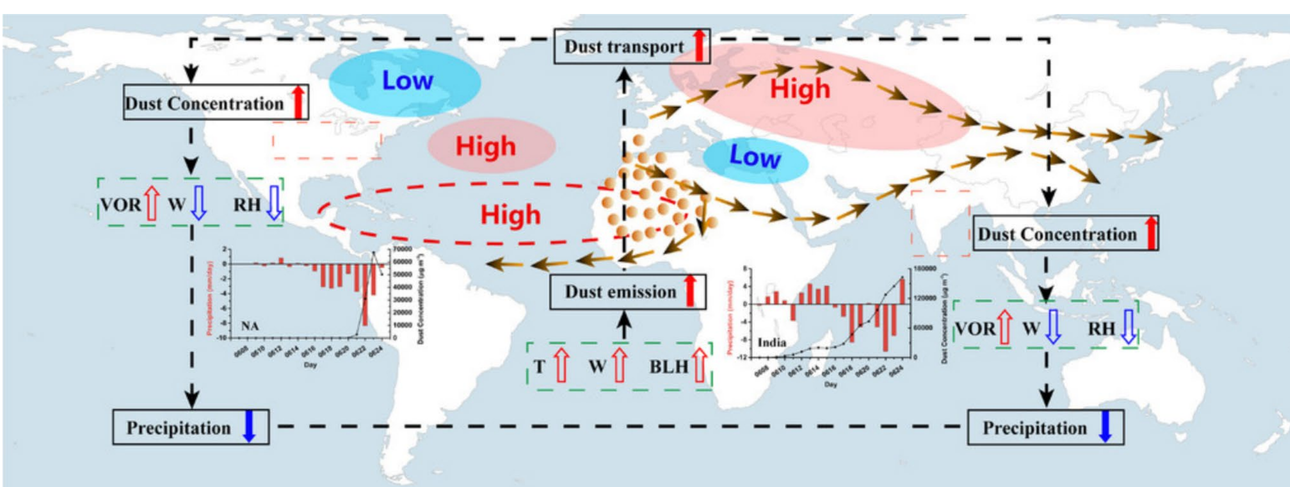

Fig. 3 Schematic of the Godzilla African dust transport and its relationship with precipitation in North America and India. The embedded graph shows dust concentration (from the SEN1_AFD_Only experiment) and daily precipitation changes (CTRL minus SEN2_AFD_OFF experiment) based on simulation results from the WRF-Chem model (from Bi et al. (2024))

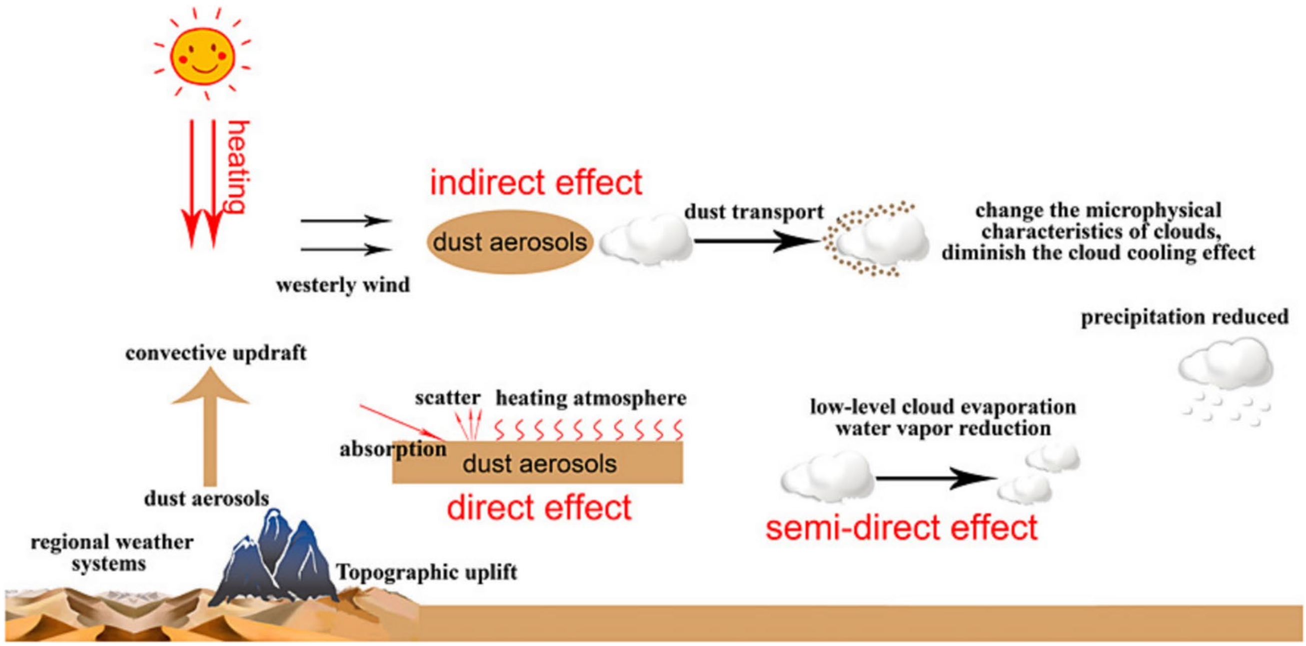

Fig. 4 The schematic diagram of dust-cloud-precipitation interaction in arid/semi-arid regions (from Huang et al. (2014))

significantly influences ice particle growth, precipitation rates, and the lifetime of high clouds through interactions under specific meteorological conditions, playing an important regulatory role in global warming and climate change [161]. Huang et al. compared cloud characteristics under dusty and dust-free conditions in the same meteorological environment in Northwest China, finding that the injection of dust aerosols into clouds reduced the effective particle size of ice clouds and the optical depth of cirrus clouds by 11% and 32.8%, respectively [162, 163].

The semi-direct effect of dust aerosols results from the absorption of radiation by dust particles within clouds, leading to cloud heating, which causes cloud droplets to evaporate, thus reducing cloud cover and altering the thermodynamic processes in the atmosphere [164]. The dust aerosol layer can either stabilize or disrupt the boundary layer, depending on its location [165–167]. When dust is located beneath the cloud layer, it can enhance deep convection and cloud cover through increased water vapor convergence. However, when dust is positioned above the cloud layer, it weakens convective clouds [157]. In arid and semi-arid regions, when aerosols are present within or above the cloud layer, dust aerosols can lead to cloud evaporation [163, 168]. The semi-direct effect has been simulated using General Circulation Models (GCM) and high-resolution cloud-resolving models, as the inclusion of absorbing aerosols in radiative schemes inherently accounts for this effect [165, 169].

Impact of Dust on Regional Climate

Dust aerosol-cloud interactions play a significant role in regional climate, particularly in arid and semi-arid regions, where these interactions may exacerbate drought conditions (Fig. 4) [157]. Research indicates that dust particles, by promoting ice cloud formation and enhancing convective processes, can also increase the occurrence of extreme precipitation events, such as urban extreme rainfall events [170]. One study, analyzing the 2018 dust storm-rain event in northwest India, found that dust aerosols, acting as effective ice nuclei, facilitated the development of deep convective clouds. This, in turn, enhanced the ice-water path and latent heat release, leading to intensified rainfall, providing observational evidence for aerosol-cloud-precipitation interactions [171]. Dust aerosols in northern India have also been found to contribute to the early onset of the Indian monsoon [123]. For example, the Tibetan Plateau serves as a transportation hub for dust aerosols, and their interaction with the plateau's heat pump effect plays a crucial regulatory role, influencing local and downstream weather and climate [172].

In addition, when dust aerosols are deposited on snow surfaces, they alter the snow's albedo, which accelerates snowmelt [173, 174]. For example, the snow darkening effect of dust and the direct radiative forcing both significantly impact the onset of the Indian monsoon, but their effects are opposite. The snowmelt effect of dust significantly weakens the Indian summer monsoon circulation and precipitation during the explosive phase [175]. Moreover, some studies have observed that dust aerosols, by lowering sea surface temperatures and lower-level humidity, increasing middle-level moisture, and inducing positive relative vorticity and wind shear, play an important role in inhibiting the formation of tropical cyclones in the North Atlantic basin [176].

The Climate Feedback of Dust

The intensity and frequency of dust activity in East Asia are also believed to be linked to changes in large-scale atmospheric circulation, such as cyclone frequency, East Asian monsoon strength, and the North–South Hemispheric Oscillation patterns [86, 98, 177]. These large-scale circulation patterns not only influence the formation of dust weather systems but also significantly regulate dust transport paths and intensity. For example, the number of dust storm days in North China is positively correlated with the strength of the East Asian winter monsoon [178]; the negative phase of the Arctic Oscillation (AO) enhances atmospheric instability, making weather disturbances more likely to move latitudinally, thereby increasing the frequency of spring dust storms [179]. Large-scale circulation factors not only provide a favorable background for the formation of weather systems that directly influence dust activity but also regulate the magnitude and direction of dust transport in the troposphere [180–182]. The Arctic Oscillation (AO) is the dominant pattern of large-scale circulation in the high-latitude regions of the Northern Hemisphere during the winter months and has a significant impact on dust activity in East Asia [65, 179, 183–185]. In addition to AO, changes in other planetary-scale climate indices such as the North Atlantic Oscillation (NAO), Antarctic Oscillation (AAO), and El Niño-Southern Oscillation (ENSO) have also been shown to directly or indirectly influence dust activity in East Asia [186–192]. For example, the Antarctic Oscillation, one of the major modes of Southern Hemisphere tropospheric circulation, plays an important role in influencing the frequency of dust storms in North China through a meridional teleconnection pattern from the Antarctic to the Arctic [187].

In the context of climate change, the abnormal sea ice conditions in the Barents Sea and Kara Sea during the winter of 2020/21, which shifted from negative to positive, led to dramatic changes in polar cold air masses. This, in turn, triggered a strong dust storm event in March 2021, following an increase in soil and near-surface air temperatures [97]. Furthermore, the warmest Northwest Atlantic and the coldest East Pacific (La Niña) between 2011/12 and 2020/21 contributed to reduced precipitation in Mongolia, leading to drought and dry soil conditions. Under the influence of a super-strong Mongolian cyclone, these conditions indirectly contributed to the occurrence of the intense dust storm event [193, 194].

Under the influence of global warming, the frequency, intensity, duration, and extent of drought events in arid regions have generally increased [195, 196], and droughts lead to more dust emissions [197], triggering intense drought-dust storm compound events [198]. Since the 1990s, dust storms have significantly increased under drought conditions [199]. The dynamic mechanisms of dust aerosol interactions with the climate system are not yet fully understood. Therefore, gaining a deeper understanding of the radiative effects of dust aerosols and their feedback mechanisms is crucial for predicting and addressing climate change.

The Impact of Dust Storms on Health

During dust storm events, the concentration of particles in the atmosphere, especially inhalable particles (PM_{10} and $PM_{2.5}$), significantly increases, causing substantial negative impacts on human health [200, 201]. Larger dust particles typically settle in the upper respiratory tract (nasopharyngeal and tracheobronchial regions), while smaller particles can penetrate into the deep lung tissue[202, 203]. Goudie summarized that exposure to dust particles is closely linked to respiratory diseases, cardiovascular diseases, valley fever, meningitis, conjunctivitis, and skin diseases [204]. In recent years, climate change has exacerbated the frequency of global dust storms, and the associated health issues have become increasingly prominent [205–207]. A search of the keywords "dust events + human health" in the Web of Science shows a growing trend in related publications from 2000 to 2021, with a peak in 2021, followed by a slight fluctuation and decline (Fig. 5).

Toxic Mechanism

Dust particles not only carry inherent toxicity but also serve as carriers of pathogens and heavy metals, posing health risks to populations during long-distance transport [208–210]. Toxicological studies indicate that dust particles, after long-distance transport from source regions, can carry higher loads of toxic substances, making them potentially more toxic than anthropogenic particles [211]. Dust particles can adsorb more heavy metals (such as Cr, As, Ni, Co, Mn, Zn), microorganisms, and atmospheric pollutants (SO_2, NO_2, O_3), further increasing health risks. Research shows that the concentration of metals in the atmosphere during dust storms is significantly higher than during non-dusty weather, and these heavy metals may enter the human body via the respiratory tract or skin, triggering respiratory, cardiovascular, neurological, and reproductive system diseases [212, 213]. For example,

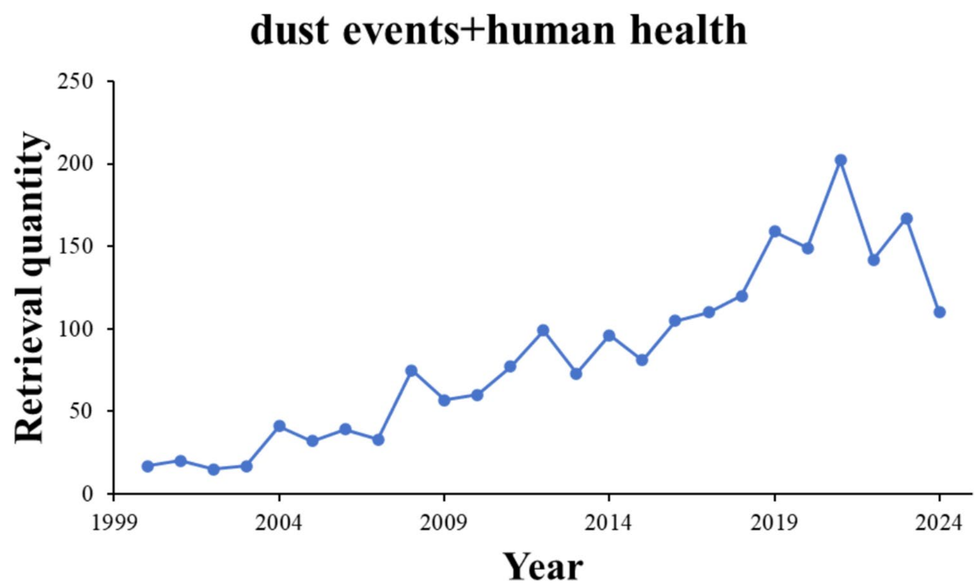

Fig. 5 The annual number of publications retrieved from the Web of Science database using the keywords "dust events + human health" from 2000 to 2024

Cr^{6+}, As, and Ni have been found to pose high carcinogenic risks [214]. Dust particles from soils and deserts contain a large number of disease-causing microorganisms [215–217]. These microorganisms can survive in the air for hours to days after being suspended by wind erosion, and resist adverse conditions during transport, allowing them to travel long distances and enter the human body, accelerating respiratory infections, pneumonia, and the spread of other infectious diseases [218–221]. Moreover, the abundance and diversity of bacteria in the air in arid regions is significantly higher than in semi-arid areas [221]. Pollutants in the atmosphere attach to dust particles during dust storm events and enter the human body, exacerbating respiratory and cardiovascular diseases [222]. For instance, Raaschou-Nielsen et al. found that the increase in SO_4^{2-} and other secondary pollutant particle concentrations was significantly associated with an increase in natural mortality rates [223].

After long-distance transport, dust particles evolve into dust storms or dust clouds with particles smaller than 10 microns, which can carry heavy metals, sulfates, organic compounds, and viruses into the respiratory tract and lungs. PM_{10} particles deposit in the trachea and bronchi, while $PM_{2.5}$ can reach the alveoli, causing more severe harm. Studies by Huang et al., found that within a range without obvious cytotoxicity, dust $PM_{2.5}$ and PM_{10} can damage the phagocytic function of alveolar macrophages, with a dose-dependent effect [224]. Moreover, dust environments can disrupt the normal microbial ecological balance in the human body, increase susceptibility to pathogens, interfere with intracellular signaling pathways, and harm health [225, 226].

Acute Health Effects

The health impacts of dust aerosols can be categorized into acute and chronic exposure based on the exposure duration [227–229]. Short-term exposure to dust particles can lead to acute health risks, primarily associated with upper and lower respiratory tract diseases, including fever, cough, and other respiratory symptoms. During dust events, the intensification of air pollution significantly increases mortality rates [230–233]. Studies show that during dust storms, mortality and hospitalization rates related to respiratory and cardiovascular diseases, as well as overall mortality rates, significantly increase [232, 234–236], while the risk of pulmonary embolism also rises [50].

Zhang et al. found that the excess mortality risk associated with dust storms in China for ischemic stroke, intracerebral hemorrhage, hypertensive heart disease, myocardial infarction, acute myocardial infarction, acute ischemic heart disease, respiratory diseases, chronic lower respiratory diseases, and chronic obstructive pulmonary disease (COPD) ranges from 3.33% to 12.51% [234]. A meta-analysis indicated that, within 3 days after dust events, mortality from circulatory diseases increased by 2.23%, and from respiratory diseases by 3.99% [237]. Research also shows that increased exposure to Asian dust storms is associated with a rise in overall mortality and cerebrovascular diseases among individuals aged 65 and above [235]. During dust storm migrations, the proportion of patients seeking treatment for cardiovascular diseases, ischemic heart disease, and cerebrovascular accidents increased by 26%, 35%, and 20%, respectively, compared to pre-dust storm levels [238]. Additionally, a systematic review showed that, compared to non-dust weather, the overall mortality rate on dust storm days increased by 0.27% [202]. Short-term exposure to dust storms is associated with an increase in inflammatory and coagulation biomarkers such as MDA, vWF, fibrinogen, and WBC count in young people [239, 240], and has a negative impact on lung function in adolescents, with a stronger correlation in asthmatic patients [241]. Dust storms also significantly increase the number of respiratory disease patients [242, 243]. A study in Africa showed that dust damages the pharyngeal mucosa, promoting bacterial invasion, and is significantly related to seasonal meningitis incidence, suggesting the inclusion of dust data in epidemiological and forecasting models to improve public health response capacity [244]. Research in the U.S. reported cases of pneumonia occurring several days after exposure to dust storms, even leading to death [245]. Additionally, dust storms in the U.S. led to a 7.4% and 6.7% increase in non-accidental mortality 2 and 3 days later, respectively [48]. Exposure to Asian dust storms was significantly associated with increased total mortality and cardiovascular disease mortality in Taiwan, China [246]. Furthermore, studies have found that dust storms are linked to the occurrence of eye watering [247]. A study in Japan indicated that short-term exposure to dust storms is associated with increased risks of cardiovascular (3-day lag), cerebrovascular (same day), and respiratory (3-day lag) diseases in elderly populations, with individuals with pre-existing respiratory conditions or diabetes having a higher risk [248].

Chronic Health Effects

Long-term exposure to dust particles can lead to chronic diseases. Both natural and anthropogenic dust contribute to an increase in environmental $PM_{2.5}$ concentrations. Long-term exposure to $PM_{2.5}$ has been significantly correlated with an increase in the incidence of diabetes [249], particularly among middle-aged and older adults, where it is associated with a higher risk of diabetes and elevated blood glucose levels[250]. Additionally, long-term exposure to dust particles is strongly associated with elevated blood pressure and increased hypertension prevalence in children and adolescents [251]. During Asian dust events, there is a marked increase in the number of patients experiencing itchy eyes, and adult chronic cough patients often experience worsening symptoms and increased allergic reactions [252]. Panel studies have shown that adults with asthma, cough-variant asthma, or atopic cough exposed to Asian dust experience a dose-dependent exacerbation of coughing [253]. Research by Hasunuma et al., also demonstrated a significant relationship between dust exposure and the exacerbation of asthma symptoms in children, suggesting that long-term use of preventive medication may help alleviate respiratory symptoms triggered by Asian dust, providing an effective preventive strategy [254].

Dust storms also influence the frequency and severity of allergic rhinitis [255]. A study in the United States showed that the frequency of dust storms correlates with the incidence of valley fever, a fungal infection caused by soil-based fungi [256]. Long-term health impacts associated with dust storms include low birth weight, with infants weighing less than 2.5 kg, gestational age over 37 weeks, and preterm births [257]. In West Africa, exposure to dust storms is associated with increased infant mortality [258]. Exposure to dust storms during the critical period of fetal brain development, particularly during the sixth and seventh months of pregnancy, has adverse effects on the cognitive function of the next generation [259]. During dust events, the significant rise in PM_{10} concentrations is closely linked to poor pregnancy outcomes [260]. Dust storms are also correlated with an increase in the incidence of measles during the spring [261]. Furthermore, several studies have reported a significant association between Sahara dust exposure and the exacerbation of asthma, chronic obstructive pulmonary disease (COPD), and hospitalization for cardiovascular and cerebrovascular diseases [45, 262, 263]. Sahara dust storms are also linked to respiratory diseases and increased mortality from severe cardiovascular and ischemic events, particularly among vulnerable populations [202].

The intensification of global droughts and the increased frequency of extreme weather events due to climate change pose significant threats to human life and health worldwide. Therefore, it is crucial to further investigate the health impact mechanisms of dust storms. This will help better understand the potential health risks posed by dust storms and provide scientific evidence for formulating more effective strategies to mitigate and prevent their adverse health effects.

Future Research Directions

In the context of climate change, the frequency, intensity, and extremity of dust events are expected to increase, posing significant challenges for future disaster prevention and mitigation efforts. To address these complexities, future research should focus on the following directions:

1. Quantifying the Climatic Effects of Dust

Utilize high-resolution climate models and satellite remote sensing to quantify the shortwave and longwave radiative effects of dust and their impacts on regional and global climate systems. Further explore the nonlinear interactions between dust events and regional climate systems under climate change. Evaluate the coupling effects of dust with atmospheric circulation patterns (e.g., ENSO, NAO) and their long-term regulatory impacts on the global climate system.

2. Understanding Dust-Climate Interaction Mechanisms

Investigate the mechanisms underlying the interactions between climatic conditions, desertification, and dust events. Analyze the relationships between historical climate changes, desertification, and dust storm events. Assess the combined effects of future climate changes and human activities on desertification and dust events, providing scientific guidance for global ecological governance.

3. Building Dust Monitoring and Forecasting Systems

Integrate diverse datasets to establish a comprehensive, high-resolution dust monitoring network capable of real-time tracking of dust storm formation, evolution, and dispersion. Combine numerical modeling with artificial intelligence to develop precise forecasting systems that capture the spatiotemporal evolution of dust events. Use satellite remote sensing, radar, and atmospheric sounding technologies to create real-time monitoring and early warning systems, ensuring timely dissemination of dust storm information to reduce impacts on production, transportation, and public life.

4. Refined Identification and Decision Support

Conduct research on precise identification and forecasting of dust storm disasters to enhance prevention measures. Develop accurate identification algorithms and regional risk management systems to assist governments in formulating evidence-based strategies, thereby reducing the social and economic losses caused by dust events.

5. Health Risk Assessment Framework and Indicators

Quantify the extent and scope of health risks associated with dust events based on their frequency and intensity, and utilize GIS technology for spatial visualization to support disaster prevention and management. Construct comprehensive assessment frameworks that consider the vulnerability of affected populations (e.g., age structure) and the resilience of social, economic, and ecological systems, providing a holistic reflection of the hazards and health risks posed by dust events.

Conclusion

The occurrence of dust events results from the complex interactions within the Earth-atmosphere system. Dust aerosols significantly impact regional and global climate systems through direct, indirect, and semi-direct radiative effects. Meanwhile, climate change further influences the intensity and frequency of dust events by exacerbating land desertification and altering wind field conditions, while atmospheric circulation systems extend their transport range and impact. The bidirectional feedback mechanisms between dust and the climate system play a critical role in regulating climate change, but their dynamic processes require further investigation.

During dust events, atmospheric particulate matter (such as PM_{10} and $PM_{2.5}$) concentrations rise, causing acute and long-term health effects. Short-term exposure increases the incidence and mortality rates of respiratory and cardiovascular diseases, exacerbating conditions such as asthma and allergic rhinitis. Long-term exposure is closely linked to risks of pulmonary fibrosis, pneumoconiosis, and chronic diseases, while also facilitating the spread of certain infectious diseases. The heavy metals and pathogens adsorbed by dust particles further amplify health risks.

This review systematically summarizes the impacts of dust events on the climate system and human health, while highlighting promising future research directions. Investigating the underlying mechanisms, formulating scientific response strategies, and developing adaptive policies to effectively mitigate the destructive impacts of dust events on public health and well-being remain vital areas of study.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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