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INTERANNUAL VARIABILITY AND DECADAL TRENDS IN MINERAL DUST AEROSOL

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Ina Tegen

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Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Regional Center for Northern Africa-Middle East-Europe (NAMEE)

C/Jordi Girona, 29 | 08034 Barcelona (Spain)

Atmospheric mineral dust concentrations may vary greatly on daily, seasonal and interannual timescales, as well as in different climates (Mahowald, 2007). Dust emissions depend on meteorological conditions (surface wind speed, precipitation) and on surface properties (e.g., vegetation cover, sediment availability, crusting), which may change at different timescales.

While dust transport is a global-scale phenomenon, small-scale regional processes control dust emissions. Dust emission events are often related to convective systems or the passage of cold fronts. Convective events causing dust emissions include dry convective events (dust devils) that are mainly of local importance. Thunderstorms forming in unstable conditions may cause vigorous surface winds. Sometimes they are accompanied by intense horizontal vortices with violent surface winds, so-called squall lines. In many regions in the Sahara, e.g. in the Bodélé depression dust emission is caused by turbulent downward mixing of momentum from a low-level jet, a process described by (Washington et al, 2006).

Seasonal changes in the atmospheric dust load are well characterized as these follow the seasonal changes in meteorology and vegetation patterns (e.g., springtime ‘Kosa’ events in east Asia, seasonal shift of the Saharan dust plume crossing the North Atlantic, high dust concentrations over the Arabian peninsula in late spring during the 'Shamal' season, summer maximum dust concentrations over the Arabian Sea).

Interannual changes and decadal trends in dust emission and atmospheric loads can be of similar magnitude as seasonal changes in some regions, but are less easy to explain. These variations are controlled by changes in relevant climate parameters like surface winds and the magnitude and distribution of precipitation. Dust loads may change in response to different meteorological conditions in individual years, which may in turn be related to climate modes like the El Nino Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO). Other reasons for multi-year trends in emission and atmospheric loads of dust particles can be changes in precipitation and vegetation cover in source regions. Modifications in vegetation cover can result from climatic changes and from modifications of surface properties in dust-emitting regions. Changes in vegetation cover or the disturbance of surface crusts as a consequence of (natural) flooding events or human activities like cultivation in dry regions can lead to enhanced dust emissions (as observed for example during the 'dust bowl' events in the United States in the 1930s and 1950s). This anthropogenic contribution to the global dust load may be considerable in semi-arid regions, but the magnitude is very uncertain on the global scale. While IPCC (2001) estimates a contribution of this enhanced dust of up to 50% to the global dust load, later investigations conclude that this contribution should be much smaller, probably less than 20% globally (IPCC 2007).

Model studies projecting changes in dust emissions for future conditions have so far led to widely differing results. Early estimates using global dust models that consider projected climate changes as well as vegetation changes in a warming climate that change the extent of dust sources have led to a wide range of results –

estimates have ranged from about 50% decrease to 50% increase in global dust emissions in the next century (Mahowald and Luo, 2003, Tegen et al., 2004, Woodward et al. 2005). On the one hand projection changes in dust source area size may vary strongly between climate models (Mahowald 2007), on the other hand reliable projections of future dust emissions can only be obtained if the meteorological and climatic conditions of dust emissions are well understood. Records of past dust changes are key to understanding such connections between dust loads and climatic changes and thus assessing the effects of these dust changes in the climate system. E.g., Mahowald et al (2010) point out that the considerable changes between the 'dusty' years 1980-1989 and the less dusty years 1955−1964 led to a difference in annual mean TOA radiative forcing by −0.57 ± 0.46 W/m^2.In addition to a temperature decrease by 0.11°C this also caused shifts in precipitation and carbon uptake.

Unfortunately only limited observations exist that can be used to assess the changes in dust emissions and atmospheric dust loads on multi-year timescales. Meteorological observations of blowing sand and dust or visibility-related dust indicators that are available for several decades have been used to study changes of dust emissions in the past (e.g., Mbourou et al., 1997, Mahowald et al., 2007). Mahowald et al. (2007) explored the use of visibility-related dust indices at global scales and related the data from meteorological records to climate indices and land use changes. They emphasized problems, which may be impacted by local pollution, subjective observation standards and possible undocumented changes in the observation protocols. Further indicators of past dust changes are long-term records of near-surface dust concentration, most notably the Barbados dust record that records dust concentrations since the end of the 1960s (Prospero and Lamb, 2003). Satellite records can provide information in dust trends since the 1980s.

In a global analysis, Chin et al (2014) find from an analysis of AOD trends between 1980 and 2009 derived from the GOCART aerosol transport model and information from several satellite instruments and ground based measurements that the atmospheric dust change over Sahara and Sahel predominantly follows changes in surface wind speeds while in Asia being influenced by changes in surface wetness. According to that study dust decreases during this period over the tropical Atlantic, which is found to be related to an increase in sea surface temperatures. These in turn may drive surface wind velocity changes over North Africa and influence Atlantic precipitation patterns.

Most other studies that interpret interannual and decadal dust variability have a more regional focus, which is outlined below for the desert regions in Asia, Saudi Arabia and North Africa.

Eastern and Central Asia

Considerable interest has been in determining the dependence of Asian dust on changes in land use and climate factors. Past dust occurrence is well recoded in East Asia, in particular northern China. Asian dust time series can be obtained from meteorological dust storm observation records. Giuan et al (2015) find for six stations in the area surrounding the Tengger Desert over the period 1960-2007 a significant decreasing trend related to wind variability as the main control.

Spring dust storms in the Gobi are generated by cold air outbreaks associated with strong low pressure systems. Zhang et al. (2006) suggest that Arctic snow cover is related to dust storm occurrence in northern China and could be used for dust storm prediction. Gong et al (2006) found a strong correlation between observed dust events in northern China and the Arctic Oscillation (AO: leading EOF of northern hemisphere sea-level pressure anomalies poleward of 20°N). Negative AO leads to more cold air flow from the Arctic into Mid-Latitudes to Northern Europe and Siberia in the winter months (Jeong and Ho, 2005) compared to that of neutral and positive AO phases. Since the passages of cold fronts are the main causes for spring dust storms originating in Gobi desert, it may be expected that the frequency of dust storms is related to this index. *Gong et al.* (2006) find a high correlation of the AO with the interannual variations of the dust storm frequency from the meteorological record. Gao et al (2010) also find from TOMS AI data that during the negative phase of the AO dust emissions and export from the Tarim Basin are high and vice versa.

Few studies focus on Central Asian dust variability. Xi and Soloklik (2015) analyze WRF-CHEM-Dust model results in combination with observations from MODIS and Seawifs satellite instruments for the years 2000 to 2014. They find that La Nina years are associated with drier conditions, less vegetation, and enhanced dust activity in Central Asia. After removing the influence of ENSO, they report a negative trend in dust emissions for these years due to decreasing wind speeds that they find to be related to changes in large-scale atmospheric rather than changes in vegetation.

Arabia and Eastern Mediterranean

In Saudi Arabia an increasing trend in dust events and dust loads in the past decade is observed by visibility and satellite data.

Dayan at al. (2008) analyze the linkages between eastern Mediterranean dust concentrations derived from visibility data in Israel and synoptic systems. They find high eastern Mediterranean dust to be strongly related to high Mediterranean cyclone activity, and the Cyprus Low to be the main cause for high dust loads over the Negev, with a lesser role of Saharv Cyclones and Red Sea Troughs for dust occurrences. Ganor et al. (2010) also find with a classification of synoptic situations that dust days over the Eastern Mediterranean are often connected with Cyprus Low situations, but find the increase with a rate of 2.7 days per decade between 1958 and 2006 to be coincident with an increase in dust events due to increase Red Sea Troughs.

Satellite data also show an increase in dust optical thickness in the Arabian region for the past decades. E.g., SeaWifs data show an increase in AOD over Saudi Arabia from 1997 to 2010 (Hsu et al 2012). This positive trend is also evident for an analysis of MODIS AOD data between 2001 and 2012 (increase in AOD by 0.014/year) and coincides with decreasing soil moisture in the region (Klingmüller et al, 2016). The increase in dust activity over the Arabian Peninsula has also been noted by Solmon et al (2015) for the years 2000-2009 and explained this by an increase of summer surface pressure over the Arabian sea, which in turn is also linked to an increasing precipitation trend over southern India. Yu et al. (2015) also investigate climatic controls on summertime Arabian dust activity a between 1975 and 2012 and find that the increasing trend since 2000 is part of an oscillation pattern connected with precipitation activity and Shamal winds. They propose antecedent rainfall over the Arabian Peninsula and North Africa, Mediterranean SSTs, and tropical eastern Pacific and tropical Indian Ocean SSTs as predictors of Saudi Arabia's seasonal dust activity. Notaro et al (2015) connect the increase in Arabian dust activity with a regime shift connected to drought conditions corresponding to La Nina and negative phase of PDO.

Sahara/Sahel

Controls on interannual variations in Saharan and Sahelian dust and the connection to climate are complex. Using multi-year records from ground-based observations (dust concentrations, visibility reduction), satellite retrievals and reanalyses many publications have attempted to understand variations in Saharan and Sahelian dust emission and transport data in relation to climate indicators. Different satellite records have been used to characterize long-term changes in dust optical thickness over the north Atlantic. In addition to ground-based and satellite observations, reanalyses of meteorology e.g. by ECMWF help to understand interannual changes and trends in Saharan dust activity. It must be noted that that such reanalysis fields reflect not only changes in surface winds in relation to large scale atmospheric circulation changes, but may also indirectly include changes in vegetation, as changes in surface roughness by changes in vegetation cover would be reflected in the meteorological data that are the basis for the reanalysis of atmospheric circulation.

Mbourou et al. (1997) examined changes in visibility caused by the occurrence of dust storms for three decades from the 1950s to the 1980s. From the meteorological records the authors infer a considerable increase by more than a factor of two in the frequency of dust events in the southern part of the Sahara from the 1950s to the 1970s. Prospero and Lamb (2003) indicate that dust emission in the southern Sahara and transport of dust aerosol across the North Atlantic have increased considerably from the 1960s to the 1970 and remain at a high level with strong interannual variability since. In contrast, SeaWifs satellite data from 1997 to 2010 (Hsu et al 2012) show a decreasing aerosol trend related to Saharan dust over the tropical Atlantic.

The interannual changes of Saharan/Sahelian dust until the 1990s are highly anticorrelated with rainfall in the Sahel. From combined optical thickness records from Meteosat and TOMS Moulin and Chiapello (2004) also found that that there was a large scale correlation between dust transport to the Atlantic and Sahel rainfall deficit in the preceding wet season. This confirmed the findings by Prospero and Lamb (2003) from independent measurements. They suggest that dust emissions in this semi-arid region are controlled by the position of the southern vegetated boundary of the Sahara. According to Wang et al (2015) interannual variability in Sahelian rainfall and surface wind speeds over the Sahara are the result of changes in lower tropospheric air temperatures over the Saharan heat low, connected to northward displacement oft he monsoonal rainfall. However, e.g., Mahowald et al. (2002) shows that the dust record from Barbados is influenced not only by dust emissions in North Africa but also by transport patterns and loss of the dust particles on their way to the remote location. Thus those records are insufficient to fully explain the factors that control the Saharan dust interannual variability, in particular changes in the source regions. On the other hand, meteorological station records are incomplete for the Saharan desert and estimates of dustiness from visibility reduction may include biases. Evan et al (2006) also found correlations between satellite retrievals over 24 years from the AVHRR instrument with summertime Sahelian precipitation deficit. From a strong observed relationship between a the AVHRR vegetation index in the Sahel and North Atlantic dustiness they postulate a possible role of Sahelian vegetation changes in dust variability. More recently, Doherty et al (2014) state that the latitudinal position of the convergence zone is significantly correlated with the quantity of mineral dust at Barbados over the period 1965–2003 . The coupling of changes in near-surface winds with changes in precipitation in source regions driven by a southward movement of the convergence zone most directly influence dust load at Barbados and over the tropical North Atlantic during summer.

From an eleven-year record of dust optical thickness derived over the North Atlantic and the Mediterranean from Meteosat retrievals, a relationship between the North Atlantic Oscillation (NAO) and dust transport to the North Atlantic and the Mediterranean was found (Moulin et al., 1997). Chiapello and Moulin (2002) supplemented an optical thickness product derived from the TOMS instrument with Meteosat-derived optical thickness to investigate the variability of Saharan dust transport over the Atlantic over a period of 20 years .The 24-year record of AVHRR data analysed by Evan et al (2006) also show a correlation between wintertime North Atlantic dust and the wintertime NAO index.. Ginoux et al., (2004) confirmed a relationship between winter dust loads over the north Atlantic and the NAO from TOMS retrievals and model computations. Also from analyzing TOMS AI retrieval records Riemer et al. (2004) found that the position of the Azores High is the most important factor in the relationship between NAO and Saharan dust transport over the North Atlantic region.

Dust emissions in the Sahara reflect the topography according to analyses of the dust index from the geostationary MSG satellite (Schepanski et al 2007, 2009). From a projection of winds from a historical reanalysis on the orographically controlled wind variability pattern Evan et al (2016) conclude that there were periods of maximum Saharan dust activity 1910-1940 and 1970-1990, and low-dust periods in the 1860s, 1950s and 2000s.

Wagner et al (2016) find that many individual factors contributed to the considerable observed differences in the numbers Saharan dust events between 2007 and 2008, including changes in the Sahel rainfall distribution, the strength of the West African Heat Low, and the occurrence of cold surges propagating from the Mediterranean into the Sahara. They find that these differences are connected to large-scale circulation patterns that are driven by differences in sea surface temperatures in the Indian and Pacific oceans and the Mediterranean.

Different climatic modes that characterize pressure and temperature patterns in particular in the Atlantic region have been used to explain the variability of North African dust. DeFlorio et al (2016) use in-situ and satellite observations with a century-long simulation by CESM finding a relationship between ENSO and North African dust transport in boreal summer in the model. La Nina summers are associated with a significant increase in easterly winds leading to stronger dust transport.

Evan et al (2011) tie interannual to decadal variability in dust emissions over West Africa to the Atlantic Meridional Mode of variability, which characterized by an interhemispheric gradient in sea surface temperatures.

The North African Dipole Intensity (NAFDI) has been found to explain interannual variability in Saharan dust concentrations the Izana observatory by Rodrigues et al (2015) for an 28-year record (1987-2004) The NAFDI characterized the dipole structure between the subtropical Saharan high and the tropical low. The position of the Saharan anticyclone is influenced by the NAFDI and in turn impacts on the wind fields influencing both Saharan dust emissions and transport. Increases in the NAFDI result in higher wind speeds with enhanced dust export over the subtropical North Atlantic (high NAFDI leading to high dust export) , and are associated with enhanced rains possibly affecting the southern Sahel (high NADFDI leading to low dust in the tropics.

Ridley et al (2014) explains the downward trend in Saharan dust over the Atlantic (10% between 1982 and 2008 according to AVHRR measurements) by GEOS-Chem model results driven by MERRA reanalyses. They find changes in dustiness in this region related to wind speed changes over the source region and no link with changes in vegetation cover in North Africa.

In addition to the roles of surface winds, atmospheric circulation and vegetation changes, the role of the activation of alluvial sediments in deserts by heavy precipitation can also be an important factor in dust mobilization, which is currently under discussion (Schepanski et al 2013, Wagner et al., 2016) but is not yet clarified.

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