Chapter 8
Climate Change Implications and Use of Early Warning Systems for Global Dust Storms

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Abstract With increased changes in land cover and global climate, early detection and warning of dust storms in conjunction with effective and widespread information broadcasts will be essential to the prevention and mitigation of future risks and impacts. Human activities, seasonal variations and long-term climatic patterns influence dust storms. More research is needed to analyse these factors of dust mobilisation to create more certainty for the fate of vulnerable populations and ecosystems in the future. Early warning and communication systems, when in place and effectively implemented, can offer some relief to these vulnerable areas. As an issue that affects many regions of the world, there is a profound need to understand the potential changes and ultimately create better early warning systems for dust storms.

Keywords Dust • Transboundary • Climate change • Aerosols • Early warning • Forecasting

8.1 The Need for Early Warning

While climate change will increase temperatures, desertification and frequency of drought across different parts of the world (IPCC 2007), and thus possibly increase the potential for dust storms (Wilcox 2012; Shao et al. 2011), the actual impact of climate change on dust storm frequency and severity is unknown. Impacts of climate change can be exacerbated by human activities which already contribute to the intensity and frequency of dust storms (Yang et al. 2007; Ginoux et al. 2010). Additionally, different regions of the globe have high interannual, as well as annual

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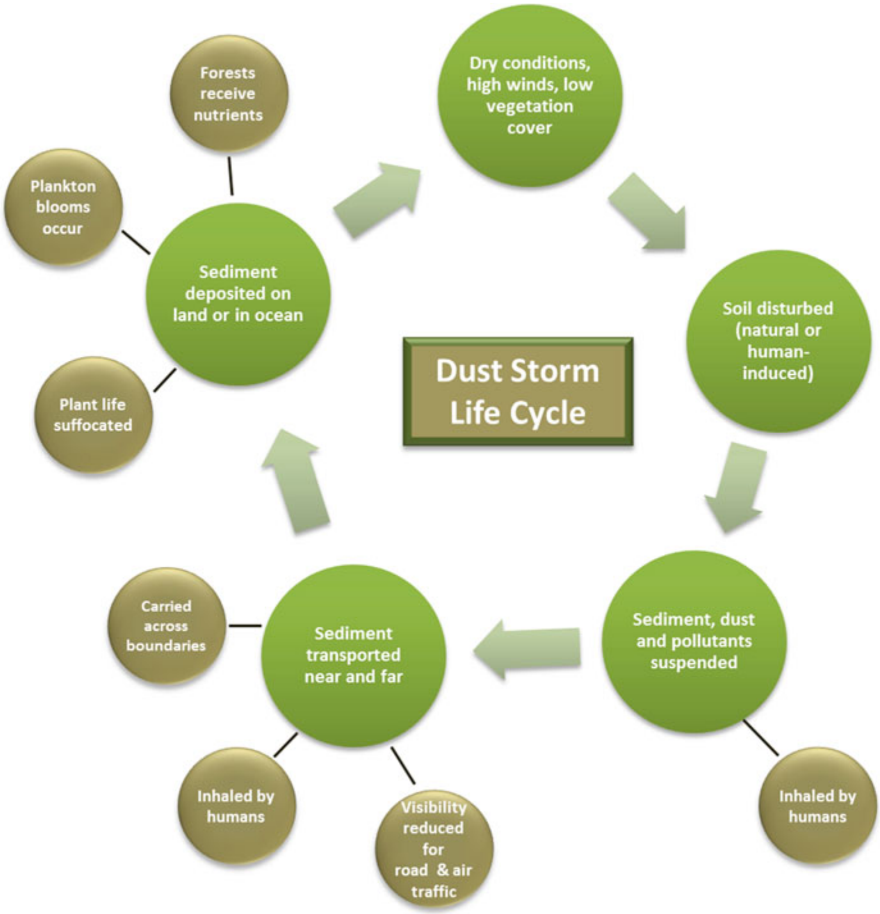

Fig. 8.1 Dust storm life cycle (Adapted from UNEP (2013), Shao et al. (2011))

and decadal, variability of dust events, thus furthering the need for more research to be conducted over longer periods of time to analyse trends of occurrences and associated severity (Ganor et al. 2010; Goudie 2009). The origin of dust storms, whether natural or human, and how aerosol circulation patterns are affected, need to also be evaluated to understand the ultimate impact on the global climate (Ginoux et al. 2010). With this accumulation of information, more accurate forecasts of dust storm movements can be developed, the appropriate efforts to mitigate damage can be put into place and effective early warning can be communicated.

The dust cycle is a dynamic process of emission, transport, transformation, deposition and stabilisation that occurs at both local and global scales on varying time scales (Shao et al. 2011) (Fig. 8.1). A thin crust, formed by desert soils, most prevalent in areas between plants, helps to stablise the ground surface and create a natural resistance to wind erosion. The plants protect surrounding soils from wind and trap suspended soil particles (Urban et al. 2009; Steenburgh et al. 2012; Wilcox 2012). A disturbance to the crust or a reduction in vegetation cover increases the risk of a dust storm occurrence, as the loosened sediments are free to be picked up by high winds. Dust storms can result in the deposition of foreign sediments on crops, blocking sunlight and causing them to suffocate. Dust particles and the pollutants they carry can contribute to compromised air quality and human health and can also influence climatic patterns and the energy balance of the earth system (Shao et al. 2011).

In general, early warning systems could help to contribute to three main elements necessary to prepare for a dust event: (1) communication of the actual event occurring, (2) its projected intensity and (3) its projected physical and geographic impact. With the first element, the general awareness of the event is heightened. The second and third elements of projected impacts can help people determine how to prepare for the dust event by taking measures such as evacuating, seeking cover, sealing doors and windows and securing outdoor assets such as vehicles, farming and manufacturing equipment. Additional preparation for farmers could include harvesting all or part of a crop early, if there is enough time before the dust storm hits (Stefanski and Sivakumar 2009).

8.2 Physical Characteristics of Dust Storms

8.2.1 Dust Storm Frequency and Origination

Dust storms can occur naturally or be induced by anthropogenic activity. A dust storm occurs naturally when high winds blow over soils that are vulnerable to surface disturbance (Wilcox 2012). Areas where soils have dried out due to prolonged drought or sudden dryness, or where there are a significant amount of dried out lakebed sediments, are also prone to dust storms. A dust storm that originated due to dried out sediments around Laguna Mar Chiquita in Argentina is pictured in Fig. 8.2. Anthropogenic activities that can cause or increase the chances or intensity of a dust storm include clearing of land for agricultural or infrastructure development, overgrazing and poor agricultural practice (Stefanski and Sivakumar 2009).

In dust storm-prone regions, storms can collectively occur on more than 300 days a year such as in Japan (MoE 2008) or fewer than 30 days a year[1] such as in the United States (NCDC/NOAA 2013). Approximately 2,000 teragrams (Tg) of dust is emitted into the atmosphere per year with land surfaces receiving 75 % of the dust that is redeposited and 25 % deposited in the ocean (Shao et al. 2011). The Sahara Desert region alone emits 500–1,000 Tg/year, making it the most significant

[1] Based on average number of dust days in the United States for the past 10 years reported in the U.S. National Climatic Data Center database.

Fig. 8.2 A dust storm occurred on 29 July 2012 near Laguna Mar Chiquita due to low lake levels and exposed, dried out sediment (NASA MODIS Aqua image, NASA 2012; visualisation by author)

regional contributor (Goudie 2009). Other dust-producing regions include the Middle East, the Taklamakan Desert in northwest China, southwest Asia, central/western Australia, the Etosha and Mkgadikgadi basins of southern Africa, the Salar de Uyuni (Bolivia) and the southwestern United States (NRL 2009; Washington et al. 2003; Shao et al. 2011). These dust-producing regions have minimal moisture saturation, as indicated by a high erodible fraction value[2] (Fig. 8.3).

[2] Erodible fraction value reflects land cover type and associated wetness.

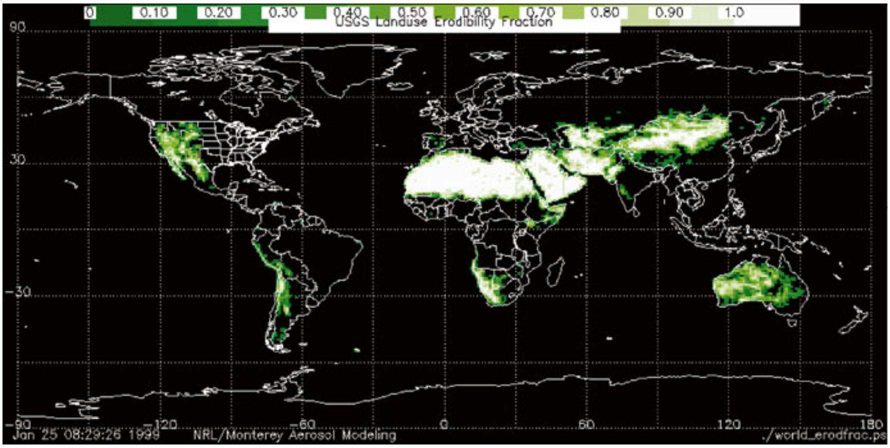

Fig. 8.3 Global dust-producing regions based on land-use erodibility fraction identified by the United States Geological Survey (NRL 2009)

8.3 Geographic and Climatic Implications

8.3.1 Transboundary Dust Travel

Dust storms not only impact their origin area, but also can impact land, water and people a great distance away where dust, and the particles it carries, finally settles. For example, dust particles originating in inner and southern Mongolia and northern China contribute to dust events in Japan, the Democratic People's Republic of Korea, the Republic of Korea and the Taiwan Province of China, causing seasonal 'yellow sands' and muddy rains (Lee and Liu 2004; Kimura 2012a, b). In the southern hemisphere, dust storms originating in eastern Australian can carry dust particles across the Tasman Sea to New Zealand, significantly contributing to soil development and geochemical cycles (Marx et al. 2009). As a result, creating policies pertaining to dust storm mitigation (i.e. vegetation restoration efforts) or developing early warning communication can be challenging. Further, since climatic changes will not affect all regions of the world in the same way or to the same degree, its influences on dust storms and their travel patterns is relatively unknown, thereby projecting uncertainty on populations that experience dust storms.

One of the most pronounced transboundary sources of dust is the Sahara Desert. Dust originating in the Sahara is frequently carried extended distances – east across the Nile Delta region and Mediterranean Sea, west across the Atlantic Ocean to the Caribbean, the USA, parts of Central and South America and north over to Europe. Dust originating in the Sahara has been reported as reaching as far east as Turkey in April 2012 (Mühr et al. 2013). This dust transport can negatively affect air quality, causing health and visibility problems (Prasad et al. 2010), but can also positively contribute to rainforests in Central and South America (Sivakumar 2005).

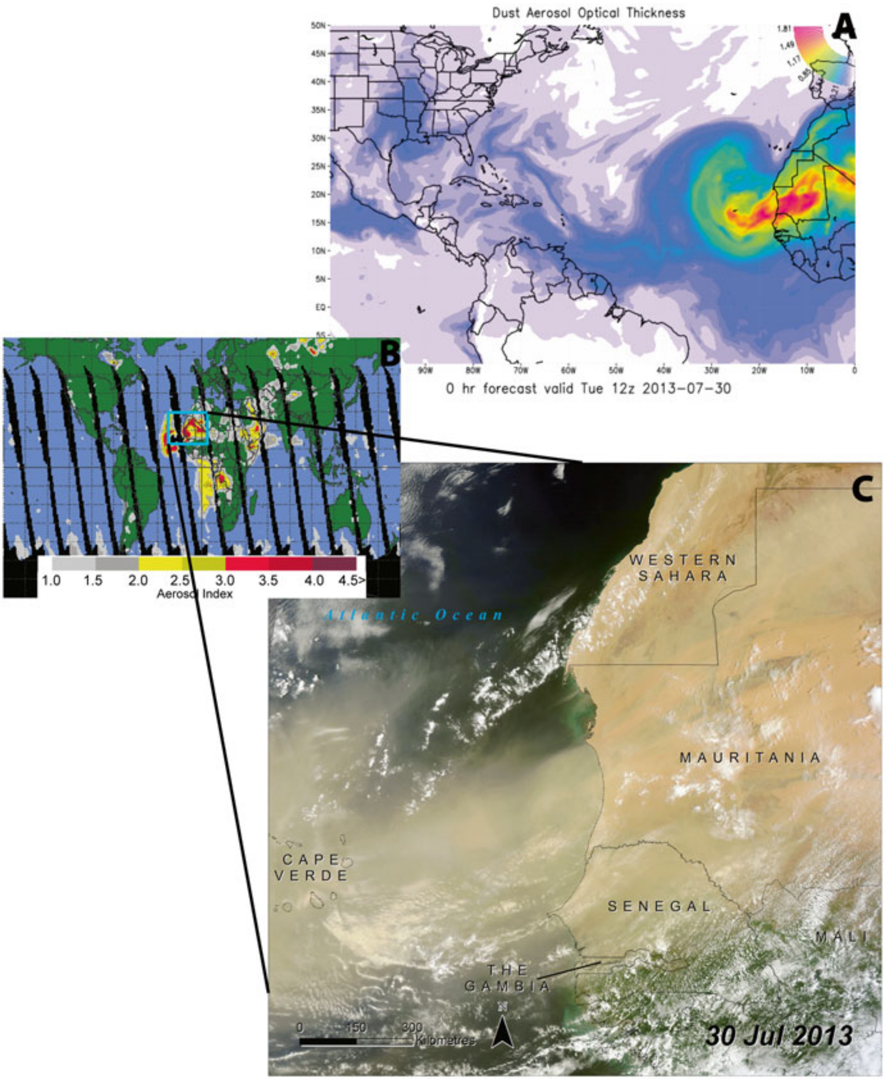

Fig. 8.4 (**a**) NASA/GMAO GEOS-5 0 hour forecast image of dust aerosol optical thickness from 30 July 2013 (NASA 2013b); (**b**) Image from NASA's OMI on the Aura satellite from 30 July 2013 (NASA 2013e); (**c**) NASA MODIS Terra satellite image from 30 July 2013 showing dust from the Sahara Desert blowing over the Atlantic Ocean and Cape Verde (NASA 2013c; visualisation by author)

Additionally, dust from the Sahara can also affect cloud development and precipitation patterns. There is some evidence that shows dust from this area can suppress tropical cyclone development, but more research is needed to confirm the claim (NASA 2013d). Figure 8.4 shows a dust storm that originated in the Sahara Desert blowing over Cape Verde and the Atlantic Ocean. The corresponding global aerosol index (AI)[3] image and the dust aerosol optical thickness image show how far offshore and over the Atlantic Ocean dust was actually being carried.

8.4 Climatic and Seasonal Variations with Transboundary Dust

Some regions are substantial dust producers year round, but seasonal changes can influence the level of dust intensity in other regions. For example, Asia experiences the most number of dust storms during its spring season, with the number peaking in April (Yang et al. 2007). Increased rainfall, snowmelt and onset of drought can influence the severity of dust events. The AI of an area is one method of identifying seasonal fluctuations in dust concentration. AI images show the presence of different aerosols, primarily dust.

Much like seasonal variations, climatic periods can also influence the frequency and intensity of dust storms. Through a comprehensive study of different regions in Northern China over a period of the past 1,000 years, Yang et al. (2007) found that the eastern arid regions experienced an increase in dust events during cold-dry periods compared to warm-wet periods as evidenced by increased amounts of dust found in ice cores. Vegetation cover was found to be relatively minimal during cold-dry periods, creating ideal conditions for dust mobilisation. Semiarid regions were also found to follow the same general correlation with dust events and cold-dry conditions, but correlated more strongly with precipitation patterns. From this observation, Yang et al. (2007) concluded that long-term precipitation changes more heavily influenced dust events than temperature changes did. Similarly, Marx et al. (2009) found that rates of Australian dust deposition varied with La Niña/El Niño patterns in which wet phases contributed to the addition of fine sediment to dust source areas, increasing the amount of sediment at the source as these new depositions dry out during dry phases and are available for transport. Climatic variations such as these need to be studied more in-depth at a regional level to understand the future implications of alterations to temperature and precipitation patterns that could be brought on by climate change.

8.5 Use of Modelling and Forecasting Networks for Early Warning Detection

The transboundary movements and issues previously discussed warrant the need for global dust storm forecast networks to help predict the onset, duration and path of a dust storm for the protection of both humans and the environment. While some

[3] The AI is a measurement of absorbing aerosol particles such as dust and smoke and is commonly used to identify dust source areas (NRL 2009; Washington et al. 2003). The AI is obtained using NASA's Ozone Monitoring Instrument (OMI) on NASA's Earth Observing Satellite Aura (NASA undated).

countries have been monitoring dust events for 50 years or more (Wang et al. 2008; Shao et al. 2011), others have not. Models can help to close the data gap that exists in long-term meteorological data collections. Forecasts, derived from models, help decision-makers and scientists gather information about where and how fast a storm is moving. Information can be used by officials to deliver early warning information and by scientists to study patterns, as well as by medical officials and policymakers who can use forecast information to aid in determining the role of dust storms in origin and transport patterns of pathogens and disease (Stefanski and Sivakumar 2009).

Both regional and global models are essential for creating accurate forecasts due to variations in dust events across the globe. For example, March to May 2012 was an extremely active year for dust storms over the northern tropical Atlantic Ocean, the Arabian Peninsula, the northern Indian Ocean and the United States (Benedetti et al. 2013). However, during the same period, China experienced fewer dust storms than normal (10 instead of 17) and northern China had the least number of dust days since 1961 (Zhang et al. 2013). Furthermore, on the western edge of China, Mongolia experienced frequent dust storms, even a few particular days of extensive damage across the country in April.

An example of a regional model is the CUACE/Dust (Chinese Unified Atmospheric Chemistry Environment for Dust) model, which is used to produce forecasts for up to 3 days and is considered a quality model for dust events in East Asia (Wang et al. 2008). The model also has the ability to provide scientists and forecasters with information to make more educated impact projections because the model can provide insight about the distribution of desert and semi-desert land cover types, soil grain size, soil moisture content, snow cover and land use (Zhou et al. 2008). Alternatively, the Dust Regional Atmospheric Model (DREAM), utilised by the Barcelona Supercomputing Centre (BSC) and the United States National Weather Service (NWS), applies a global model to different regions and most extensively in the Mediterranean, North Africa and Middle East regions (NASA 2013a). With open online access, the BSC offers animated cycles of forecasts, using the 8b version of the DREAM model, in 6-h intervals from real time to 72 h in the future, for four substantial dust-producing regions in the world (BSC 2012). Forecasts using models such as the DREAM help to not only identify the immediate location of a dust particle, but also to determine point (or points of origin) and the anticipated path of the storm.

Other methods of creating forecasts and early warning information include using Light Detection and Ranging (LiDAR) data which allows for real-time monitoring. For example, the Ministry of Environment in Japan uses LiDAR to measure the presence of yellow sands and distinguish dust particles from other pollutants. The information is then incorporated into regional dust and sand storm monitoring networks to warn citizens of incoming dust storms as opposed to haze caused by pollutants. Ground-based global networks such as the Global Atmosphere Watch Aerosol LiDAR Observation Network (GALION) also use LiDAR data from several different regions and help to create a more complete picture of dust movement and the global dust cycle (Shao et al. 2011).

8.6 Early Warning Information Dissemination

An early warning message is only as effective as its method of delivery and interpretation. There are many ways to communicate messages with today's technology including text message alerts, national and regional news broadcasts, website updates, email alerts and broadcasted warning signals through small communities. (Methods and challenges of early warning communication are further discussed in later chapters.) Most commonly, weather networks observe dust conditions (Shao et al. 2011) and disseminate the information (Davidson et al. 2003). The World Meteorological Organisation (WMO) has operated one of the most extensive forecasting networks since 2007. As described on the WMO website, the WMO Sand and Dust Storm Warning Network (SDS-WAS) is comprised of two nodes covering four regions: (1) Africa, the Middle East and Europe and (2) Asia (WMO undated).

Technological advances have encouraged information dissemination through websites and cell phone text messages. For example, the website for the Asia/Central Pacific Regional Centre with the SDS-WAS has a colour index with accompanying explanations to describe the severity of an impending dust event and China, which is included in this region, uses this information to display symbols to the public indicating time until a dust storm will occur (Zhang et al. 2007; WMO 2013). Text message, or SMS, warnings can also be used to instantly alert widespread populations of impending danger. Since 2012, the US NWS has supported a free Wireless Emergency Alert (WEA) service that delivers alerts to WEA-enabled mobile phones. The alerts warn of many types of hazards, including dust storms, and also offer suggestions of how to handle the situation, such as to avoid travel (NWS and NOAA 2013). However, with both websites and text messaging, if a vulnerable region does not have supporting infrastructure for Internet and cell phone alerts, then alternative means of communicating early warning information need to be developed.

8.7 Future Outlook

To increase the effectiveness of current forecasting and early warning initiatives, and to make future ones successful, some steps need to be taken. Primarily, several areas of research (Table 8.1) need to be addressed. The use of meteorological data and remote sensing information from satellite imagery could be used to complete much of this research (Stefanski and Sivakumar 2009; Urban et al. 2009; Kimura 2012b). In addition, increased awareness about forecast availability and education pertaining to how to interpret a forecast is needed to better prepare vulnerable populations and work towards mitigating the effects of dust events.

Efficient and effective early warning systems, used not only to broadcast safety information for local populations, but also to predict drought conditions to prevent human-induced dust storms, can become more mainstream for current and future dust events. Global systems are also needed to address transboundary dust movements

Table 8.1 Research aspects needed for the development of future forecasting and early warning

Research aspect	Specific area of study	Outcome
Atmospheric conditions	Localised ground station monitoring (i.e. of air quality, wind speed and direction, aerosol concentrations, etc.)	Improved regional models, more accurate forecasts and extended length of valid forecasts; improved ability to determine where a dust storm originates
	Increase record-keeping of seasonal and climatic trends, including those projected with regional climate change implications	More accurate forecasts and extended length of valid forecasts
	Dust model validation for global and regional models	Improved models and forecasts
Origin point of storm	Differentiate between dust storms originating because of climate change conditions and those caused by human activities	Improved ability to understand human impact on land and climate influences
	Research geomorphological characteristics of the land such as topography, glacial presence and particle composition to refine the extent of dust source areas	Contribute to improved and more specific regional forecasts and early warning efforts
Impacts	Dust implications on health	Determine what is being caused by dust storms as opposed to other environmental factors; create better preparation and prevention plans
	Continue studies on transboundary issues such as dust transport from the Sahara and its role in tropical storm formation and intensification	Create better understanding of the impact dust has on the climate and what that means for future climate change
Mitigation efforts	Measure and evaluate aid and risk reduction activities such as re-vegetation projects (i.e. Grain to Green Program in China)	Improvements on existing programmes can be made or those that are not effective can be stopped; more specific and result-driven programmes can be developed for the future
	Develop policies and practices regarding land use, development, desertification and any other risk increasing activity	Attempt to reduce the possibility or intensity of future dust storms
Early warning systems	Measure and evaluate effectiveness of existing methods of early warning information dissemination and their influence in increasing preparedness and decreasing impact costs and severity	Determination of information best-practices for future warning systems

Compiled from Leys et al. (2011), Wang et al. (2008), Ginoux et al. (2010), Yang et al. (2007), de Longueville et al. (2013), Thalib and Al-Taiar (2012), NASA (2013d), Kimura (2012a), Shao et al. (2011)

and effects. With impending climate change and a growing global population, consensus exists that additional research to fully understand the life cycle and prevalence of dust storms is needed.

References

Benedetti A, Jones LT, Inness A et al (2013) Global climate: aerosols. In J. Blunden & D.S. Arndt (eds), State of the climate in 2012. Bull. Am Meteorol Soc 94(8):S34–S36

BSC (2012) BSC-DREAM8b v2.0 Atmospheric Dust Forecast System. Barcelona Supercomputing Center Earth Sciences. http://www.bsc.es/projects/earthscience/BSC-DREAM/. Accessed 1 Sep 2013

Davidson J, Lam H, Lam CY et al (2003) Considerations in bilateral or regional exchange. In: Kootval H (ed) Guidelines on cross-border exchange of warnings. WMO, pp 13–16. http://www.wmo.int/pages/prog/amp/pwsp/pdf/TD-1179.pdf

de Longueville F, Ozer P, Doumbia S et al (2013) Desert dust impacts on human health: an alarming worldwide reality and a need for studies in West Africa. Int J Biometeorol 57(1):1–19

Ganor E, Osetinksy I, Stupp A et al (2010) Increasing trend of African dust, over 49 years, in the eastern Mediterranean. J Geophys Res 115, D07201

Ginoux P, Garbuzov D, Hsu NC (2010) Identification of anthropogenic and natural dust sources using Moderate Resolution Image Spectroradiometer (MODIS) Deep Blue level 2 data. J Geophys Res 115(D5, 16):D05204

Goudie AS (2009) Dust storms: recent developments. J Environ Manage 90:89–94

IPCC (2007) Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Switzerland, Geneva

Kimura R (2012a) Effect of the strong wind and land cover in dust source regions on the Asian dust event over Japan from 2000 to 2011. Sci Online Lett Atmos 8:77–80

Kimura R (2012b) Factors contributing to dust storms in source regions producing the yellow-sand phenomena observed in Japan from 1993 to 2002. J Arid Environ 80:40–44

Lee H, Liu C (2004) Coping with dust storm events: information, impacts, and policymaking in Taiwan. TAO 15(5):1035–1060

Leys J, Heidenreich SK, Strong CL et al (2011) PM10 concentrations and mass transport during "Red Dawn" – Sydney 23 September 2009. Aeolian Res 3:327–342

Marx SK, McGowan HA, Balz KS (2009) Long-range dust transport from eastern Australia: a proxy for Holocene aridity and ENSO-type climate variability. Earth Planet Sci Lett 282:167–177

MoE (2008) Dust and sandstorms. Ministry of Environment Japan. http://www.env.go.jp/en/earth/dss/pamph/pdf/full.pdf. Accessed 20 Oct 2013

Mühr B, Ehmann C, Bissoli P et al (2013) Regional climates: Mediterranean, Italy, Balkan states. In Blunden, J & Arndt, DS (eds), State of the climate in 2012. Bull Am Meteorol Soc 94(8):S178–S179

NASA (undated) OMI Ozone Monitoring Instrument. National Aeronautics and Space Administration. http://aura.gsfc.nasa.gov/instruments/omi.html. Accessed 26 Aug 2013

NASA (2012) Dust Storm in Argentina. National Aeronautics and Space Administration Earth Observatory. http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=78715. Accessed 28 Aug 2013

NASA (2013a) Dust REgional Atmosphere Model. Goddard Space Flight Center National Aeronautics and Space Administration. http://gcmd.nasa.gov/KeywordSearch/Metadata.do?Portal=GCMD_Services&KeywordPath=ServiceParameters%7CMODELS%7CATMOSPHERIC+GENERAL+CIRCULATION+MODELS&EntryId=ATOM_ARIZONA_DREAM&MetadataView=Full&MetadataType=1&lbnode=mdlb1. Accessed 20 Oct 2013

NASA (2013b) GMAO 2D ChemMaps: dust Aerosol Optical Thickness. National Aeronautics and Space Administration. http://portal.nccs.nasa.gov/cgi-fp/fp_2d_chem.cgi?region=hs3&prod=

1dustaot&model=fp&tau=000&&region_old=hs3&dtg_old=2013082812&prod_old=1dustaot&model_old=fp&tau_old=000&&loop=0&dtg=2013073012. Accessed 28 Aug 2013

NASA (2013c) MODIS Terra West Africa 11:40 UTC. Rapid Fire Image Gallery National Aeronautics and Space Administration. http://rapidfire.sci.gsfc.nasa.gov/imagery/gallery/2013211-0730/WestAfrica.A2013211.1140.2km.jgw. Accessed 26 Aug 2013

NASA (2013d) NASA's 2013 HS3 Hurricane Mission to Delve into Saharan Dust. National Aeronautics and Space Administration. http://www.nasa.gov/mission_pages/hurricanes/missions/hs3/news/saharan-dust.html#.Uf02Mayt-40. Accessed 26 Aug 2013

NASA (2013e) OMI Aerosol Index. National Aeronautics and Space Administration. http://ozoneaq.gsfc.nasa.gov/OMIAerosol.md. Accessed 26 Aug 2013

NCDC/NOAA (2013) Storm Events Database. National Oceanic and Atmospheric Administration National Climatic Data Center. http://www.ncdc.noaa.gov/stormevents/. Accessed 03 Sep 2013

NRL (2009) Description of NAAPS (Navy Aerosol Analysis and Prediction System) Global Aerosol Model. Naval Research Laboratory. http://www.nrlmry.navy.mil/aerosol/Docs/globaer_model.html. Accessed 27 Aug 2013

NWS and NOAA (2013) Weather warnings on the go! Weather Ready Nation National Oceanic and Atmospheric Administration. http://www.nws.noaa.gov/com/weatherreadynation/wea.html#.UmK8jhukpVJ. Accessed 19 Oct 2013

Prasad AK, El-Askary H, Kafatos M (2010) Implications of high altitude desert dust transport from Western Sahara to Nile Delta during biomass burning season. Environ Pollut 158(11):3385–3391

Shao Y, Wyrwoll KH, Chappell A et al (2011) Dust cycle: an emerging core theme in Earth system science. Aeolian Res 2:181–204

Sivakumar MVK (2005) Impacts of sand/dust storms on agriculture. In: Sivakumar MVK, Motha RP, Das HP (eds) Natural disasters and extreme events in agriculture. Springer, Berlin, pp 150–177

Steenburgh WJ, Massey JD, Painter T (2012) Episodic dust events of Utah's Wasatch front and adjoining region. J Appl Meteorol Climatol 5(9):1654–1669

Stefanski R, Sivakumar MVK (2009) Impacts of sand and dust storms on agriculture and potential agricultural applications of a SDSWS. IOP Conf Ser Earth Environ Sci 7:012016

Thalib L, Al-Taiar A (2012) Dust storms and the risk of asthma admissions to hospitals in Kuwait. Sci Total Environ 433:347–351

UNEP (2013) Forecasting and early warning of dust storms. Global Environmental Alert Service. Division of Early Warning and Assessment United Nations Environment Programme. http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=96. Accessed 1 Sep 2013

Urban FE, Reynolds RL, Fulton R (2009) The dynamic interaction of climate, vegetation, and dust emission, Mojave Desert, USA. In: Fernandez-Bernal A, De La Rosa MA (eds) Arid environments and wind erosion. Nova Science Publishers, Inc., New York, pp 1–25

Wang X, Xia D, Wang T et al (2008) Dust sources in arid and semiarid China and Southern Mongolia: impacts of geomorphological setting and surface materials. Geomorphology 97:583–600

Washington R, Todd M, Middleton NJ et al (2003) Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations. A Assoc Am Geog 93(2):297–313

Wilcox B (2012) Dust Storms Roll Across Arizona. United States Geological Survey Science Features. http://www.usgs.gov/blogs/features/usgs_top_story/dust-storms-roll-across-arizona-2/. Accessed 3 Sep 2013

WMO (undated) Sand and Dust Storm Warning Advisory and Assessment System. WMO. http://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html. Accessed 3 Sep 2013

WMO (2013) Asia/Central Pacific Regional Centre. World Meteorological Organization. http://www.sds.cma.gov.cn:8080/business/website/mainPageIndex.do. Accessed 3 Sep 2013

Yang B, Bräuning A, Zhang Z et al (2007) Dust storm frequency and its relation to climate changes in Northern China during the past 1000 years. Atmos Environ 41:9288–9299

Zhang X, Gong S, Zhou CH et al (2007) CMA China Sand and Dust Storm Forecasting System & Asia/Pacific Regional Centre. Presented at the WMO/GEO Expert Meeting, Barcelona, Spain, 7–9 Nov 2007

Zhang P, Liu Y, Yamada R et al (2013) Regional climates: East Asia. In: Blunden J, Arndt DS (eds), State of the climate in 2012. Bull Am Meteorol Soc 94(8):S187–S188

Zhou CH, Gong SL, Zhang XY et al (2008) Development and evaluation of an operational SDS forecasting system for East Asia: CUACE/Dust. Atmos Chem Phys 8:787–798