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A review on the research of modern aeolian dust in Central Asia

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Abstract The Central Asian Arid Zone (CAAZ) located in the temperate desert belt of the Northern Hemisphere is one of the most important sources for global aeolian dust and aerosol. It is widely acknowledged that aeolian dust plays a vital role in the Earth system through participating in the energy and material budget of the planet. Except for the existed natural desert areas, the newly human-induced deserts that originally used to be the bed of terminal lakes (like the Aral Sea, Caspian Sea, Balkhash Lake, etc.) are becoming the much more significant sources for aeolian dust/salt in this region. Dust and associated aerosols have complex impacts on local ecological system and human health for its special chemical composition. In recent years, a slight declining trend of dust storm frequency in the region was reported, which may be explained by the weakened human disturbances in desert areas or climate variations. The dust dynamics in the CAAZ represent considerable variations in both spatial and temporal distribution, which makes it harder to forecast the dust events and mitigate its damages to ecosystems and social economics. Nevertheless, there is not much evidence of its climatic and environmental impacts both on the regional and global scales. Therefore, further related studies and regulation measures in the region are essential and emergent, as well as the strengthening cooperation between the associated countries and organizations.

Keywords Central Asia · Aeolian dust · Global change · Anthropogenic activities

Introduction

Aeolian dust mostly emitted from soils in arid and semi-arid regions is a key component of the atmosphere, geosphere, hydrosphere, and biosphere. Each year, megatons of dust are lifted into the atmosphere by strong near-surface winds over the global arid regions (Flagg et al. 2013). These fine dust particles can be blown to high upper atmosphere and transported hundreds even to thousands of kilometers around the planet. There are a range of important impacts of aeolian dust on the Earth system, which acts on timescales from minutes to millennia. Suspended dust particles significantly influences radiation budget of the Earth system not only through absorbing and scattering the incoming shortwave solar radiation but also by interacting with the outgoing longwave radiation and modifying the optical properties of clouds and snow/ice surfaces on which they are deposited (Lau et al. 2006). In addition, because of its condensation nuclei effect (Creamean et al. 2013; Karydis et al. 2011; Twohy et al. 2009), dust can regulate climate through altering cloud lifetime, fraction, and precipitation processes. Dust also alters chemical processes in the geosphere, such as influencing soil available nutrient content and water retention ability, and plant growth in both source and downwind areas (Flagg et al. 2013). Essential nutrients for plant growth contained in dust fertilize both terrestrial and marine ecosystems. Specifically for Fe, a kind of limiting nutrient in many ocean regions can significantly increase ocean primary productivity and consequently impact the global carbon cycle (Falkowski et al. 1998; Jickells et al. 2005; Mahowald et al. 2009). However, aeolian dust might increase soil salinity (Popov 1998), reduce

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photosynthetic efficiency (Razakov and Kosnazarov 1996), deteriorate air quality and visibility for traffic, and impair the human health. Last but not the least, dust deposits in glaciers, soils, and ocean or lake sediments constitute an important archive of past environmental changes (Ravi et al. 2011). Because of its important influence on so many aspects of human society, scientists pay much more attention to the origins, formation, transportation, and deposition of aeolian dust, especially in the current context of global change.

So far, most of the studies on aeolian dust mainly focus on arid and semi-arid regions of northern Africa, western USA, and Australia. However, as a major source of the global dust aerosol, the drylands of Central Asia experience the most frequent dust storms in the world (Orlovsky et al. 2005); the related scientific studies of dust phenomenon in the region are poorly both in Russian literature and English language. This paper reviews the recently published literature regarding the modern aeolian dust of Central Asia in hope that studies on dust of this area would attract more scientific attentions.

Central Asia is situated in the hinterland of the large Eurasian continent and extending from the Caspian Sea in the west to China in the east and from Afghanistan in the south to Russia in the north (Fig. 1). This review is focused on the five Central Asian states of the former Soviet Union namely Turkmenistan, Uzbekistan, Tajikistan, Kyrgyzstan, and Kazakhstan; therefore, we use the term "Central Asia" as referring to the five republics (Lioubimtseva and Henebry 2009).

Aeolian dust sources, sinks, and transport patterns in Central Asia

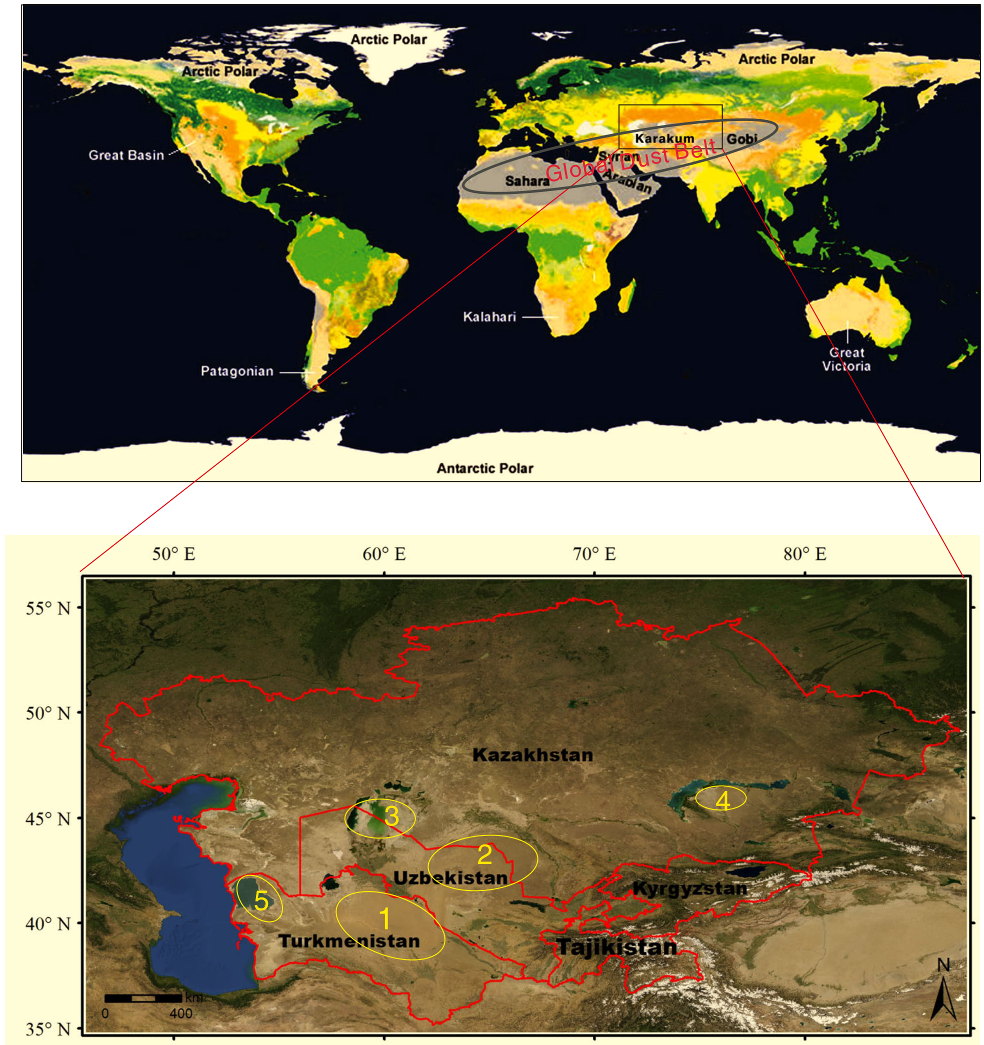
Due to its situation in the center of Eurasian mainland and far from any oceans on the Earth, less water vapor can be transported to Central Asia, so that its annual precipitation is about 100–400 mm, while the evaporation is up to 900–1500 mm (Qin 1999). In addition, the region is characterized by strong near-surface winds, vast desert areas, as well frequent soil and atmospheric droughts (Indoiu et al. 2012). All of these conditions make the Central Asian Arid Zone (CAAZ) a powerful source of aeolian dust, which could be even traced to glacial maxima when large aeolian dust fluxes had been carried out of Central Asia (Phillips et al. 1993). In spite of large amount of aeolian dust emitted from this region, little is known with regard to the nature of aeolian dust so far. Aeolian dust is defined here by McTainsh and Strong (2007) as a kind of terrestrial sediment, smaller than 100 μm, and transported in suspension or saltation. Unlike fluvial systems that are spatially bonded within river ways, aeolian transport systems are to great extent unconstrained. Dust transport patterns can variate in scales from local to global; thus, its potential influences on ecosystems can operate over a similar range of scales. In addition, the emission, transport, and final deposition of aeolian dust have severe effects on climate and many important ecological processes. One way to understand these ecosystem impacts of aeolian dust is to track them from its source to sink (McTainsh and Strong 2007).

Dust sources

The source region of sand or dust occurred mainly in the desert regions, and on the Earth, major contribution to global aeolian dust production comes from the regions extending from northwest Africa to China, which was known as global dust belt (Prospero et al. 2002). Deserts of Central Asia such as Kyzylkum and Karakum are just located in this belt (see in Fig. 1), which mostly cover lowlands and stretch from the eastern coast of the Caspian Sea to the piedmonts of the Tien-Shan and Altai, occupying about 250 million hectares (Babaev 1999). Among those, the identified active sources are primarily situated in the sandy land which are most prone to the dust/sand/salt storms, including the southern deserts, Moiyn-Kum deserts, Ryn sands (northern Caspian plain), southern Pre-Balkhash deserts, sandy deserts between the Caspian and Aral Sea, the Turan Lowlands, and southeast part of the Turan Plain (Indoiu et al. 2012; Issanova et al. 2015a; Shao et al. 2011; Zolotokrylin 1996). Of the five Central Asian republics, Turkmenistan suffered most seriously from the aeolian dust. In the country, there is an extend area where the annual frequency of dust storms exceeds 40 and some locations are even more than 80 which is one of the highest occurrences in the world. Takhiyatas of Uzbekistan Republics was reported to have the highest occurrences of dust storms in southwest Asia, reaching 108 per year (Middleton 1986). There is also strong dust event in the southeastern tip of the Turan Plain, close to the mountains of Tajikistan (Prospero et al. 2002).

What was worse, in recent decades, due to climate change and overexploitation of water resources in agriculture, some inland lakes like Aral Sea and Balkhash Lake rapidly shrunk. Consequently, the vast dry lakebed is becoming a new active source of dust events and aerosols. The desiccation of the Aral Sea has been well-known as one of the most staggering ecological disasters of the last century and is still endangering the local society. Since 1960s, the increasing water demand taking from the two main feed rivers—the Amu Darya and Syr Darya—as well the Kara Kum Canal of Turkmenistan has resulted in the dramatic desiccation of the Aral Sea, and with a 88 % decrease in surface area and 92 % in volume (Micklin 2010). At present, the Aral Sea does not exist any longer as a whole; only the northern part has a constant water level. In fact, the Aral Sea basin is occupied by natural deserts like the Kyzylkum and Karakum that were identified as the major dust sources in the Aral region. However, the Aralkum which was once the seafloor is a human-induced desert and becoming the

Fig. 1 Map showing the location of Central Asia and the distribution of major aeolian desert dust sources



dominant source of salt dust storms and sandstorms. Its impact of salt dust is confined to a region of about 500,000 km^2 in the Circum-Aral region. The exposed bottom of the Aral Sea which was estimated to be more than 57,000 km^2 in 2011 (Indoitu et al. 2015) has significantly increased the availability of particle mass for deflation (22.8 t ha^{-1} year^{-1}) (Singer et al. 2003a; Breckle et al. 2011; Indoiu et al. 2012; Groll et al. 2013). Analysis of land cover changes indicated that the northeastern part of the Aralkum Desert created the most dust emission of the region, while from 2005 to 2008, the dust sources were detected on the eastern and southern shores and the Vozrojdenie Peninsula (Indoitu et al. 2015). The solonchaks occupying approximately 1.5 × 10^5 km^2 of the Aral Sea basin provide a convenient condition for deflation processes and, consequently, salt dust emission (Orlovsky et al. 2004). Moreover, the dust originated from the Aralkum has a high salt content (sometimes up to >90 % in winter), and the mean annual salt dust transported by wind was 0.5 × 10^6 to 20 × 10^6–30 × 10^6 t, leading to salinization of soils in the southern Aral Sea where the deflated material deposited (Orlovsky et al. 2001).

On the eastern coast of the Caspian Sea, the most intense dust activity centered over the large lagoon embayment (9600 km^2) of Garabogazkol, which used to be a gulf of the Caspian Sea in Turkmenistan but dried into a salt-covered playa (Gills 1996). The playa is surrounded by lowlands that are largely covered with seasonal swamps or marsh. So, the exposure of saline deposits combined with the hot and arid climate of the eastern shore caused severe ecological problems from salt dust plumes (Prospero et al. 2002).

Last but not the least, the agricultural areas as well are the potential sources of aeolian dust in the CAAZ. Agricultural activities that alter the soil structure and composition can significantly increase the strength and dimension of aeolian dust (Prospero et al. 1983). Wind erosion of soils on farmland and pasture is a global problem which is not exceptional but more severe in Central Asia. Almost all of the agricultural lands in the region are arid types, and 63 % of which is grassland (FAO 2012). However, in recent decades, due to overgrazing, anthropogenic desertification of meadows is expanding rapidly and has caused more frequent dust activities in the region. The irrigation arable land would be another important aeolian dust source during its fallow period when the land surface has no vegetation cover, and removal of vegetative cover is a documented cause of increased aeolian dust (Leys 1999). Wiggs et al. (2003) reported that in the Aral Sea region agricultural fields, overgrazed grassland and off-road tracks are important sediment sources, particularly in the early summer when the climate is hot and dry, as well lacking of vegetation shelter.

Dust transport patterns

Desert regions of different landforms and surface structure showed significant differences in the erodibility. Generally, dry desert sand dunes and playa are most susceptible to wind erosion. The transport patterns such as direction and flux of aeolian dust are largely determined by the wind regime (namely the velocity and direction) as well as the geomorphology. Wind transport direction of dust will shift accordingly with wind direction that is continually changing in a chaotic manner as time passes; therefore, it becomes much more challenging to accurately descript the wind transport direction. The challenge is that dust transportation is a vector quantity with both magnitude and direction, of which transport direction remains an important and fundamental aspect of aeolian research as wind direction is to the atmospheric sciences (Stout 2014).

In most part of Central Asia, the north direction winds are dominant and dust storms were primarily caused by northern, northeastern, and northwestern winds, while in the southern Turkmenistan, it is eastern and southeastern winds that invoke the occurrence of dust storms. The predominant northern winds change their directions to the southeast and entrain dust to Afghanistan when meeting with the Kopetdag Mountain range. In the CAAZ, about 40 % of registered dust storms were induced by northwestern, northern, and western cold air invasions, 22 % were caused by southwestern, southeastern, and southern peripheries of an anticyclone, and 14 % of dust events were connected with the southern cyclones. The remaining 24 % occurred due to other synoptic process (Orlovsky et al. 2005).

In Uzbekistan, Kazakhstan, and Turkmenistan, a long-term monitoring program of the dust deposition that covered 21 stations revealed that the aeolian dust transport occurs mainly in the southern direction during 2003 and 2010 (Groll et al. 2013). In the Aral Sea region, the mass transport of sand and dust variated considerably with the climatic fluctuation. Satellite observations showed that with north and northeastern winds prevailing, dust plume is removed and deposited to the south and southwest of the southern Aral Sea basin (Singer et al. 2003b). Aeolian sands and dusts flowed mainly from northeast and east toward the southwest and west directions that, respectively, count 60 and 25 % of the total amount, and the latter travels westward over the Ustyurt Plateau (Issanova et al. 2015b; Micklin 1988). However, from 2005 to 2008, dust plumes were registered mainly toward the west (57.1 %) and only 11.9 % toward the southwest. Still, 14.3 % of those were also captured rising from the eastern shore and flowing toward the east (Indoitu et al. 2015). Due to location to the south of the Aral Sea, the people living in Karakalpakstan are those most exposed to ecological disaster (Bennion et al. 2007). It is reported that the Aral dust could be transported as far as Belarus and Lithuania to the northwest, Georgia to the west, and Afghanistan to the southeast (Letolle and Mainguet 1993). In the southern Pre-Balkhash deserts, winds of western directions are prevailing; consequently, the aeolian transport of sand and dust occurred primarily toward the east, southeast, and northeast. While in the southern parts of the region, the relief and local orographic conditions provoke strong winds. Therefore, an eastern movement of aeolian sand/dust is observed at the Kapshagay station, which is a maximum of east direction along the Ili River valley due to a well-known local easterly Shelek wind (Issanova et al. 2015a).

With respect to impacts of dust deposition upon downwind terrestrial ecosystems, the scientific awareness is rapidly expanding over time. Where and which kind of ecosystem the dust sinks would represent different environmental effects, which was largely determined by wind strength, landform, landscape, and so on. Dust plumes actually can carry very large quantities of dust, as reviewed by Goudie (1978) that dust contents within dust storm plumes range from 100 to 100,000 $\mu m\ m^{-3}$. Dust from deserts and sands in Kazakhstan contribute 4 to 7 % of the total emission of Asian dust, which was estimated up to be 400–500 × 10^{12} g and mostly deposited in the North Pacific Ocean every year (Zhang et al. 2003).

Because of being surrounded by many deserts, the Aral Sea not only emits but also traps remarkable amounts of aeolian dust every year (Orlovsky and Orlovsky 2002). Dust⁄salt storm impact covers high dimension surrounding the Aral Sea and the Amu Darya delta at the south end of the lake where it has the densest inhabitants and is the most ecologically and economically important region around the Aral Sea that suffered most severe storms (Micklin and Aladin 2008;

Micklin 2010). This must be the worst situation that is worth paying much more attention.

Aeolian dust characterization in Central Asia

The major characteristics such as deposition rate, particular size distribution (PSD), and chemical composition of aeolian dust are closely related to dust generation, transport, and deposition processes. For example, the type and intensity of the consequences of aeolian dust mainly depend on the chemical and physical properties of the dust. Moreover, according to the PSD characteristics of deposited sediment, we could obtain the exact information about the erosional, transportation, and depositional history of the sediment (McCave and Syvitski 1991; Pye 1994).

Aeolian dust deposition rate

During transport, dust particles experience deposition processes that strongly affect their atmospheric lifetime and their radiative and geochemical impacts. Dust deposition is an inevitable consequence of the dust cycle. Aeolian dust is removed through dry deposition that is mainly controlled by gravity, impaction, and diffusion or by wet removal in or below clouds. Most of the aeolian dust deposited in the peri-desert regions, where increasing rainfall washes it out from the atmosphere or removed by gravitational settling or trapped by vegetation and massif, while the fine part would be transported far away from the source region.

The aeolian transport of dust is controlled by the complex interaction of several atmospheric parameters and is characterized by strong temporal and spatial dynamics (Orlovsky et al. 2005). Modern remote sensing analysis tries to track these fluxes, but there is still much uncertainty about when and where the dust is deposited again in the region. So far, there are several different estimates of the dust deposition rate in the CAAZ. As described in Table 1, the overall dust deposited in the study area is higher in comparison to surrounding regional and global area except for those nearby the famous Sahara Desert. Affected by the geomorphology and dominant wind directions, it was observed that there was great spatial heterogeneity between the sites in the annual dust deposition throughout the study area. The fallout of dust primarily occurred in the three low altitude upwind Central Asian countries, namely Uzbekistan (674.4 g m^{-2} $year^{-1}$), Turkmenistan (148.8 g m^{-2} $year^{-1}$), and Kazakhstan (58.8 g m^{-2} $year^{-1}$). While in the mountainous courtiers like Kyrgyzstan and Tajikistan, the dust deposition is very few. In addition, the annual deposition rate is very low in the northern part, for example, it is of the order of 3.1–3.9 g m^{-2} on the Usturt Plateau (13,000 km^2). In contrast, it becomes relatively higher in the south, increasing to 9.0–10.0 g m^{-2} $year^{-1}$ in the Amu Darya delta region (about 10,000 km^2) where there are 90,000–100,000 t of dust dropped every year (Orlovsky et al. 2001). In parts of the Amu Darya delta region, the deposition rate of wind transport salts is up to 15.0 g m^{-2} $year^{-1}$ (Orlovsky et al. 2004). Findings of O'Hara et al. (2000) revealed that the sites of highest deposition rates were located in the desert in the northern region that were closest to the original shoreline and lower at sites in the northwestern and eastern regions closer to the remnant Aral Sea. In the eastern Turkmenistan, the monthly dust deposition rates were among the highest in the world and varied considerably in the range of 5.0–168.0 g m^{-2} across the region for each month. The percentage of months with a very intense (and potentially harmful) dust deposition flux was highest in Turkmenistan (36.4 %). In the region close to the Kyzyl Kum, monthly dust deposition rates were registered up to 9615.9 g m^{-2} (Groll et al. 2013).

In addition to the spatial heterogeneity, the deposition rate as well shows a significant variation in temporal distribution (Fig. 2), which is the second and equally important component of the dust deposition dynamic. It could be observed that the monthly deposition rate showed a slight rising trend in the CAAZ during 2003–2010 and the maximum value occurred in 2009. Usually, in the inner annual scale monthly dust deposition reached their peak during the summer months and valley point during the winter months. And, this was confirmed in Fig. 2b that the high dust fallout occurred in June, September, and July, while in January, it is the lowest. Bennion et al. (2007) also reported that in the Aral Sea region, the highest average dust deposition was registered in June, and a second phase of intense dust deposition was identified in February.

Particle size distribution

The size distribution of aeolian dust is one of its most important properties, as it dominates its impact on any process. First of all, the movement of grains in any fluid is governed partly by the size, shape, and density of the grains and partly by the physical properties of the fluid (Pye and Tsoar 2009). Aeolian dust in the atmosphere generally decreases in particle size downwind of source (Pye 1987), and bimodality in a PSD can be indicative of mixing of sediments from different sources and deposition processes (McTainsh et al. 1997). In other words, the coarse fractions of dust mostly originated from local sources, moving in the form of saltation or short-term suspension, while the finer fractions could be transported for longer and farer. On the other hand, it has particular radiative impact, for example, the scattering cross-section scaling with powers of 3–5 of particle size. Besides, the PSD not only influences the

Table 1 Average annual dust deposition rate recorded in different regions of Central Asia and global areas

Location	Political region	Deposition rate (g m^{-2})	Reference
Amu Darya delta	Uzbekistan	9.0–10.0	Orlovsky et al. (2001)
Usturt Plateau	Kazakhstan	3.1–3.9	
Eastern Turkmenistan	Turkmenistan	66.4–914.4	O'Hara et al. (2000)
Repetek	Turkmenistan	214.0	Groll et al. (2013)
Bozaubay	Uzbekistan	8365.0	
Aralskoe	Kazakhstan	162.5	
Kyzyl-Orda	Kazakhstan	31.4	
Kuwait	Kuwait	16.8–61.3	Al-Dousari and Al-Awadhi (2012)
Khur Al-Zubir	Iraq	75.9	Khalaf et al. (1980)
Um Qasir	Iraq	193.4	Gharib et al. (1987)
Al Fahal	Oman	89.0	Badawy et al. (1992)
Riyadh	Saudi Arabia	392.0	Modaihsh (1997)
Dead Sea	Palestine	45.0	Singer et al. (2003a)
North Diamena	Chad	142.0	Maley (1982)
Kano	Nigeria	137.0–181.0	McTainsh and Walker (1982)
Crete	Greece	10.0–100.0	Pye (1992)
Arizona	USA	54.0	Péwé (1981)
Neveda	USA	4.3–15.7	Reheis (2006)
California	USA	6.8–33.9	
Libya	Libya	155.0	O'Hara et al. (2006)
Tan Tan	Morocco	175.0	Rott (2001)
Dakhla	Mauritania	191.0	
Boujdour	Western Sahara	219.0	Khiri et al. (2004)
Along Niger River	Mali	913.0–10,446.0	McTainsh et al. (1997)
Namoi Valley	Australia	16.9–58.2	Cattle et al. (2002)
Shapotou	China	372.0	Li et al. (2004)

multiphase chemical reactions (particle surface area/surface to volume ratio) and cloud process (threshold sizes) but also its removal processes efficiencies both in the forms of sedimentation and wet removal (Knippertz and Stuut 2014).

However, there are significant differences between the dust particle size distributions throughout the world (see in Table 2). Generally, the majority of aeolian dust particles are larger than 10 µm, while in salt dust storm,

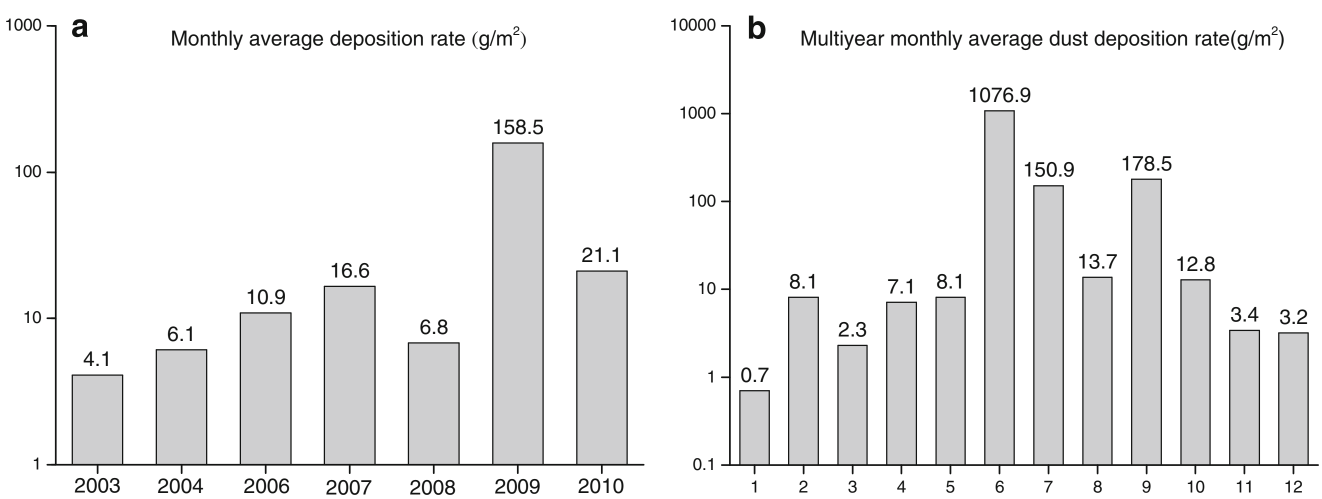


Fig. 2 Inter and inner annual dynamics of the monthly average dust deposition in Central Asia during 2003–2010 (**a** inter annual and **b** inner annual, Groll et al. 2013)

Table 2 Particle size distribution of dust fallout within world major dust-affected areas

Location	Modal, mean, or median size (μm)	Clay (<2 μm, %)	Reference
Kano, Nigeria	8.9–74.3 (Median)	2.3–32.0	McTainsh and Walker (1982)
Tanezrouft (central Sahara)	72 (Modal)	9.4	Coudé-Gaussen (1981)
Off northwest Africa	8–42 (Modal)	–	Stuut et al. (2005)
Canary Islands	16.9–20.67 (Mean)	7.2–9.6	Criado and Dorta (2003)
Ghana, West Africa	6.8–16.4 (Median)	–	Breuning-Madsen and Awadzi (2005)
Maghreb, North Africa	5–40 (Median)	–	Coudé-Gaussen (1991)
South of France	8.0–11.0 (Median)	–	
Mallorca, Mediterranean Sea	9.3–58.9 (Median)	–	Fiol et al. (2005)
Crete, Mediterranean Sea	4.0–16.0 (Median)	15.0–45.0	Pye (1992)
West Germany	2.2–16.0 (Median)	–	Littmann (1991a,b)
Texas, USA	23.0–35.0 (Mean)	–	Chen and Fryrear (2002)
Japan	6.0–21.0 (Median)	–	Osada et al. (2004)
China	3.97–93.54 (Median)	–	Liu et al. (2004)

about 79 % particles are smaller than 10 μm (Mahowald et al. 2011a, b). Particle mass-size distributions of aerosol samples from dust storms collected in Tadzhikistan appear to be characterized by a common log-normal mode between 1 and 10 μm (Gomes and Gillette 1993). In eastern Turkmenistan, the dust particle size varied in the range of 12–107 μm, and on average, 23 % in the deposited dust was PM10 in size or smaller (O'Hara et al. 2000). In the southern Aral Sea basin, the dominant particle size in the center of the dust plumes is between 10 and 50 μm, and samples collected nearby during a dust storm displayed a dominance of silt-size (6–63 μm) fractions, amounting to 77 vol% of total sediments; the clay (<6 μm) and sand-size (>63 μm) fractions only consist of 8.7 and 14.3 vol%, respectively. It suggested that the medium silt fraction is more sensitive to aeolian process while fine silt and clay fractions are not (Singer et al. 2003b; Huang et al. 2011). Wiggs et al. (2003) reported that most of collected dust from that area was very fine with high proportions smaller than 20 μm, which is often above 40 % and sometimes exceeds 70 % and indicative of appreciable long-distance transport and also significant impact on the potential health resulting from the inhalation of PM10.

In terms of antierosion effect of land surface, the sediment PSD fractal dimension is an effective indicator. On the desiccated bottom of Aral Sea, grain sizes of soil sample on average are 90–160 μm, smaller in young territories (desiccation 1980, 1990, 2000) and larger in older territories (1960, 1970). Adjacent desert areas (former coastal dunes, islands, sandy deserts) have an average particle size of 170–270 μm, which are the ideal sizes for deflation and wind transport. Average size of sand particles in the weather stations of Auyl 4, Kapshagai, Kuigan, Shyganak, Bakanas, and Matay all belong to the easily deflated type because the mean size is more than 100 μm in most areas (Issanova et al. 2015b).

Composition: mineralogical, isotopic, and elementary

Aeolian dust is believed to play an important role in many biogeochemical processes. Table 3 summarized the mineralogical composition of bulk dust samples from global major dust affected determined by X-ray diffraction (XRD). It could be observed that dusts on our planet are mainly composed of silicates and carbonates. The major mineralogical phases are the silicates quartz (SiO_2), feldspar and members of the group of phyllosilicates, and the carbonates calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). However, it also represents great spatial heterogeneity in different regions. Compared to the dust of Sahara Desert, dust in the Western and Central Asia is characterized by higher carbonates and has lower clay minerals in contrast with those from Eastern Asia. In some cases, the aeolian dust has some special mineralogical components like volcanic ash, salt, black carbon, and so on. For example, in Western Central Asia, especially in the lower reach of the Amu Darya River, the dust plumes consist of minerals, including salts mixed with pesticide-contaminated particles (Huang et al. 2011).

As displayed in Table 4, the comparison of physical-chemical characteristics between aerosol samples collected from dust storms in Central Asia and soil-derived dust of other regions shows that chemical composition of the sampled material is particularly rich in calcium and poor in iron, of which the content of Ca is about

Table 3 The XRD mineralogical percentages (weight, %) of dust in global major dust-affected areas

Location	Political region	Quartz	Calcite	Dolomite	Feldspars	Clay	Others	Reference
Tripoli	Libya	64	27	0	5	4	0	O'Hara et al. (2006)
Souss-Massa	Morocco	45	46	0	8	1	0	Khiri et al. (2004)
Bawku	Ghana	87	0	0	9	2	2	He et al. (2007)
Cairo	Egypt	51	20	14	15	0	0	Al-Dousari (2009)
Negev Desert	Palestine	41	21	2	18	17	0	Crouvi et al. (2008)
Riyadh	Saudi Arabian	68	32	0	0	0	0	Modaihsh (1997)
Baghdad	Iraq	57	16	0	17	3	7	Al-Dousari and Al-Awadhi (2012)
Um Qasr	South Iraq	13	77	3	7	0	0	Gharib et al. (1987)
Doha	Qatar	48	21	7	24	0	0	Al-Dousari and Al-Awadhi (2012)
Amman	Jordan	21	52	16	4	0	7	
Sabiya	Kuwait	39	26	11	12	6	5	
Dubai	UAE	21	25	21	6	0	27	
Andong	South Korea	28	8	0	19	45	0	Jeong (2008)
Beijing	China	20	8	0	10	40	23	Shao et al. (2007)
Shapotou	China	38	28	0	21	7	5	Nishikawa et al. (2000)
Bald Hill	East Australia	58	0	0	21	14	7	Cattle et al. (2002)

double times of Fe. Estimated mineral composition of dust indicates that this enrichment in Ca and Si for the dust must be related to high contents of carbonate and quartz, respectively. Different Fe/Al also suggests a specific chemical composition for clay minerals in the Asian dust (Gomes and Gillette 1993). Orlovsky et al (2001) reported that in salt deserts like Aral-Kum region and salinized farmland, the loose particles on the topsoil prone to wind deflation usually have a high percentage (8–10 %) of various salts (chlorides, sulfates, carbonate), the most harmful of which include sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4). Because of containing high concentrations of fine salts (such as NaCl and Na_2SO_4), pesticides, heavy metals (Mn, As, Cr, Rb, Pb, etc.), and the salt dust storm is also called white or chemical dust storms. In the southern Aral Sea basin, high values of phosalone were found in all dust samples and concentrations were noticeably higher at sites located in the irrigated zones. Of particular note is the high concentration of phosalone recorded 126 mg kg^{-1} at Dashkhous which is located in the main irrigation zone around the basin (O'Hara et al. 2000). The concentrations of cadmium (Cd) and lead (Pb) are probably high in the Aral Sea and surrounding soil, and it is likely that these and other toxins will also be carried in the dust.

Precipitation as snow to a glacier surface provides a natural sampling of atmospheric dust. On the basis of elemental and isotopic data of the Inilchek Glacier firn core in Kyrgyzstan, three components of the remote central Asian atmospheric dust load were identified as follows: loess, calcite, and gypsum. The Ca record indicates that there is calcium carbonate deposition far above that can be supported by loess deposition. Rare earth element (REE) patterns indicate that the loess is a ubiquitous component of the aerosol load in the remote Central Asian atmosphere, during both low and high dust flux event.

Dust modeling and observation in Central Asia

Mineral aerosols are potentially a major forcing mechanism for climate change. Therefore, monitoring aeolian dust dynamics and improving our understanding of the factors influencing dust emissions is a key scientific challenge (Weaver and Wiggs 2006). Before analyzing in detail the climatic effects of dust, it is important to understand its production, transport, and loss in the global atmosphere. To determine the long-range transport and deposition of Central Asian dust, data of observation and simulation is indispensable. The observations and model simulations outline the general pattern of dust transport and deposition, vertical profile, and spatial distribution. Meteorological records are regularly used to calculate wind erosion indices relevant to dust storm occurrence, and remote sensing is increasingly being used for monitoring regional atmospheric aerosol loading. Although studies have been carried out to simulate and observe aeolian dust in Central Asia, the long-range dust transportation, deposition, and spatial distribution are still

Table 4 Element concentrations of Central Asian aerosols collected from glacier firn core (Kreutz and Sholkovitz 2000)

Element	Al ng g^{-1}	S ng g^{-1}	Ca ng g^{-1}	Fe ng g^{-1}	La pg g^{-1}	Ce pg g^{-1}	Pr pg g^{-1}	Nd pg g^{-1}	Sm pg g^{-1}	Eu pg g^{-1}	Gd, pg g^{-1}	Tb pg g^{-1}	Dy pg g^{-1}	Ho pg g^{-1}	Er pg g^{-1}	Yb pg g^{-1}	Lu pg g^{-1}
High dust	5477.5	264.1	33,398.0	2305.8	2308.8	5812.8	624.0	2065.8	372.9	92.0	308.7	44.5	250.5	44.6	117.7	107.5	15.0
Mid dust	1007.4	245.7	5192.2	484.8	536.3	1350.1	141.8	479.1	87.9	21.0	73.2	10.6	62.5	10.8	28.7	26.4	3.8
Low dust	420.8	221.1	2896.2	224.3	229.4	586.4	60.6	203.0	37.5	9.2	31.6	4.5	27.4	4.6	12.4	11.3	1.7
	Weight ratio		Gomes and Gillette (1993)				Andronova et al. (1993)				Gomes and Gillette (1992)						
	Fe/Al		0.40				0.23				–						
	Ca/Al		0.84				0.50				–						
	Ca/S		–				–				3.95						
	Fe/S		–				–				1.79						

poorly understood because of the lack of continuous and simultaneous observational data on dust.

Dust modeling

As to identifying and evaluating dust source regions, numerical modeling becomes an important and conventional approach nowadays (Shao 2001), which has been certified to be a useful tool to understand the production, transport, and sink of aeolian dust on the Earth. The difficulty and key of these numerical methods lie in parameterizations of dust deflation and as such require exact information on the geographical distributions of the deserts, their surface roughness elements, grain size, soil moisture, etc. (Marticorena and Bergametti 1995). At the end, validation of model simulations is also a dispensable step. Many global models were used to simulate dust emissions, transport, and deposition in a coherent manner. For example, the Model of Aerosol Species in the Global Atmosphere (MASINGAR), a chemical transport model (CTM) for tropospheric aerosol species, was applied to calculate the global dust budget and estimated that the annual dust emissions of Central Asia is about 140×10^{12} g, 67 % of which is dry deposition and the rest 46×10^{12} g is settled in precipitation (Tanaka and Chiba 2006). Nonetheless, global models of dust cycle are used to investigate dust at large scales and long-term changes, and regional dust models are the ideal tool to study in detail the processes that influence dust distribution as well as individual dust events.

In CAAZ, the simulation of dust events has not been fully developed and the related work is elementary and plain. Semenov and co-authors have built a physical model to estimate the dust amount originated from the dry bottom of Aral Sea (Galayeva et al. 1996). The simulation results revealed that the annual rate of dust transportation is about 3850 t km^{-1} $year^{-1}$ at Aralsk and 1560 t km^{-1} $year^{-1}$ at Barsa-Kelmes; the lowest transportation record (330 t km^{-1} $year^{-1}$) occurred in the Kazalinsk station at Syr Darya Delta. As well at the Aralsk station, a decrease trend of sand deflation is registered in recent decades (Semenov et al. 1990). With the same model, Issanova et al. 2015b calculated the amount of sand/dust transported during the storm in the southern Pre-Balkhash desert and mapped its movement direction distribution.

Dust observation

In order to model the environmental impacts of dust, we need a better knowledge of sources and transport processes. For dust observation, the early data generally comes from conventional observation such as instrumental records of the meteorological stations and history books, which have been playing an important role in dust research and other climatic studies. Conventional observation of dust mainly describes its frequencies (dust storm days), duration, intensities (atmospheric visibility), movement directions (wind regime), and deposition rates. Nowadays, some meteorological stations in the dust source areas have set up instrumentations that could determine the emission fluxes of both vertical and horizontal. However, this kind of record was rare in the CAAZ due to lack of fund and studies.

Documents of dust in the Central Asia have lasted for almost 100 years, during which the vast deserts across the region have experienced dust/sand storms of different frequencies, intensities, and durations. Table 5 gives an overview of the average annual frequencies of dust storms occurred between 1960 and 1992, and Fig. 3 displays the annual dust storm days during the period of 1936–2006. Most meteorological stations found three maximums of sand and dust transportation, namely in 1966–1970, 1984–1986, and 2000–2002, like a cycle about 15 years. The most frequent storms were observed in Pre-Aral Karakum and Kyzylkum deserts, where these storms occurred from 40 to 110 days per year. The study of Orlovsky et al. (2005) suggested that the annual dust storm days reached 25–42 days per year in the Caspian Sea shore from 1936 to 1995. While in agricultural regions and Amu Darya River valley, the days with dust storms can be high up to 40–70 each year. The Karakum Desert and western part of Turkmenistan are considered to be two of the most active sources of dust storms in Central Asia, and dust storms here reoccur nearly throughout the year. In the southeastern Karakum, the dust storm days were up to 68–83 for each year, Central Karakum (85–113), and the western Turkmenistan (106–146). In most plain areas of Turkmenistan, the peak frequency of dust storms occurs in spring and summer, while in mountainous regions, additional activities happen in winter or autumn. Observation data on dust storms of most Central Asian meteorological stations in the last 30 years of the twentieth century uncovered a clear decline trend of dust storm activities over Central Asia, which was most significant over the Karakum Desert where dust storm activities decreased from annual mean value more than 30 days to less than 20 days (Indoiu et al. 2012). The slight decrease trend may be explained by fixing sand control measures and other activities which have been done against deflation processes in recent decades in the region.

Except for regular record of dust events from local meteorological stations, another efficient mean is satellite remote sensing. It is capable of providing timely, long-term, and large dimensional observation of aeolian dust and aerosol, which can help fully evaluate the importance of different sources (Washington et al. 2003). Remote sensing is an important tool for monitoring the aeolian dust cycle and may be the only source of the dust information in some places where there are no meteorological stations. For example, in the sparsely populated region of Central Asia, the daily satellite data are one of the most convenient sources of information about the intensity and duration of dust storms (Spivak et al. 2012). Nowadays, different satellite-based platforms have been widely used to monitor and collect data regarding dust emission sites and trajectories of dust aerosol movement such as Advanced Very High Resolution Radiometer (AVHRR), Total Ozone Mapping Spectrometer (TOMS), METEOSAT, Geostationary Operational Environmental Satellite (GEOS) series, Sea-Viewing Wide Field-of View Sensor (SeaWiFS), and Moderate Resolution Imaging Spectroradiometer (MODIS). The above-listed high

Table 5 Average number of days per year with dust events in Central Asia (Breckle et al. 2011)

Meteorological station	Period		Geographical site of the station
	1960–1979	1980–1990	
Karakalpakya	6	20	Ustyurt Plateau
Muinak	11	4	Amu Dyara Delta
Nukus	20	9	Amu Dyara Delta
Chimbai	14	11	Upper Amu Dyara Delta
Tamdy	18	8	Kyzylkum
Ajakagitma	16	6	Kyzylkum
Aralsk	80	88	Northern coast of the Aral Sea
Ujaly	32	13	Eastern coast of the Aral Sea
Kazalinsk	13	1	Syr Darya Delta
Saksaulski	65	34	Northern coast of the Aral Sea
Monsyr	43	29	Northern coast of the Aral Sea
Chirik-Rabat	14	3	Kyzylkum

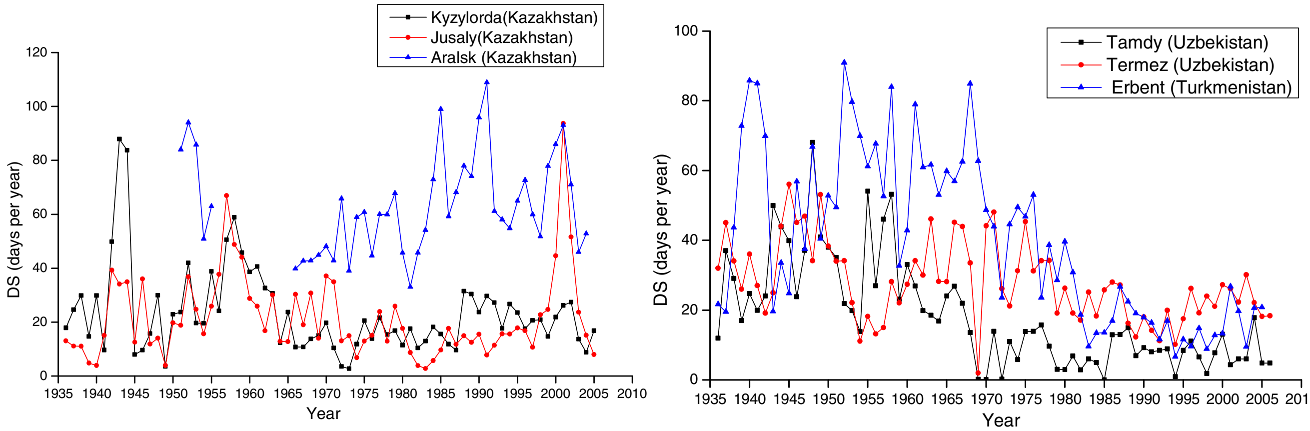


Fig. 3 Annual frequencies of dust storms recorded in different regions of Central Asia for the period 1936–2006 (in the Aralsk, the record was available for 1951–1955 and 1966–2006, Indoiu et al. 2012)

temporal resolution data as well as moderate spatial resolution data such as Landsat and SPOT play important role in the studies of aeolian dust (Chavez et al. 2002; Prospero et al. 2002). The TOMS aerosol index (AI), METEOSAT IDDI, and MODIS Rapid Response images are the three main methodologies, which have provided new insights into the dust cycle, identifying the major sources as predominantly endoreic drainage basins (White 2009). TOMS has proved to be one of the most important instruments for monitoring atmospheric dust, and the AI values can be used to map the spatial and temporal distributions of atmospheric aerosols and, correspondingly, the dust storm sources (Engelstaedter et al. 2006; Prospero et al. 2002; Washington et al. 2003). Since the mid-1970s, remotely sensed data have been adopted to track the major dust storms that deposit dust and salt over a considerable area adjacent to the Aral Sea in Uzbekistan, Kazakhstan, and Turkmenistan (Micklin 2010). For instance, Indoitu et al. (2015) applied AVHRR imagery, TOMS, and OMI AI maps to monitor the dust events originating from the desiccated bed of the Aral Sea and revealed the active dust emission sites in the study area.

Both of these two kinds of observation have their merits; more often, we make their respective advantage in the application to obtain much more accurate information about the aeolian dust. A study aiming to validate correlations between measured dust deposition, meteorological conditions, and TOMS AI suggested that dust storms in the Karakalpakstan were strongly controlled by seasonally changing surface erodibility parameters rather than erosivity and at temporal scales greater than 1 month can provide a prosper description of regional dust occurrence (Weaver and Wiggs 2006). Also, on the basis of satellite monitoring data and field observation, Issanova et al. (2015a) revealed the major sources of salt/dust storms that are located in the eastern shore of the Aral and Amu Darya Delta region, size distribution, and main transportation directions as well identified strong dust storms occurred in the Betpakdala Desert during October of 2005 and April of 2003 in the northern Caspian Sea.

Impact of aeolian dust on the ecosystems in Central Asia

Dust, sand, and salt storms originated from natural and anthropogenic deserts transport large amounts of deflated material over long distances, significantly affecting agricultural areas as well as human health in Central Asia. But only during periods of active dust production was there a significant contribution of dust to total absorption (Gills 1996; Micklin 2007; Hansen et al. 1993). Dust storms are very common in CAAZ, while salt dust storms are endemic in playas or salinized agricultural land, especially in the desiccated Aral Sea bottom, exposing areas of susceptible salty materials to wind erosion, with the annual blow-off of 43 million tons of salt (Goudie and Middleton 1992). They are particularly endangering human health as well as productivity of agricultural areas by enhancing salinization in adjacent farmland, directly resulting in decreased soil fertility and degradation of pasture. Salts in both dry and aerosol forms settle on natural vegetation and crops, particularly in the Amu Darya delta, and the most harmful of which are sodium bicarbonate ($NaHCO_3$), sodium chloride ($NaCl$), and sodium sulfate (Na_2SO_4) (Micklin 2010). Although plants are killed outright in some cases, their growth and yields are more substantially reduced. In addition, the soluble salt contained in aeolian dust could cause electrolytic corrosion damage and hinder social and economic development.

Meanwhile, heavy metals and other toxic substances posed pollution to air, water, and soils, causing serious harm to physical health of human and animals. Aeolian dust carries sulfates, phosphates, chlorinated hydrocarbons, and their ilk—fertilizers and pesticides whipped up from the bare floor of the shriveled Aral Sea and the poisoned land around it. The desiccation of the Aral Sea and its implications, which have been most severe for the population inhabiting its coastal regions, presented one of the major ecological catastrophes of the twentieth century (Saiko and Zonn 2000). There is considerable concern as to the impacts of toxic dust on human health that respiratory, digestive afflictions, and cancer result from inhalation and ingestion of blowing salt and dust (O'Hara et al. 2000). According to statistics data, the Aral dry seabed transported more than 650,000 t of toxic dust each year to downwind area which reached 2×10^6 ha in the south. People living in the region report an increase in the prevalence of respiratory illness, particularly in children (Wiggs et al. 2003). Uzbek government statics suggested that the incidence of childhood pneumonia in Karakalpakastan was the highest in the former Soviet Union. Its death rate from respiratory illnesses that reached 167 per 100,000 people in 1993 is among the world's highest (Stone 1999). In Turkmenistan, respiratory diseases are a major cause of illness and death among all age groups and 50 % of all reported cases in children are respiratory sickness in nature (UNDP 1997). It is widely believed, but little researched that this is due to the increased dust storm activity from the Aral Sea bed (Bennion et al. 2007). Based on the dose-response relationship method, scientists have explored the toxicological effect of salt dust on the heart, liver, lungs, and other tissues of oxidative damage. Local health experts take airborne salt and toxic dust as a contributing factor to high levels of respiratory illnesses and impairments, eye problems, and throat and esophageal cancer in the near Aral Sea region. Wiggs et al. (2003b) found that associations were statistically significant for all measures of dust exposure but were most marked for levels of winter dust and PM2.5 exposure. There is also evidence of a dose-related impact of aeolian dust on the risk of having abnormally low lung function in children of the region. Provisional analysis of the respiratory health data suggests that children living in the north of the country, where aeolian dust deposition rates are greater, show a lower frequency of respiratory problems. This inverse relationship requires further investigation but highlights the complexities of environmental and human health inter-relationships (Wiggs et al. 2003a). The low prevalence of asthma in the Aral Sea appears to be unrelated to dust exposure, so that exposure to dust did not explain the main variations in lung function between geographical regions. However, high levels of dust exposure during summer may have an adverse effect on lung function. Further investigations are required to establish which factor is the most important as a prelude to effective interventions (Bennion et al. 2007).

It has been accepted that aeolian dust plays a major role in soil formation. For example, the well-known loess that is one of major soil types and important climatic records around the world was formed by the aeolian dust deposition in ancient time. Evidence is growing that desert dust is influencing nutrient budgets within marine and terrestrial ecosystems far from the source. On the other hand, aeolian dust would lead to the expansion of desertification, and the salty dust has become another incentive of soil salinization except groundwater. Salt dust deposited on vegetation and crops may lead to reduced growth and lower yields as the plant expends more energy to extract water and to survive under stressed conditions (Rhoades and Goudie 1990). The degree to which salt effect vegetation is dependent on the tolerance of the individual plant to salt (native desert plants like spars folia and wolfberry were hardly affected, while oil sunflower and corn once were contaminated by salt dust, their leaves immediately withered and turned yellow) and the stage of its growth, the most sensitive period being during the seedling stage (Rhoades and Goudie 1990).

In terms of response of water resources (mainly refer to ice and snow) to aeolian dust, the dust settled on the surface of ice and snow during the transport plays an important role in their mass balance and chemical composition. Short-term (6 months to 17 years) glacio-chemical records of ice core and snow collected from the mountains of Central Asia suggested that the spatial distribution of snow chemistry in this region is controlled predominantly by the influx of dust from the arid and semi-arid regions in Central Asia (Wake et al. 1993, 1994). It is widely known that salt and dark material in aeolian dust deposited on surface can accelerate the melting of snow and glaciers by disturbing the ice structure and absorbing more heat, and the chloride salt is now often used as snow removal salt of road. The salty dust increased the proportion of liquid precipitation, melting of glaciers and alpine glacier, and posed a serious threat to the ice and snow security that is the main freshwater supplies in Central Asia.

Actually, as a common natural phenomenon in the arid environment, aeolian dust has become an important part of the geochemical cycle, though the aeolian dust surely poses so great negative impacts on the local environment and ecosystems in Central Asia. Dust has some unique positive effect and should be taken as component of the ecological system. For example, it could not be ignored that the influence of nutrient-rich dust (like nitrogen, phosphorus, potassium, iron, trace element that could promote plant growth) on plants should be positive. On the other hand, aeolian dust that enters into the high atmosphere could do some good to the planet energy budget and precipitation process. More specifically, its umbrella effect could compensate for some of the global warming caused by rising greenhouse gas, and the increasing availability of cloud condensation nuclei (CCNs) in the atmosphere would no doubt augment the probability of precipitation, which especially means more in arid land. However, because the associated studies in Central Asia were so less in the published literature in English, we did not offer the review and discussion on this aspect.

Concluding remarks and future directions

There are general indications that dust may be the only aerosol that has the potential to increase or decrease atmospheric temperature and by a similar order of magnitude to CO_2 (IPCC 2001). Despite the remarkable progress made in dust research over the past three decades or so, many challenges remain in Central Asia. There is only scope in this review for us to focus on the main issues. Most of these studies above were confined by the available data and short periods of their observations and gave only a first impression on the development of dust storms in Central Asia. At present, reliable ground data, however, are collected only sporadically, so the knowledge about the spatial and temporal distribution and dynamics of the dust deposition in the Aral Sea basin is fragmented and inconsistent at best. Further study on spatial and temporal dynamics of salt and dust storms not only the successive years of observational data are essential to strengthen cooperation between the regions.

Many investigations suggest that there is a good connection between dust activities and climate change (Huang et al. 2011; Goudie 2009; IPCC 2007). However, the response of dust activities to global change in the CAAZ remains extremely confusing. Although the aeolian transport of dust is a natural process, its intensity and impacts can be amplified in regions where an anthropogenic component is added, as is the case of Aral Sea basin in Central Asian, where human activities have indeed accelerated the lake dried up process and promoted the dust storm occurrence. In most cases of soil salinization, salt accumulation in topsoil is driven by the evaporation of groundwater. But now, salt in dust storm provided a new way to evoke the process, which is the so-called salt comes with wind. The superposition of both further intensified salinization degree, while the contribution of each is still unclear. What was worse, it appears in the foreseeable future that the area of deserts around the former Aral Sea bed outside the deltaic areas will experience a further decline in groundwater levels. Under the current conditions of increasing aridization, aeolian processes here will be further accelerated (Saiko and Zonn 2000).

As reviewed above, studies of dust impact upon ecosystems of Central Asia are still at an early stage. With respect to the unique toxic dust storms in those desiccated salt lake basins, few data exist on the dust's constituents (Stone 1999). Urgently, the risk assessment of human health exposure to highly contaminated dust for inhabitant in the affected area needs to be done. Possible ecological impacts of dust upon forest, crops, and glacial seem to be negative, while nutrient-rich dust impacts upon plants should be positive. Last but not the least, the significant effects of dust and associated aerosols upon regional and global climate is still unmeasured.

In some cases, no vegetation cover may be more resistant to deflation, for example, in desert gravel surface where the loose fine particles are very few. In general, threshold friction velocities of soil consisted of high content of fine grains are the lowest, such as Takyrs and Takyr-like soils, while the salt crusts with more coarse grains had the highest, which indicates that the former two types are most erodible and salt crust the least. These differences can be explained by the presence of salts that create tightly packed large aggregates and more cohesive fine-grained materials in the soil crusts. Given this principle, wind erosion strength of soil can be weakened by creating crusts on land surface which has the same effect of tree planting. But once the crusts were ruptured, strong deflation commenced (Argaman et al. 2006). Besides, other efficient measures to weaken soil deflation include maintaining a high water table in the soils/sediments as well as the applications of chemical stabilizers. Therefore, it was suggested to make the dry lakebed be submerged again and control potential wind erosion by increasing the income runoff of the lake. However, the current inflowing runoff cannot satisfy the lake's high demand; therefore, this solution is not applicable.

During the past three decades, there have been interesting variations in dust deposition observed in Central Asia. Indoitu et al. (2012) reported a notable declining trend of dust storm activities and explained that it could be to some extent attributed to the recovery of desert ecosystems because human disturbances have gradually weakened and meanwhile some protection measures have been made in the region since 1980s. Moreover, the same decreasing trends were registered throughout the world, which suggested that the impact of global climate change rather than anthropogenic activities must be the major factor for aeolian dust in Central Asia. Still, it is seemed to be impossible to make a detailed prediction of dust events in the future. Nonetheless, the area of the desiccated seafloor or playa with smaller size and higher salt content particles will expand in the foreseeable future and will increase the dust transported distance as well the affected dimensions. Due to lacking associated studies, we still do not get exact information about the chemical components of erodible soil and aeolian dust, as well the spectral properties of the dust plumes. Still, we need more observation data on the wind regime, the dust emission fluxes, and the size distribution of dust profile along transport route. However, because of out of fund or lacking focus monitoring program of such data and even basic data of dust emitted from the significant sources like the Aral Kum and Kara Kum had suspended instead of strengthening and improving observation system for further studies in the future.

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