A global satellite view of the seasonal distribution of mineral dust and its correlation with atmospheric circulation

O. Alizadeh-Choobari a,⁎, A. Sturman b, P. Zawar-Reza b

a Institute of Geophysics, University of Tehran, Tehran, Iran
b Center for Atmospheric Research, University of Canterbury, Christchurch 8140, New Zealand

ARTICLE INFO
Article history:
Received 10 February 2014
Received in revised form 12 July 2014
Accepted 15 July 2014
Available online 13 August 2014

Keywords:
Dust aerosols
Transport of mineral dust
Atmospheric circulation
Satellite data
Seasonal

ABSTRACT
Aerosols make a considerable contribution to the climate system through their radiative and cloud condensation nuclei effects, which underlines the need for understanding the origin of aerosols and their transport pathways. Seasonal distribution of mineral dust around the globe and its correlation with atmospheric circulation is investigated using satellite data, and meteorological data from ECMWF. The most important sources of dust are located in North Africa, the Middle East and Southwest Asia with an observed summer maximum, and East Asia with a spring peak. Maximum dust activity over North Africa and the Middle East in summer is attributed to dry convection associated with the summertime low-pressure system, while unstable weather and dry conditions are responsible for the spring peak in dust emission in East Asia. Intercontinental transport of mineral dust by atmospheric circulation has been observed, including trans-Atlantic transport of North African dust, trans-Pacific transport of Asian dust, and transport of dust from the Middle East across the Indian Ocean. The extent of African dust over the Atlantic Ocean and its latitudinal variation with season is related to the large-scale atmospheric circulation, including seasonal changes in the position of the intertropical convergence zone (ITCZ) and variation of wind patterns. North African aerosols extend over longer distances across the North Atlantic in summer because of greater dust emission, an intensified easterly low level jet (LLJ) and strengthening of the Azores-Bermuda

⁎ Corresponding author. Institute of Geophysics, University of Tehran, Tehran, Iran. Tel. +98 (21) 61118270.
E-mail address: omid.alizadeh@ut.ac.ir (O. Alizadeh-Choobari).

http://dx.doi.org/10.1016/j.dynatmoce.2014.07.002
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anticyclonic circulation. Transport of East Asian aerosol is facilitated by the existence of a LLJ that extends from East Asia to the west coast of North America.

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1. Introduction

Dust aerosols, the tiny soil particles in the atmosphere from both natural and anthropogenic sources, modify the radiation budget of the Earth-atmosphere system directly by scattering and absorbing solar and infrared radiation (McCormick and Ludwig, 1967; Miller and Tegen, 1998), semi-directly through changes in atmospheric temperature structure and the evaporation rate of cloud droplets (Hansen et al., 1997; Ackerman et al., 2000; Koren et al., 2004), and indirectly through impact on optical properties of clouds (Gunn and Phillips, 1957; Liou and Ou, 1989) and suppression (Ferek et al., 2000; Rosenfeld, 2000) or invigoration (Andreae et al., 2004) of precipitation formation. Additionally, dust aerosols degrade air quality (Prospero, 1999) and adversely affect human health (Pope et al., 2002). Dust is also a source of iron which is a nutrient for phytoplankton (Fung et al., 2000). Therefore, dust particles can affect marine biogeochemical processes, thereby contributing to the oceanic uptake of carbon (Jickells et al., 2005). Their contribution to the climate system and atmospheric environment is therefore of considerable significance, underlining the essential need for investigation into the origin of dust aerosols and their temporal variation, as well as their transport pathways in the atmosphere.

Mineral dust from wind erosion of dry soils is among the most abundant atmospheric aerosol components in terms of aerosol dry mass (Textor et al., 2006; Chen et al., 2007) and contributes more than half of the total global aerosol burden (Textor et al., 2006), with an estimated global annual burden of 17.4–35.9 Tg (trillion grams; Ginoux et al., 2001; Tegen et al., 2002; Luo et al., 2003; Zender et al., 2003) and a global annual emission of 1950–2400 Tg (Ginoux et al., 2004). Remote sensing analyses have shown that major sources of mineral dust are located in arid regions, including deserts, semi-arid deserts (with sparsely vegetated ground) and dry lake beds, where annual rainfall is extremely low (Goudie and Middelton, 2006), and substantial amounts of alluvial sediment have been accumulated (Prospero et al., 2002; Ginoux et al., 2012). In addition to these natural sources, human induced disturbance of the land surface and climate variability, have created anthropogenic sources of mineral dust (Prospero et al., 2002; Tegen et al., 1991) that have contributed to an increase in the wind-blown dust concentration within the atmosphere.

Despite their short atmospheric lifetime of 1–2 weeks, mineral dust aerosols regularly travel long distances of an intercontinental scale (Swap et al., 1992; Chin et al., 2007) and are occasionally transported a full circuit around the globe (Uno et al., 2009). Previous studies have used ground-based measurements, satellite data and model analysis to identify major sources of mineral dust aerosols and their transport pathways. Using the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) over the East Asian region, Huang et al. (2008) demonstrated that dust events are more frequent over Taklimakan, while less frequent and more intense over the Gobi desert. Their results also indicated that dust aerosols from these sources can reach to an altitude of 9 km where they are subject to long-range transport over eastern China and across the Pacific Ocean by the upper tropospheric westerly jets. Analysis of the first full year of the CALIOP dataset by Liu et al. (2008) revealed the spring peak of dust activity over Tibetan Plateau, with dust plumes reaching to the height of 11–12 km.

The influence of dust aerosols on the climate system and cloud properties has also been extensively studied. For example, a decrease of surface incoming shortwave radiation and atmospheric heating by dust layers was noted by several numerical analyses (e.g. Huang et al., 2009; Mallet et al., 2009) and from satellite observations (e.g. Kaufman et al., 2001). The net direct radiative forcing by dust at the top of the atmosphere (TOA) is controversial and both negative and positive radiative forcing was identified (Claquin et al., 1998; Liao and Seinfeld, 1998), although general agreement is that it is negative over the ocean where shortwave backscattering dominates, while positive above high surface albedos (such as deserts) and clouds where shortwave and/or longwave absorption dominates (e.g. see Claquin et al.,...
Observational analysis of Huang et al. (2006) over East Asian region demonstrated that due to the semi-direct effect of mineral dust the water path of dust-contaminated clouds is considerably smaller than that of dust-free clouds. Analysis of various satellite data over northwestern China revealed that dust aerosols substantially reduce ice cloud effective particle diameter, optical depth and ice water path of cirrus clouds. These changes in cloud microphysics lead to a reduction of negative radiative forcing by clouds (Huang et al., 2006).

Strong regional and seasonal variation of mineral dust distribution within the atmosphere has been observed and simulated (e.g. Tegen and Fung, 1994; Kaufman et al., 2005; Gong et al., 2012). Such high temporal variability of atmospheric dust load suggests that there is a correlation between emission and transport of dust aerosols with seasonal variation of atmospheric circulation, but studies that have highlighted this correlation are limited. In particular, seasonal variation of the vertical distribution of mineral dust over major dust source regions around the globe is not well understood. As the extent of dust transport and its radiative forcing is sensitive to the height of particles (Chung and Zhang, 2004), estimates of the seasonal variation of the height of dust aerosols over major source areas need to be determined. The present study therefore aims to investigate the correlation between dust emission, dust transport pathways and its vertical distribution with the atmospheric circulation. To this end, this study utilizes long-term aerosol optical depth (AOD) data from the Multi-Angle Imaging Spectoradiometer (MISR), dust extinction coefficient profiles from CALIOP, and meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) dataset.

The credibility of satellite-derived dataset including MISR and CALIOP has already been evaluated. Using ground-based measurements, Diner et al. (2001) showed that AOD obtained from MISR has a positive bias of 0.02 and an overestimation of 10% over southern Africa. Qi et al. (2013) compared AOD retrieved from MISR with four AERONET sites in northern China for the period 2006–2009. They found relatively good performance of MISR, with only 14% bias in the Angstrom exponent. Comparison of MISR and AERONET AOD over desert sites where particles are larger was also conducted by Martonchik et al. (2004). Their comparison for a two-year period from December 2000 to November 2002 demonstrated very good performance, with no obvious systematic error. For example, for the retrieved AOD with a spatial resolution of 17.6 km and 52.8 km, the estimated uncertainty was only 0.08 and 0.05, respectively. The accuracy of the aerosol-above-cloud properties derived by CALIOP against the NASA Langley airborne High Spectral Resolution Lidar (HSRL-1) was recently examined by Kacenelenbogen et al. (2014). Their results indicate substantial underestimation of the occurrence frequency of aerosol above cloud when optical depths are less than 0.02. Underestimation of AOD by the CALIOP’s level 2 products was also noted previously by Kacenelenbogen et al. (2011).

The structure of the paper is organized as follows. Section 2 presents the observation data used in this study. Dust aerosol distribution within the atmosphere and their global seasonal variation is discussed in Section 3, while vertical distribution of mineral dust is the subject of Section 4. Section 5 provides an overall conclusion.

2. Observation data

The large spatial extent and high temporal variation of aerosols makes satellite data the best tool for monitoring their global coverage, although the retrieved values contain biases as a result of variability of surface albedo and contamination by clouds, as well as uncertainties associated with aerosol chemical and microphysical properties (Liu, 2005).

2.1. MISR

The MISR instrument was launched on board the sun-synchronized polar orbiting NASA Terra satellite in 1999 and has been used to measure aerosol optical depth (AOD) since February 2000. MISR observes at nine distinct zenith angles ranging from 70° afterward to 70° forward in four spectral bands centred at 446, 558, 672, and 866 nm (Diner et al., 1998). As a result, MISR can retrieve aerosol properties over both land and ocean including highly reflective land surfaces such as deserts (Martonchik et al., 2004). The data used here are the latest version of the MISR Level 3 seasonally mean AOD at 0.55 μm wavelength for the 11-year period (2001–2011) with a 0.5° × 0.5° horizontal
and 500 m vertical resolution. AOD retrieved from multiple orbits are combined to make complete Level 3 global maps. White regions in the satellite dataset indicate areas with no satellite measurements due to high surface albedo over snow covered surfaces at high latitudes, as well as persistent cloudiness over tropical regions.

2.2. CALIOP

CALIOP has been carried on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) spacecraft since April 2006 to measure aerosol optical properties at the global scale. CALIPSO is a sun-synchronized polar orbiting satellite which orbits the globe about 15 times per day, providing both day and night measurements (Winker et al., 2007, 2009). The data used here are long-term aerosol extinction coefficients at 0.532 μm for the 6-year period (2006–2011) available from the CALIOP Level 3 aerosol profile monthly products with a horizontal resolution of 2° (latitude) × 5° (longitude) and a vertical resolution of 60 m, and both daytime and nighttime CALIOP data are taken into consideration. Cloud-aerosol discrimination (CAD), an indicator to discriminate between clouds (positive CAD) and aerosols (negative CAD), is used to exclude extinction caused by clouds. Only aerosol layers having CAD scores between −100 and −20 are used because layers with CAD scores between 20 and −20 are often the result of erroneous layer detection triggered by noise. As stated in the introduction, unlike the retrieved aerosol extinction coefficients from MISR, values are generally underestimated by CALIOP. Several reasons for this underestimation are (1) regions that are identified as clear air by the CALIOP feature finder are assumed to have an aerosol extinction coefficient of 0.0 km−1; (2) multiple scattering is ignored in the CALIOP retrievals (Wandinger et al., 2010); (3) a fixed value of 40 sr at 0.532 μm is used in the CALIOP algorithm to retrieve mineral dust, which is lower than the lidar ratio of 55 ± 10 sr obtained from ground-based lidar observations (Wandinger et al., 2010); and (4) the other important reason is that the layer signals from dense aerosols and thin clouds are very similar in the CALIOP measurements, and the CALIOP can possibly misidentify the dense dust as the thin cloud (Chen et al., 2010).

2.3. ECMWF

ERA-Interim monthly averaged re-analysis meteorological data from 2001 to 2011, with a 0.75° × 0.75° horizontal resolution, provided by ECMWF are used in this study. ERA-Interim is the latest global atmospheric re-analysis dataset covering the period from 1 January 1979 onwards. A full description of the ERA-Interim dataset can be found in Berrisford et al. (2009).

3. Global seasonal distribution of aerosols

3.1. Africa

3.1.1. Spatial distribution

Satellite data indicate that mineral dust aerosols are present and notably high over tropical and subtropical North Africa and the Atlantic Ocean throughout the year (Figs. 1 and 2). In particular, the observed high AOD over subtropical North Africa (15–25° N) is related to extensive dust storm activities. Persistent high aerosol concentrations over the region suggest that North Africa is more affected by dust events than any other continent (Dwyer et al., 2000) as there is a large area over which dust can be lifted.

3.1.2. Temporal evolution

Significant seasonal variation in aerosol concentrations over Africa is observed (Figs. 1 and 2). Heavy aerosol loading is detected over North Africa during winter (DJF) and spring (MAM), spreading westward as far as South America (Figs. 1a and 2a). Mineral dust aerosols over the semi-arid Sahelian and Saharan regions partly contribute to such heavy aerosol-laden air over the North Atlantic Ocean in winter and spring. Indeed, it is believed that northeasterly Harmattan winds carry the dust from the Sahara and Sahel towards tropical Africa, causing westward transport of wind-blown dust
by easterly trade winds (Ben-Ami et al., 2009). The maximum AOD is observed over North Africa during summer (JJA) due to more frequent dust events. Large quantities of the summer dust plumes are carried by the easterly trade winds across the tropical Atlantic to the Caribbean, Central America and southern United States (Fig. 1b). Aerosol concentrations over North Africa and their westward transport across the North Atlantic Ocean is considerably reduced during autumn (SON, Fig. 1d).

More detailed analysis of the satellite data (Figs. 1 and 2) indicates that North African dust also drifts to the eastern and central Mediterranean during spring in association with the eastward passage of frontal systems (Goudie and Middleton, 2001), as well as to the central and western Mediterranean during summer. In contrast, dust transport to the Mediterranean is significantly reduced during autumn and winter when North African dust outbreaks are weakened. It should be mentioned that the easterly trade winds are prevalent over the tropical North Atlantic all year long and therefore have a significant contribution to the westward transport of dust plumes across the region, while the frontal systems discussed above are intermittent and occur mostly over mid-latitude regions, so that there is no consistent pathway for dust transport.

Seasonal latitudinal changes of aerosol distribution over the North Atlantic Ocean are also evident from satellite data presented in Figs. 1 and 2. In winter, the maximum AOD lies roughly between 8° S and 20° N, but migrates northward in spring when a heavy aerosol load is located between 5 and
Fig. 2. Similar to Fig. 1, with AOD (filled colours) and mean sea level pressure (contours, hPa) in (a) MAM and (b) SON. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

25° N. In summer, aerosol transport is more pronounced between 8 and 30° N over the west coast of North Africa, but becomes narrower over the middle and western Atlantic Ocean (farther away from sources of dust), ranging between 8 and 25° N. In autumn, aerosol plumes again retreat southward to the latitudinal range of 10–25° N.

3.1.3. Underlying atmospheric systems

Seasonal variation in the spatial distribution of aerosols over Africa and nearby oceans is related to the large-scale atmospheric circulation, which is manifested by seasonal changes in the position of the intertropical convergence zone (ITCZ; Sachs et al., 2009; Bain et al., 2011) and subsequent variations in the location and intensity of circulation centres (Engelstaedter et al., 2006; Engelstaedter and Washington, 2007; Klose et al., 2010). The ITCZ is characterized by the convergence of dry northeasterly trade winds blowing over the Sahara, the so-called Harmattan winds, and humid southeasterly winds originating farther south over the tropical Atlantic Ocean (Engelstaedter et al., 2006).

In spring and summer, the ITCZ shifts north and pushes the subtropical high-pressure belt to higher latitudes, allowing low-pressure systems to be established over North Africa, as shown in Figs. 1b and 2a. As a result, spring and summer months are characterized by depressions centred over North Africa (~23° N and 0° E, with an average central pressure of 1007 hPa in summer, as shown
in Fig. 1b). Although the observed dust emission is stronger in summer, near-surface wind speeds are generally lower at this time of year, suggesting that the increase of summertime dust activity is related to the establishment of low pressures associated with the ITCZ over North Africa. An increase of convection associated with the establishment of the ITCZ contributes to an increase in near-surface turbulence, which in turn increases dust emission over the Sahara (Engelstaedter et al., 2006). The significant contribution of convective processes for dust emission has been demonstrated in previous studies. For example, Koch and Renn (2005) estimated that 35% of the global dust budget is attributed to convective plumes and vortices. More recently, Heinold et al. (2013) indicated that convective cold pools are responsible for approximately 40% of dust emission over West Africa.

Farther south in the Sahel and southern fringes of the Sahara, the rainy season associated with northward movement of the ITCZ and invasion of southerly warm and moist air from tropical regions results in reduced dust activity in summer (Engelstaedter and Washington, 2007). In winter, on the other hand, the increased anticyclonic circulation over North Africa (Fig. 1a) counteracts the occurrence of low-pressure systems that are favourable for dust storms over the Sahara. Over the Sahelian region, however, the summertime southerly warm and moist air is replaced by the wintertime northerly dry continental flows, which tend to generate dust storms in desert areas (Tesche et al., 2011).

The extent of African dust over the Atlantic Ocean and its latitudinal variation with season is also related to changes in wind patterns over the region. During winter, the easterly low level jet (LLJ; Cook, 1999; Pu and Cook, 2010) at 700 hPa is located approximately between 0 and 10° N (Fig. 3a) where major amounts of Sahelian dust are transported over the tropical North Atlantic towards South America (Fig. 1a). The location of the LLJ in spring is quite similar to winter, but slightly intensified (compare Figs. 3a and 4a), causing longer distance transport of dust-laden air. In summer, there is longer westward transport of North African dust to the Caribbean, Central America and southern United States, partly due to significantly higher dust emission over the Sahara, although the location and strength of the easterly LLJ also contributes to such long-range transport. Indeed, the easterly LLJ is intensified in summer, extending from central North Africa to the Caribbean and Central America. It is also shifted north compared to winter and located between 10 and 20° N (Fig. 3b), the major dust pathway from North Africa to Central America (as shown in Fig. 1b). Note that while the summertime LLJ acts as a western corridor and causes the dust plumes to reach South America, this western corridor is shifted northwards in summer, causing dust particles to be mostly transported towards Central America. Longitudinal extension of the easterly LLJ is reduced during autumn (Fig. 4b), reaching around 30° W, causing the dust-laden air from North Africa to mostly reach the mid-Atlantic rather than the American continent (as shown in Fig. 2b).

During summer, when the maximum dust activity over North Africa and its westward spread over the North Atlantic is observed, the North Atlantic subtropical high pressure (Azores-Bermuda high (35° N); Iqbal et al., 2013) is intensified (with an average central pressure of 1025 hPa, as shown in Fig. 1b) and centred over the central Atlantic, but it becomes much weaker during other seasons. The Azores-Bermuda high extends from the Mediterranean Sea and west coast of North Africa to the eastern United States and Central America. The stronger clockwise circulation of the intensified summertime Azores-Bermuda high pressure is partly responsible for stronger near-surface easterly winds over the Atlantic Ocean (not shown). Not surprising, higher dust entrainment by the summertime convection processes over North Africa, combined with stronger near-surface and mid-troposphere wind speeds (as shown in Fig. 3b) over the tropical Atlantic Ocean, contribute to longer distance transport of African dust during summer. Note that the Azores-Bermuda high-pressure circulation also transports aerosol-laden air from the tropical North Atlantic into subtropical regions (Jickells et al., 1998; Goudie and Middleton, 2001).

3.2. Middle East and Southwest Asia

The MISR data clearly indicate that AOD values are notably high over the Arabian Peninsula and nearby seas during summer, extending from the Red Sea to the west and to northern India to the east (Fig. 1b). Aerosol concentrations still remain relatively high over the Arabian Peninsula during spring, but reduce substantially in autumn and winter, with the minimum observed values in winter. The maximum AOD in the spring–summer period is similar to that over North Africa, demonstrating
Fig. 3. Seasonally averaged horizontal wind speed (both shaded and vectors, $\text{m s}^{-1}$) at 700 hPa for (a) DJF and (b) JJA obtained from re-analysis ECMWF data for the period of 2001–2011.

that generation of dust over both regions is the result of similar atmospheric processes. However, unlike North Africa where large quantities of dust are carried westward by the easterly trade winds, dust particles from the Middle East are mostly transported eastward as mid-latitude westerlies are prevalent over the region (see Fig. 3).

The maximum dust emission and its transport over the Middle East during summer is the result of atmospheric circulation driven by surface low pressures. The mean summertime wind speed near the surface is relatively weak across the Arabian Peninsula (not shown), suggesting that wind speed is not the major reason for dust emission. More detailed analysis of the meteorological data shown in Fig. 1 indicates that the wintertime subtropical high pressure, which covers a large part of the Arabian Sea and Saudi Arabia, is replaced by a summertime extensive low-pressure system and high near-surface temperatures. Dry convection associated with this thermal low is responsible for a well-developed mixed layer and subsequent generation of dust storms over the Arabian Peninsula (Clemens, 1998). There is also extensive dust activity and therefore moderate observed AOD values along the Iran-Afghanistan border from late spring to late summer (Fig. 1b) due to the strong northerly “wind of 120 days” (Middelton, 1986; Alizadeh Choobari et al., 2013). Maximum dust activity over Pakistan and northwestern India in summer is due to the fact that this region is not affected by the summer monsoon, leaving the land surface sufficiently dry, and hence susceptible to wind erosion by strong...
Fig. 4. Similar to Fig. 3, with seasonally averaged horizontal wind speed (both shaded and vectors, m s\(^{-1}\)) at 700 hPa for (a) MAM and (b) SON for the period of 2001–2011.

winds and meso-scale thunderstorm activities typical of this time of year (Goudie and Middleton, 2000).

3.3. East Asia

Satellite data clearly indicate that the highest aerosol concentration over East Asia and its eastward propagation occurs during spring, followed by summer, with a rapid decrease during autumn and winter (Figs. 1 and 2). The spring peak is due to highly unstable weather and dry conditions (Sun et al., 2001). In contrast, East Asia is under the influence of strong Siberia–Mongolia high-pressure systems during winter (with an average central pressure of 1036 hPa centred at around 50° N and 95° E, see Fig. 3a). As a result of the land-sea thermal contrast, the northwesterly to northeasterly winds from the high pressures towards the oceanic regions create a winter monsoon over the region which is associated with reduced dust storm occurrence (Xu et al., 2006).

The Taklimakan desert of the Tarim Basin in northwestern China and the Gobi desert, east of the Tarim Basin in southern Mongolia and north central China, are two strong sources of dust in East Asia (see Figs. 1 and 2). These source areas have greater dust emissions during spring and summer,
with a larger contribution from the Taklimakan desert. Mineral dust particles originating from these regions and other minor source areas are transported over long distances across the continent and over the Pacific Ocean by predominant westerlies that are typical in spring over northern mid-latitudes, and ultimately reach as far east as North America (Zhao et al., 2006) and beyond. Such transport is facilitated by a westerly LLJ that lies between around 25–50° N all year long (except in summer when the LLJ is located roughly between 35 and 50° N), extending from East Asia to the west coast of North America (Figs. 3 and 4).

The Aleutian low reaches its maximum intensity in winter with an average central pressure of 998 hPa centred south of the Bering Sea off the northwest coast of Canada, while the subtropical North Pacific high is disrupted by the Aleutian low (Fig. 1a). In spring, the Aleutian low is notably weaker and centred farther east over the west coast of North America with an average central pressure of 1008 hPa, while the subtropical North Pacific high is located at around 30° N, extending from the western North Pacific to the west coast of North America. The Aleutian cyclonic circulation transports East Asian aerosols southward and the North Pacific anticyclonic circulation transports them northward. Where these two flows meet they turn eastward, thereby creating a channelling effect between the regions of low and high pressures. Consequently, a significant amount of the East Asian dust plumes is restricted and transported in eastward direction towards North America between roughly the latitude range of 30–60° N. The Aleutian low reaches its maximum intensity in winter with an average central pressure of 998 hPa centred south of the Bering Sea off the northwest coast of Canada, while the subtropical North Pacific high is disrupted by the Aleutian low (Fig. 1a). In spring, the Aleutian low is notably weaker and centred farther east over the west coast of North America with an average central pressure of 1008 hPa, while the subtropical North Pacific high is located at around 30° N, extending from the western North Pacific to the west coast of North America. The Aleutian cyclonic circulation transports East Asian aerosols southward and the North Pacific anticyclonic circulation transports them northward. Where these two flows meet they turn eastward, thereby creating a channelling effect between the regions of low and high pressures. Consequently, a significant amount of the East Asian dust plumes are restricted and transported in eastward direction towards North America between roughly the latitude range of 30–60° N.

3.4. Other smaller sources

Satellite data show that the Indian subcontinent has moderate levels of AOD in autumn, winter and spring (Figs. 1 and 2). White spots over the region during the summer monsoon indicate that the aerosol distribution is being masked by clouds. However, relatively small quantities of aerosols are expected over central and southern India at this time of year due to the summer monsoon and associated southerly warm and moist air advection over the subcontinent. Note that a low aerosol loading is present over the southern fringes of the subcontinent and over the Indian Ocean during summer which is associated with transported dust from the Middle East and Southwest Asia. Over the western United States and its west coast, there is one zone of high aerosol content during spring and summer due to dust activity (Prospero et al., 2002). The Karakum Desert along the east coast of the Caspian Sea is also a source of dust with a spring–summer maximum activity (Orlovsky et al., 2005). Dust from the Karakum Desert is mostly transported to northeastern Iran and western Afghanistan by the dominant mid-latitude westerlies (Figs. 1 and 2).
Contribution of dust source regions in the Southern Hemisphere to the total global dust burden is significantly lower than their counterparts in the Northern Hemisphere. For example, it is estimated that dust emission from South Africa, South America and Australia to be 22, 55 and 61 Tg yr$^{-1}$, respectively, which are substantially less than the contribution of North Africa with an estimated value of 1430 Tg yr$^{-1}$ (Ginoux et al., 2004).

Figs. 1 and 2 show that during austral spring (SON) and summer (DJF), central to southern Australia has some low AOD values due to dust emission from Lake Eyre Basin (Alizadeh Choobari et al., 2012, 2013), the most important source of dust in the Southern Hemisphere (Prospero et al., 2002; Ginoux et al., 2012). There are also some sources of dust in western Bolivia and Argentina (Prospero et al., 2002), among which Patagonia is the most important one in South America (Gaiero et al., 2007). Contribution of these sources is manifested by persistent aerosol-laden air off the west coast of South America north of 30° N (except in austral winter (JJA)) when it is masked by clouds.

4. Vertical distribution of aerosols

Seasonally averaged vertical profiles of the CALIOP dust extinction coefficient at 0.532 μm are shown in Fig. 5 for the period 2006–2011 over the major dust source regions. The maximum dust extinction coefficients over North Africa (20° N, 2.5° E) occur during summer with a peak value near the surface. Dust concentrations remain reasonably high at higher levels, demonstrating a summertime well-developed boundary layer that facilitates vertical transport of mineral dust. Associated with this well-mixed layer, dust aerosols reach as high as around 6.5 km in this region. Dust extinction coefficients are considerably reduced in other seasons, with the lowest concentrations in winter. Furthermore, as boundary-layer depth is shallower in winter, dust aerosols only reach a maximum height of around 3 km.

Notably high dust extinction coefficients close to the surface have been observed over the Middle East (20° N, 57.5° E), with maximum values in summer and substantially reduced values in other seasons. The peak summertime dust extinction coefficient (0.5 km$^{-1}$) drops off quickly with height, reaching a value of 0.2 km$^{-1}$ at around 1 km. This implies that unlike the Sahara, dust from the Middle East is mostly transported in the lower atmosphere. However, due to intense solar heating and associated development of the boundary layer, some of dust aerosols reach as high as 6 km in summer, while they are lifted to less than 5 km in other seasons. The dominance of anticyclonic circulation during winter, characterized by subsidence, contributes to high dust loading near the surface (compared to spring and autumn) and a marked reduction of dust concentration with height.

The Taklimakan desert (40° N, 82.5° E) in the Tarim Basin in northwestern China has the greatest dust activity in spring with a peak dust extinction coefficient of 0.5 km$^{-1}$. As the basin is surrounded
by mountains to the north, south and west, dust aerosols can be lifted by orographic forcing (Zhao et al., 2010); consequently high dust extinction coefficients have been observed at higher levels. This implies that it is more likely for the elevated dust aerosols from Taklimakan to be transported long distances across the Pacific Ocean. Dust concentration gradually decreases with height during spring and summer, while subsidence associated with the establishment of strong Siberia–Mongolia high-pressure systems during autumn and winter contributes to a marked reduction of dust concentration with height. It appears that due to substantial elevated dust aerosols over the basin, CALIOP could not retrieve dust concentration below 1 km.

5. Conclusions

The global seasonal distribution of dust aerosols and its correlation with atmospheric circulation has been investigated using aerosol concentration measurements from MISR and CALIOP satellite dataset and meteorological re-analysis data from ECMWF. Observed aerosol concentrations clearly show that atmospheric aerosol loading in the Southern Hemisphere is significantly smaller than its counterpart in the Northern Hemisphere, primarily because major sources of dust are located in the Northern Hemisphere. In the Northern Hemisphere, sources of dust are significantly greater in North America compared to other source regions, the feature that is attributed to the larger area over which dust is lifted.

Dust emission is greater over North Africa and the Middle East during the spring and summer period as a result of thermally driven dry convection associated with intense solar heating. The North African aerosols extend over longer distances across the North Atlantic Ocean in summer compared to other seasons because of greater dust emission, an intensified easterly LLJ (locating between 10 and 20° N) and strengthening of the Azores-Bermuda anticyclonic circulation. Furthermore, CALIOP data indicate that during summer substantial amounts of North African dust aerosols are lifted to higher altitudes (due to intense solar heating which increases surface sensible heat flux and hence boundary-layer depth), where winds are generally stronger, and hence aerosol-laden air can be transported longer distances.

Analysis of the satellite data clearly show the dominance of Central and East Asia in terms of the areal distribution of aerosols. Dust covers broad oceanic areas in spring, starting from East Asia and spreading across the North Pacific towards North America and beyond. Such long-range transport of East Asian dust is consistent with previous studies. For example, traces of Asian dust have been found in Europe (Bory et al., 2003; Grousset et al., 2003) and a full circuit transport of dust from the Taklimakan desert around the globe has been identified (Uno et al., 2009). The aerosol transport occurs mainly between 30 and 60° N, which is facilitated by the existence of a LLJ at around 30 and 50° N, extending from East Asia to the west coast of North America. After East Asia, summer dust plumes of North Africa cover extensive oceanic areas, covering a broad area from the west coast of North Africa to Central America, ranging roughly from 17 to 90° W. Bearing in mind that North Africa is the largest source of soil dust, the longer distance travel of East Asian aerosol plumes can be attributed to stronger mid-latitude westerlies over the Pacific compared to easterly trade winds over the tropical Atlantic. Analysis of the satellite data clearly show the dominance of Central and East Asia in terms of the areal distribution of aerosols. Dust covers broad oceanic areas in spring, starting from East Asia and spreading across the North Pacific towards North America and beyond. Such long-range transport of East Asian dust is consistent with previous studies. For example, traces of Asian dust have been found in Europe (Bory et al., 2003; Grousset et al., 2003) and a full circuit transport of dust from the Taklimakan desert around the globe has been identified (Uno et al., 2009). The aerosol transport occurs mainly between 30 and 60° N, which is facilitated by the existence of a LLJ at around 30–50° N, extending from East Asia to the west coast of North America. After East Asia, summer dust plumes of North Africa cover extensive oceanic areas, covering a broad area from the west coast of North Africa to Central America, ranging roughly from 17 to 90° W. Bearing in mind that North Africa is the largest source of soil dust, the longer distance travel of East Asian aerosol plumes can be attributed to stronger mid-latitude westerlies over the Pacific compared to easterly trade winds over the tropical Atlantic.
Acknowledgements

The authors would like to thank the Atmospheric Sciences Data Center (ASDC) at NASA Langley Research Center for providing MISR/CALIPSO satellite data, and the European Centre for Medium-Range Weather Forecasts (ECMWF) dataset. The authors also like to thank the Foundation for Research, Science and Technology and the National Institute for Water and Atmospheric Research (New Zealand) (Grant no. C01X0813) for their financial support.

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