Mapping the Global Dust Storm Records: Review of Dust Data Sources in Supporting Modeling/Climate Study

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Abstract Dust storms, as extreme environmental events, are one of the Earth's major natural hazards. Their impact on socio-economics can range from local urban to (trans-) continental and from minutes to decades, such as the dust bowl of the 1930s in the United States. Research on dust storms can be traced back for several decades as a meteorological extension. Latest technology developments have enabled comprehensive studies on dust storms, including sampling improvement, analytic studies, and numerical modeling. However, inhomogeneity of the data has hampered and sometimes even misguided research on comprehensive understanding of dust storms and exploring their feedbacks with climate. This review will focus on currently available observations of dust activities, which include routine meteorological records, in situ air chemistry observations, and satellite remote sensing. The aim is to show data sources and the status of their usage in a common framework for global dust regions. Emphasis is placed on data continuity and the spatial and temporal coverage of dust storms, since it is anticipated that this brief summary of dust data will benefit modeling and climate studies. Therefore, it must be noted that field campaign data are outside of the scope of the current review, although they play an important role in research and understanding.

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Introduction

A dust storm or sand storm is a meteorological phenomenon common in arid and semi-arid regions. The term sand storm is used mostly in the context of desert sandstorms, especially in the Sahara Desert, or places where sand is a more prevalent soil type. The term dust storm is more likely to be used when finer particles are blown long distances, especially when it affects urban areas. In context of this review, both terms are referred as dust storm [1].

Dust storms are a major natural hazard in many parts of the world. As a major source of particulate matter, they bring dust particles into the air, which can reduce visibility, affect the breathing of human and animals, cause the reduction of agriculture produce, and further affect socioeconomic orders. For instance, serious dust storm hazards during the 1930s created one of the most severe environmental catastrophes in US history and led to the popular characterization of much of the southern Great Plains as the "Dust Bowl" [2]. Recent seasonal dust storms in China have seriously affected the capital city Beijing [3], resulting in bad air quality, increased traffic accidents, and more respiratory diseases [4••]. Therefore, studies on dust storm activities will greatly benefit human society. Unfortunately, systematic studies on the characteristics and mechanisms of dust storms have yet to be performed in many parts of the world [5]. The main obstacle that hampers understanding the dust climatology and developing numerical prediction techniques [6••] is the lack of consistent dust storm records.

Since there is no specifically designed observing network for dust storms, recent research and developmental efforts have focused on construction of systematic records for historical dust storms based on available observations of multiple networks [5, 7, 8]. These observations include regular meteorological observations, air quality observations, stationary optical observations, and satellite dataset [9••]. The approaches in

reconstruction of dust storm records are usually based on certain physical connections between dust and the observed physical factors [10••], such as wind speed and direction. The reconstructed dust storm records would contain specific limitations [10••] for each observation method. The availability and quality of these datasets vary among different regions, which results in not all types of dust records available and useful in a region. Although reconstructed dust storm records could reveal certain characteristics of dust activities and might benefit applications such as agriculture, caution must be taken while analyzing and comparing these records. In research, there is a huge need to compare these reconstruction methods and check the availability and quality of reconstructed records.

The purpose of this work is to review the principal types of dust storm records and available data sources over the major dust storm-affected regions including Sahara desert, Gobi desert, Arabian Desert, Australia deserts, North American desert, and South American deserts. The major issues affecting potential applications of the observational records are also discussed. In addition, the characteristics of dust storms over each desert region are also composed and analyzed. It is anticipated that this review could serve as a reference for the use of dust storm datasets and provide a summary of the characteristics of dust storms over major desert regions.

Major Data Sources Used as Dust Records

Meteorological Records for Dust Weather Conditions

Regular meteorological records include information that can be used to characterize dust storm activities. These include the descriptions for weather conditions, wind speed, visibility, and air pressure. Among the observed physical variables in a standard meteorological record as described by the World Meteorological Organization (WMO), two types of observations, dust weather codes and visibility, are used as direct dust weather indicators [11]. In this section, we mainly focus on methods that can directly result in datasets for dust storm activities. The dust weather codes included in the regular meteorology record show directly the strength of dust storm conditions. Table 1 shows all the codes and their corresponding descriptions of dust weather conditions.

We noticed that these codes could describe dust weather from weak to strong in a continuous sequence. Therefore, they can provide a wide variety of information on historical dust storms. Recent studies use this information to reconstruct dust storm climatology over different regions of the world. By determining whether a storm code is recorded on a single day, daily dust storm/dust weather frequencies can be constructed to study dust climatology [10••, 12, 13]. Further analysis of computed dust climatology with other meteorological parameters shows that these meteorological codes can represent dust storm

activities on a climate scale. More comprehensive methods, e.g., calculation of the dust storm index, have been developed for characterizing the dust climatology [8, 14] to better use the information on dust strength defined in the weather codes. The index is based on different weights and contributions from these dust weather codes, as shown in the following equation [8]:

$$\text{DSI} = \sum_{i=1}^{n} \left[(5 \times \text{SDS}) + \text{MDS} + (0.05 \times \text{LDE}) \right]_i$$

The weight is defined according to the strength of dust weather, where DSI=Dust Storm Index at n stations, and i is the ith value of n stations for i from 1 to n. The number of stations (n) is the total number of stations recording a dust event observation in the time period. The time is normally a year but can be a month or any sub-period of a year. SDS denotes severe dust storm days (daily maximum dust codes: 33–35), MDS is moderate dust storm days (daily maximum dust codes: 30–32 and 98), and LDE represents local dust event days (daily maximum dust codes: 07–09).

In using weather codes and their associated methods, the quality of records is an important issue. Since the code is recorded by individual observers, personal judgments and/or mistakes may seriously affect the data quality. Large uncertainties from human subjective judgments, the observational location, and environmental factors (e.g., brightness of sky) affect subsequently the data quality. The advantage of weather code data is their consistence. Although an absence of recording person may result in inconsistent data, the consistence of weather recording on the climate scale is very good compared with other data records.

Visibility can also be used as a dust weather indicator, and so it is recorded in regular weather observations metrically. Over dust storm source regions, the main air contaminant affecting air quality is dust, and so visibility is a good indicator for airborne dust concentrations. Several methods have been developed to identify dust weather based on this approach. A popular one is based on the Air Force Manual (AFMAN) surface weather observations [15], which define levels of dust storm as in Table 2.

Similar to the method of using dust weather codes, the dust storm climatology based on visibility can be reconstructed by determining whether the dust storm or severe dust storm occurred during a day. This method has been used in a series of dust climatology applications [16], but the potential problems in using visibility data may be similar to those in using weather code data. The standard approaches in measuring visibility have been updated several times as prescribed in the WMO's data manual. The early approach heavily depended on the observer's personal judgments, and the current approach is still subject to the observer's individual decisions. In addition, other environmental factors including cloud, precipitation, and downward solar radiation can also affect visibility. The

Table 1 Weather observational codes for dust conditions

Dust weather codes	Description
06	Widespread dust in suspension in the air
07	Dust or sand raised by wind at or near the station at the time of observation
08	Well-developed dust whirls or sand whirls seen or near the station
09	Dust storm or sand storm within sight at the time of observation
30	Slight or moderate dust storm or sand storm has decreased
31	Slight or moderate dust storm or sand storm shows no appreciable change
32	Slight or moderate dust storm or sand storm has begun or increased
33	Severe dust storm or sand storm decreased
34	Severe dust storm or sand storm shows no appreciable change
35	Severe dust storm or sand storm has begun or increased
98	Thunderstorm with dust or sand storm at time of observation

criteria in determining the dust storms may vary with locality, which is not considered in current methods. Therefore, using visibility data in identifying dust storms may contain significant uncertainty.

In Situ Measurements of Air Quality

In situ measurements of air quality are also used in analysis and identification of dust storm processes. Regular air quality observations on sites include two types, the aerosol optical depth (AOD) and concentration measurements and the atmospheric composition measurements. Both types can be used for dust storm studies. Similar to weather stations, air quality observations are limited by location. However, the spatial coverage of air quality networks is not as good and comprehensive as for meteorological observations. Thus, coverage and uniformity, especially over non-urban regions, are mainly problematic for analysis and applications of in situ air quality data. Table 3 summarizes the major stationary air quality observational networks or datasets that can be used for dust storm identification or climatology studies.

The AERONET (AErosol RObotic NETwork) program is a federation of ground-based remote sensing aerosol networks [17]. The EPA AQS (Air Quality System) is the repository of ambient air quality data maintained by US Environmental Protection Agency (EPA). The IMPROVE stands for Interagency Monitoring of Protected Visual Environments, a program resulted from the USA Clean Air Act and aimed to prevent future and remedy existing visibility impairment in the National Parks and wilderness areas. The Clean Air Status and Trends

Table 2 Dust storm definition using visibility observations

Strengths of dust storm weather	Visibility range
Severe	Less than 500 m
Regular	More than 500 m and less than 1 km
Suspension	More than 1 km and less than 5 km

Network (CASTNET) is a national air quality monitoring network designed to provide data to assess trends in air quality, atmospheric deposition, and ecological effects due to changes in air pollutant emissions. The European Environmental Agency (EEA) Airbase is the public air quality database system of the EEA. The GALION is GAW (Global Atmosphere Watch, WMO) Aerosol Lidar Observations Network, and a network of networks, which makes use of existing systems at established stations, of the experienced operators of these systems, and of existing network structures. The major contributors to the GALION are EARLINET (European Aersol Research Lidar Network) in Europe, NDACC (Network for the Detection of Atmospheric Composition Change), ADNET (Asian Dust Network) in Asia, and MPLNET (Micro Pulse Lidar Network).

The implementation of surface AOD is used in desert regions where dust particles are the dominant contributor to atmospheric aerosols. Many regional and global AOD networks are available for dust storm identifications. As one of the most broadly distributed networks, AERONET has been used in dust storm studies over many areas of the world [18–20]. Alam et al. [21] studied the dust storms over the Middle East and their impacts on total aerosols, whereas Prasad and Singh [22] studied the dust storm climatology over northern India by using the AERONET sites over these regions. Since AOD observations can only be made during the day, records of nighttime dust storm processes are unavailable.

Relatively, stationary atmospheric composition measurements are not affected by diurnal cycles. Dust particles are major components of captured atmospheric aerosol samples. In desert regions, the mass ratio of dust particles in total aerosols can be above 35 % in non-dust storm days [23]. However, it must be pointed out when attempting to obtain dust measurements in areas that are in, adjacent, or downwind of cities, there are diurnal cycles of vehicle traffic and transportation which need to be subtracted to get the dust data [24].

Observed total aerosol samples can also provide mass concentrations estimated for dust through composition analyses. Methods using the dust mass concentrations have been

Table 3 Summary of major in situ air quality datasets or networks

Name	Coverage	Data type	Availability	Web address
AERONET	Global	Aerosol optical	2006~Present	aeronet.gsfc.nasa.gov
EPA AQS	USA	Mass composition	1993~Present	www.epa.gov/ttn/airs/airsaqs
IMPROVE	USA	Mass/chemical composition	1988~Present	vista.cira.colostate.edu/improve
CASTNET	USA	Chemical composition	1991~Present	www.epa.gov/castnet
EEA airbase	Europe	Mass composition	1997~Present	acm.eionet.europa.eu/databases/airbase/index.html
GALION	Global	Aerosol optical	~Present	wmo.int/pages/prog/arep/gaw/aerosol.html

developed for dust climatology reconstructions over regions with air quality observations [5, 7]. Several criteria have been suggested for dust storm identification based on dust aerosol mass concentrations. One of the major challenges for this method is that the bases of dust aerosol concentration are non-comparable in different surface environments. For instance, dust aerosol concentration classified as a dust storm over an urban region may be close to the level on a non-dust storm day over a desert region. This may result in the erroneous identification of dust storms by using these criteria [10••]. In addition to the instant concentration information that stationary atmospheric composition measurements can provide, the concentration variation trend can also be used for dust storm identification [10••]. For many locations, dust mass concentration changes during the dust storm process and is significantly above the normal concentration level. An approach based on the trend identification has been developed by Lei et al. [10••] to avoid the defects in using dust concentrations alone. Based on the variation trend, dust storms can also be classified into several types.

Satellite Observations of Dust Records

As a recent developed high technology, satellites have been used in monitoring dust storms, resulting in a significant improvement in their mapping and examination. Specific satellite sensors and equipment have been developed to observe the detailed structure, processing, and impact of dust storm events. These sensors include microwaves, visible channels, and lidar. The observation is also not limited to snapshots for single/individual dust storm events, since the satellites can cover a large area with a consistent temporal frequency. On the global scale, major dust source regions have been identified using satellite data, such as from the Total Ozone Mapping Spectrometer (TOMS; [25, 26]). The passage of dust storms and along their transport pathways over land and ocean have also been tracked using TOMS and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [27]. A few satellites provide higher temporal and spatial resolutions for dust storm diagnostics and identification, and they are listed in Table 4.

Sensor-retrieved parameters (such as MODIS aerosol size parameters; [39–41]) or complex statistical analyses (such as Principal Component Analysis; e.g., [40, 42, 43]) have also been used to differentiate dust and non-dust with some success.

Among various satellites, CALIPSO and MODIS observe the global AOD [44], which is suitable for providing consistent dust data over dust regions. With the Cloud–Aerosol Lidar with Orthogonal Polarization instrument on board, CALIPSO can provide a global profile that complements passive sensors when observing dust aerosols from space.

As introduced above, MODIS satellite data cover a global domain. For the bare ground surface of the Sahara desert, MODIS can provide a series of daily products in investigating the global aerosols including the AOD, deep blue AOD, dust mask, and visible images [45]. Since the dust aerosol dominates the total aerosols over desert regions, these aerosol optical products provide a very good reference to dust concentrations. Ma et al. [46••] compare nearly 6 years of CALIPSO AOD data (June 2006 through 2011) with AOD from MODIS during the same period (Fig. 1). While the spatial distribution and seasonal variability of CALIPSO AOD is generally consistent with that of MODIS, CALIPSO is overall lower than MODIS as the latter has a higher frequency than the former for most bins of AOD. The correlation between MODIS and CALIPSO is better over ocean than over land. The study also found that CALIPSO AOD is significantly lower than MODIS AOD over dust regions during the whole time period, with a maximum difference of 0.3 over the Saharan region and 0.25 over Northwest China. Although this may indicate that the satellite-retrieved algorithm may need further adjustment, the result of AOD can be a good reference to dust storm studies [47].

Beside the products listed above, a few other satellite instruments may also provide aerosol optical information. These platforms include MISR (the Multi-angle Imaging SpectroRadiometer), OMI (Ozone Monitoring Instrument), and VIIRS (Visible Infrared Imaging Radiometer Suite).

Common Data Sources for Major Desert Regions

Sahara Desert

Northern Africa is the most seriously dust storm-affected region of the world, with dust storms in the Sahara Desert

Table 4 List of high resolution satellite data sources

Data sources	References
AVHRR (advanced very high resolution radiometer) polar orbit operational satellite	[28, 29] and etc.
VISSR (visible infrared spin-scan radiometer) geostationary operational environmental satellite	[30] and etc.
MODIS (moderate resolution imaging spectroradiometer) sun-synchronous orbit satellite	[31–35] and etc.
MSG SEVIRI (meteosat second generation-spinning enhanced visible and infrared imager) EUMETSAT	[36, 37] and etc.
SeaWIFS (sea-viewing wide field-of-view sensor) polar orbit environmental satellite	[38] and etc.

mainly caused by the northeasterly trade winds over Nigeria and Guinea [50]. The major source areas include the Bodélé Depression [51, 52], an area comprising southern Mauritania, northern Mali, and central southern Algeria [53]; southern Morocco and western Algeria; the southern fringes of the Mediterranean sea in Libya [54] and Egypt [55]; and northern Sudan [56].

Data quality of meteorological observations is a major issue in many African countries. Studies using weather codes need careful quality control strategies, but there are not many studies on Saharan dust using weather code methods. However, Cowie et al. [57] recently analyzed the detailed dust emission from long-term (1984–2012) surface synoptic observations over the Saharan and Sahel regions. This study set a good reference to future studies on African dust storms using meteorological data and attempts to balance the quality of the dataset with spatial coverage by including imperfect station records and making their limitations clear. Initial criteria were used to eliminate
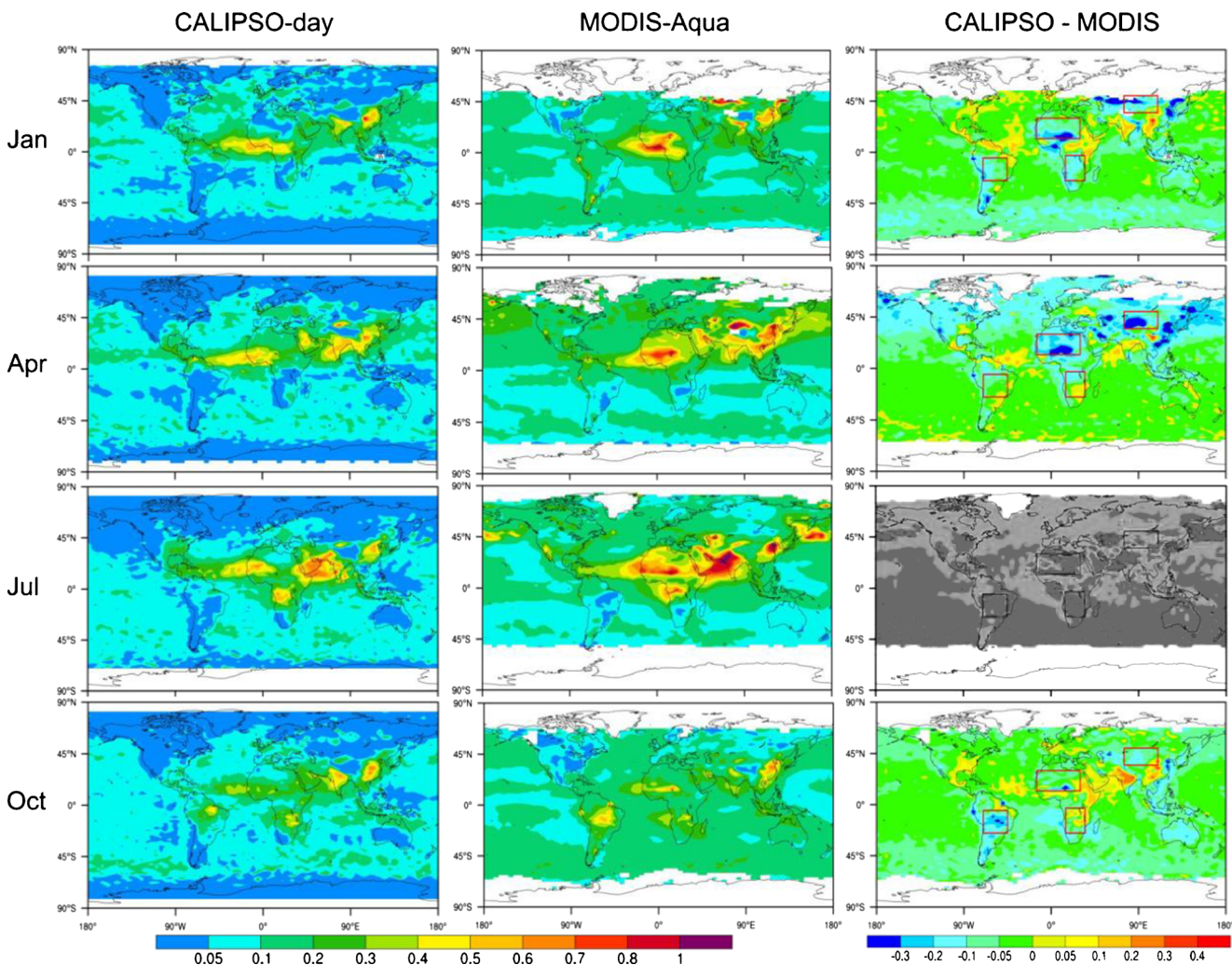

Fig. 1 Multi-year averaged (2006–2011) AOD from CALIPSO daytime, MODIS Aqua, and their differences in January, April, July, and October. The *red rectangles* shown in the *right-column plots* mark the regions of the Sahara, Northwest China, South Africa, and South America (Fig. 6 of [46••])

extremely biased and patchy stations or those that simply did not have enough dust reports to produce meaningful statistics, which left 70 stations to work with. Quality flags assigned to these stations gave indications as to the results that should be approached with caution, such as the diurnal cycle in the Sahel where a daytime bias is present. Frequency of dust emission is compiled from the weather codes of 7–9, 30–35, and 98. These statistics are further split into dust storm frequency (DSF) including only the codes of 9, 30–35, and 98 and blowing dust frequency represented by the codes of 7 and 8. The result shows that spring is the dominant season for Saharan dust storm activities with dust events in cool seasons less frequent but more intense when they occur [57].

Due to the lack of consistent air quality monitoring networks over the African countries, a long-term dust storm climatology study based on particulate matter data is unavailable. However, air quality measurements in this region have been used to examine the Saharan dust events, especially in transport and impact studies [58–60]. Figure 2 shows the typical chemical compositions of dust storms observed in the Sahara desert or its closely impacted area. It is also found that the chemical composition of the transported Saharan dust was more homogeneous than the composition of individual soils [61]. As confirmed by the air mass back trajectories, the higher level of homogeneity of the aerosol is partly because a dust event affects a large area of the Sahara desert and the composition of the particles reflects its average composition [62].

Limited studies and data sources are available to draw a comprehensive dust composition map. However, a series of major components and their ratios have been provided in previous studies. Although these observations did not use a unified analysis standard, the characteristics and difference among sources can be identified. All figures of chemical characteristics in this section show only the reported ratios of components in samples. The unreported mass ratio for each region is summarized as others, which may include some regular compositions of the earth crustal, e.g., H_2O, C, O, etc.
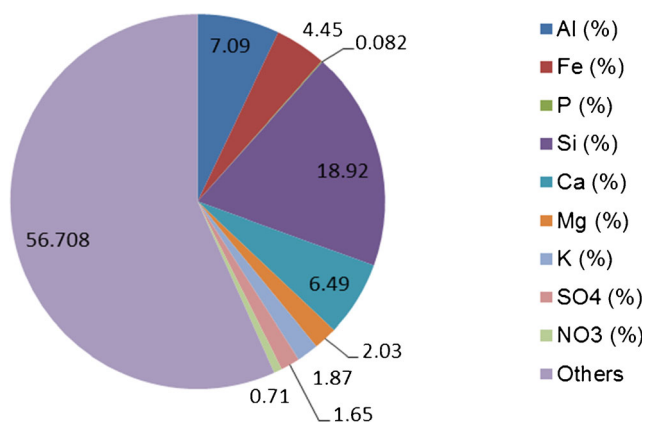
Fig. 2 Chemical characteristics of Saharan dust. Mean percentages of components measured in previous studies (Data source: [58, 59])

Asian Deserts

Middle and eastern Asia is also a significant dust storm source region, and studies of dust loading and fluxes indicate major source deserts including the Gobi [63, 64], Taklimakan [65], and Badan Jarain [66] deserts. Dust storms over this region have been well studied in the past decades due to their serious impacts on the social-economic centers of East Asian countries.

Dust weather codes in meteorological records have been widely used in dust storm studies in East Asia. However, the name and category of dust weather codes are defined differently, in comparison with those discussed in section 1.1, and these practices are still ongoing in places such as China. Observed surface weather phenomena is usually required in this method [63, 67] and describes the dust weather by four strength codes: dust-in-suspension, blowing dust, dust storms, and severe dust storms. Ding et al. [68] used the dust weather records from 338 stations over China to study long-term (1960–2003) dust climatology and its tele-connection with atmospheric circulations, while Lei et al. [67] and Sun et al. [63] used the weather codes to validate their dust storm prediction models. A long-term seasonal trend of Asian dust storm activities has been constrained from meteorological records [69]. Spring is shown as the most frequent season for dust storm disasters [70, 71].

The air quality monitoring network was established gradually in China during the last couple of decades, and therefore, the data are too limited to reveal long-term dust climatology. Independent observations and field campaigns over China can provide effective information about dust compositions in the country. Zhang et al. [72] studied the chemical compositions of spring dust storms in Beijing and their comparison to the deposition in non-dust storm days. Wang et al. [73] analyze the monthly samples obtained from April 2001 to March 2002 at 29 sites in sandy and Gobi deserts, steppes, and loess areas across North China. The results show the typical characteristics of chemical compositions of dust storms in East Asia (Fig. 3), revealing that Asian dust features high concentrations of Si, Al, Fe, Ca, and K. Compared with Saharan dust, the relative ratio increase in K and P and decrease in Ca and Mg indicate that East Asian dust is more affected by farming sources.

Middle Eastern Deserts

Dust storms in the Middle East are mainly from the Arabian desert [74, 75], with Oman and parts of Saudi Arabia providing large generation areas in the east, and northern parts of Iraq and Iran are also major dust lofted areas [76]. Studies of dust activities and impacts of the Arabian Desert are usually combined with Saharan dust [60], since the surrounding regions are affected by both sources. Independent studies of dust storms were also made in Arabian desert regions and it showed different characteristics from the Sahara desert.
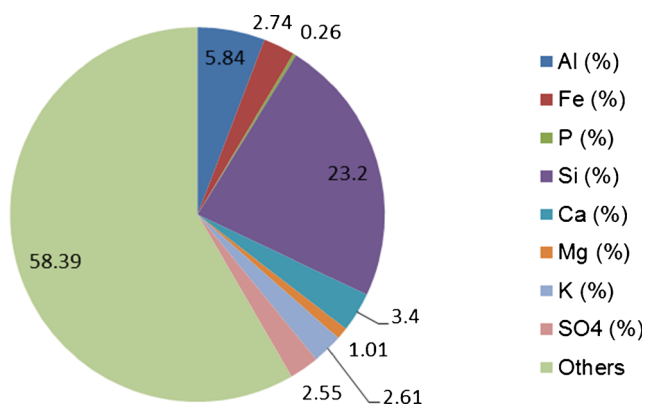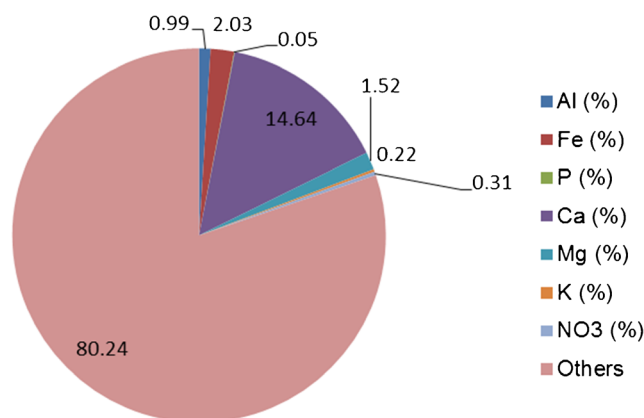
Fig. 3 Chemical characteristics of East Asian dust. Mean percentages of components measured in previous studies (Data source: [73, 74])

Fig. 4 Chemical characteristics of Arabian dust. Mean percentages of components measured in previous studies (Data source: [81, 82])

Previous studies of Middle East dust storms based on meteorological records usually used visibility as the parameter to identify dust storm events. Kutial and Furman [77] use the visibility data at 117 synoptic stations over the middle-western region into a cluster analysis to group the typical dust storms. The identification of dust storms is based on the similarity in visibility reduction. A recent study by Yu et al. [78] further use the visibility records in this area to analyze dust storms, but adopts a simple identification criteria which defines dust storms as having visibility less than 1 km. Notaro et al. [79] examined dust observations from 13 Saudi Arabian stations, revealing a mid-winter peak in DSF along the southern coast of the Red Sea, a spring peak across northern Saudi Arabia around the An Nafud desert, and an early summer peak in eastern Saudi Arabia around the Ad Dahna Desert.

Chemical compositions of the Arabian Desert have been investigated in a series of studies [80]. Aydin et al. [81] studied the chemical characteristics of Arabian and Saharan dust in the impact region of Anatolia, Turkey. Through analyzing the trace metal concentrations in dust day PM10 samples, the study shows that four metals (Fe, Al, Cr, Mn) are dominant in settled particles. Modaihsh [82] studied the dust sediments in Riyadh city, Saudi Arabia from March 1991 to February 1992, with the entire data set revealing that the dust fractions lie between loam and silt loam, having an average composition of 37 % sand, 47 % silt, and 16 % clay. It is also shown that CaCO3 content, EC, and pH value were rather high and averaged 31.8 %, 4.8 dSm–1, and 8.9, respectively. The data from both studies are combined and analyzed in Fig. 4 as the typical composition fraction of the Arabian Desert. Compared with other deserts, it is noted that the ratio of Ca is exceptionally high, which indicates that high granite component is a major feature in the Arabian Desert.

North American Desert

Northern American dust storms mainly occur over the western United States, including the Great Basin, Mojave, Sonora, and Chihuahua deserts and the Great Plain [5, 10••]. The dry climate drives dust storms all year round with peak strength and frequency in spring and summer [10••]. The decadal variability of North American dust is significant, with serious dust storm hazards during the 1930s creating one of the most severe environmental catastrophes in US history, which led to the popular characterization of much of the southern Great Plains as the "Dust Bowl." Recent dust activities have reduced and serious impacts usually occur in near-desert states including Arizona, Texas, and New Mexico.

The study of North American dust storms through meteorological records has been carried out in recent years. Through investigating the weather code, Hahnenberger and Nicoll [13] used regular meteorological records to study the meteorological characteristics of dust storm events in the eastern Great Basin of Utah. Similarly, Lei et al. [83] combined the weather code, air quality observations, and satellite AOD in investigating the long-term dust climatology in Phoenix, Arizona. Both studies show a skewed distribution with higher frequency of dust storm activities in July and August and relatively low activity during the remaining months.

Since the air quality monitoring network is relatively well developed in the United States, systematic observations of particulate matter have been used in previous dust storm analysis. Many approaches have been used in US dust storm identification. For instance, Kavouras et al. [84] developed a semi-quantitative method to assess local dust contribution in the western USA by assuming that dust concentrations are equal to the sum of fine soil and coarse particles. Escudero et al. [85] used the increase in daily particulate matter concentration, with smaller than 10 μm in diameter (PM10) over the regional background level, to quantify the daily dust load. Ganor, Stupp, and Alpert [86] developed and tested three criteria for determining a dust event: average PM10 level in half-hour exceeds 100 μgm^{-3}, the high level is maintained for no fewer than three hours, and peak PM10 is above 180 μgm^{-3}. Furthermore, Tong et al. [5] use the aerosol observations derived from the Interagency Monitoring of Protected Visual

Environments (IMPROVE) network to construct the DSF during 2000–2007 over the western United States based on a high PM10 level, a relatively low PM2.5 level [87], and the element distribution in the sample. The resulted dust climatology shows a similar summer peak as that from the meteorological record.

Figure 5 shows the composition characteristics of dust measurement in the Phoenix area of Arizona. The composition data was from the continuous aerosol measurements on an IMPROVE site in the rural area of Phoenix, which is a typical US southwestern city that is affected by dust storm weather all year around [83]. The IMPROVE monitoring sites that, with a few exceptions, are deployed in the national parks and wilderness areas of the United States [88], provide a good reference to natural dust storm events. The composition features high concentrations of Fe, Ca, and SO_4^{2-} and low concentrations of K, Mg, and P. The high concentrations are typical components of sand, while the low concentrations are typically composed of clay. This indicates that the dust source is likely to come from wind erosion of rocks rather than agricultural regions. However, it must note that the composition shown in the Fig. 5 over the Phoenix area may not be representative to dust storms peaked in Spring season over different locales in southwestern USA, such as in Texas.

Australian Deserts

Australia is a dry continent, with over 75 % of its land surface classified as arid or semi-arid land. Dust storms are natural events that occur widely over Australia [89]. As a seriously affected region, Australian scientists began researching dust storms decades ago, and many case studies and modeling studies on Australian dust storms have been published (e.g., [90–93] and many others).

In Australia, the meteorological records have been used in dust storm studies for several decades [94, 95]. The approach was continuously improved, and advanced methods have

been developed in using weather codes [8]. This progress has also benefited from good quality meteorological operations on dust weather recording. The Bureau of Meteorology has been a key component of national drought management since 1965. The dust weather codes are an integral portion of the nationwide daily observation network and help to assess the current situation and provide early indication of the need for contingency action. Therefore, Australian meteorology data are highly utilized in dust storm studies. As a latest progress on the weather code approach, O'Loingsigh et al. [8] update a Dust Storm Index (DSI) by using different weighting on the dust weather codes. This method considers the strength variations among different dust storm events or over different locations. The DSI can represent the temporal and spatial pattern of dust storm activities. Similar to most continental dust storm activities, Australian dust storms show a late spring peak (October–November for the late spring of the southern hemisphere).
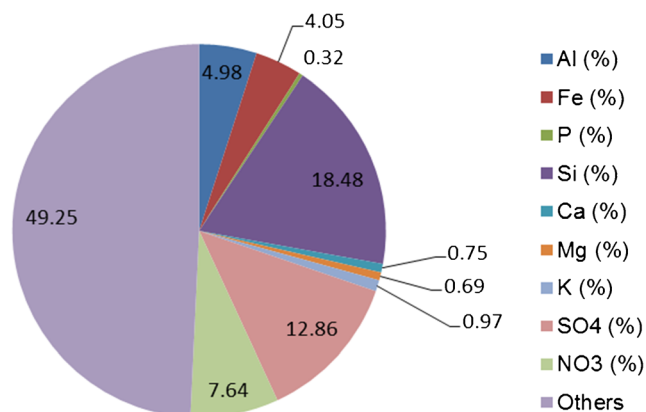
Chemical characteristics of Australian dust storms have been studied by several field campaigns [96–98], although a consistent monitoring network specifically designed for dust aerosols is unavailable in the country. Through integrating data from these field campaigns, a composition diagram is presented in Fig. 6. This composition shows a different type of source, which may originate from both desert and agricultural areas.

South American Deserts

In South America, dust storms occur in the western parts of the continent covering areas of Bolivia, Chile, and Argentina. Prospero et al. [25] have shown that there are three persistent dust sources: Patagonia, central-western Argentina, and the Puna-Altiplano Plateau. To the west of Buenos Aires in Argentina, more than eight dust storms are reported per year [97]. Winter (June to August for the South Hemisphere) is a peak season for South American dust storms [25, 98].
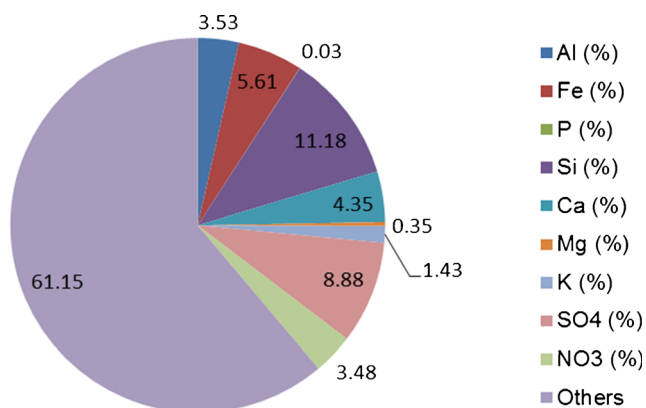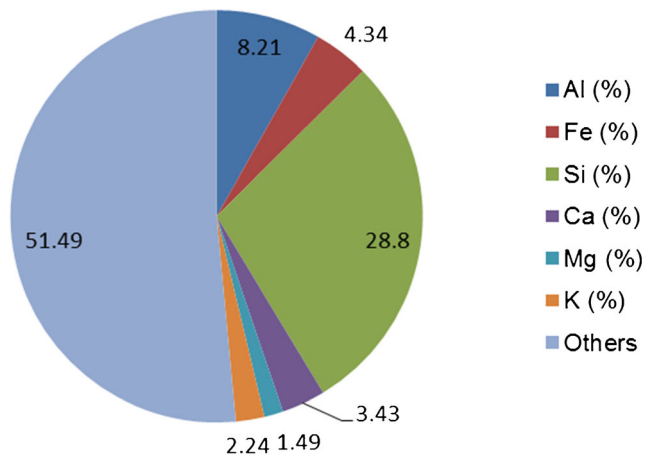

Fig. 5 Chemical characteristics of dust in Phoenix, Arizona, USA. Mean percentages of components measured by IMPROVE network in March 2003

Fig. 6 Chemical characteristics of dust in Australia. Mean percentages of components measured during dust storm events (Data source: [48, 49])

Fig. 7 Chemical characteristics of dust in Patagonia, South America. Mean percentages of components measured during dust storm events (Data source: [100])

The presence of extensive areas of closed depressions and of wind fluted topography, combined with the probable importance of salt weathering in the generation of fine material for deflation [99], suggest that the dry areas of the Puna and Altiplano should be major source areas for dust storms [98]. TOMS identifies one area where aerosol values are relatively high, the Salar de Uyuni, a large closed basin in Bolivia. It is probable that the deflation of fine sediments from its desiccated floor is one of the reasons for the existence of high aerosol values in this region. Gaiero et al. [100] studied the chemical composition of the dust storms in Patagonia, finding that the volcanism has important contributions to the dust storm source in Patagonia (Fig. 7).

Discussion

As extreme meteorological events, dust storms are major natural hazards. Research has been conducted into major dust affected regions, yet studies are far from comprehensive and the status of research is unbalanced for all regions. Such limitations are the result of a lack of quality observational data on dust storms, with a serious influence on long-term climatology studies and model verifications.

Since specifically designed observations with good coverage for dust activities are unavailable, other data sources have been analyzed in recent decades, with significant progress made in this aspect. Table 5 summarizes the characteristics of major dust-prone regions over the world.

Seasonal variability of dust frequency in each region largely depends on their local climate and surface conditions. Previous studies show that the peak dust frequency tends to occur in spring when the meteorology and soil conditions are suitable for wind erosion. As approaches used in recent studies, meteorological records, air quality measurements, and satellite AOD can provide a good coverage to constrain the historical dust storm images. Through the review, it is noted that not all dataset or dust series reconstruction approaches are used in each region. Due to the diversity in data quality and availability, the final choice of data for appropriate studies may differ in different regions.

However, existing datasets may not meet the requirements for dust storm studies. The modeling study of dust storms needs accurate observations of dust concentrations, which means not only accurate on instantaneous value but also the exact description of the location and temporal stage of the dust storm event. Current meteorological records do not provide dust concentration information, and air quality observations usually are obtained over a period of time. There is a lack of information on instantaneous flux and dust concentrations on different vertical layers. The temporal intervals of air quality sampling are too large to capture the peak value of a dust storm, and satellite AOD can provide the reference to total column integration on dust concentrations. It is necessary to identify the vertical structure in data retrieval. Satellite AOD is also seriously affected by cloud coverage, which may largely reduce the effectiveness of data for practical use. Another limitation of Satellite AOD is differentiating dust from volcanic ash, urban aerosols, etc. Further improvements in satellite technology and related data retrieval algorithm are needed to enhance these aspects.

Although the seasonality of dust storms over each dust-prone region is well understood, an understanding of long-term dust storm climatology and climate feedback still needs much work. The inter-annual variability of dust storms over most dust-prone regions is not well understood, which may further affect the improvement of climate-scale numerical dust

Table 5 Characteristics of dust activities

Region	Peak season	Dust sources type	Common data source
Sahara	Boreal spring	Desert	Weather code, AOD, satellite data
Asian	Boreal spring	Desert, farm	Weather code, satellite data
Middle East	Boreal spring-summer	Desert	Weather code, visibility, satellite data
North America	Boreal spring-summer	Desert	Weather code, visibility, AOD, satellite data
Australia	Austral spring (October–November)	Desert, farm	Weather code, satellite data
South America	Austral winter (June, July, August)	Desert, volcano	Satellite data

prediction systems. Further work on long-term dust storm climatology may need to improve the approaches in historical dust storm identification based on current datasets. For instance, the dust storm index method is an advancement on the weather code method. However, the method has not been used in other regional studies, which may need further modification to adapt to the diversity of data quality. Climate and dust interaction studies may also facilitate the improvement of physical dust models by providing effective clues.

Finally, it must be noted that there have been many field campaigns either designed for dust monitoring or carrying dust-monitoring equipment. These campaign data have played a pivotal role in dust storm research including modeling. This important data source is beyond the scope of the current review that focuses on climate studies related to long-term data availability and continuity.

Conflict of Interest   Julian X.L. Wang declares that he has no conflict of interest.

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