Modulation of Saharan dust export by the North African dipole

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Abstract

We have studied the relationship between the long term interannual variability in large scale meteorology in western North Africa - the largest and most active dust source worldwide – and Saharan dust export in summer, when enhanced dust mobilization in the hyper-arid Sahara results in maximum dust impacts throughout the North Atlantic. We address this issue by analysing 28-years (1987-2014) of summer averaged dust concentrations at the high altitude Izaña observatory (~2400 m.a.s.l.) in Tenerife Island, satellite and meteorological reanalysis data. Summer meteorological scenario in North Africa (aloft 850 hPa) is characterised by a high over the subtropical Sahara and a low over tropic linked to the monsoon. We measured the variability of this high-low dipole like pattern in terms of the North AFrican Dipole Intensity (NAFDI): the difference of geopotential heights anomalies averaged over the subtropic (30-32ºN, Morocco) and the tropic (10-13ºN, Bamako region) close to the Atlantic coast (at 5-8ºW). We focused on the 700 hPa standard level due to dust export off the coast of North Africa tends to occur between 1 and 5 km.a.s.l. Variability in the NAFDI is associated with displacements of the North African anticyclone over the Sahara and this has implications on winds and dust export. The correlations we found between the 1987 - 2014 summer mean of NAFDI with dust at Izaña, satellite dust observations and meteorological re-analysis data, indicates that increases in the NAFDI (i) results in higher wind speeds at the north of the Inter-Tropical Convergence Zone which are associated with enhanced dust export over the subtropical North Atlantic, (ii) influences the long term variability of the size distribution of exported dust particles (increasing the load of coarse dust) and (iii) are associated with enhanced rains in the tropic and northern shifts of the tropical rain band that may affect southern Sahel. Interannual variability in NAFDI is also connected to spatial distribution of dust over the North Atlantic; high NAFDI summers are associated with major dust export (linked to winds) in the subtropic and minor dust loads in the tropic (linked to higher rainfall), and vice versa. The evolution of the summer NAFDI values since 1950 to present days shows connections to climatic variability (through the Sahelian drought, ENSO and winds) that have implications on dust export paths. Efforts to anticipate how dust export may evolve in future decades will require a better understanding on how the large scale meteorological systems represented by the NAFD will evolve.

1. Introduction

Desert dust aerosols influence global climate by scattering and absorbing radiation (Forster et al., 2007), influencing rainfall (Creamean et al., 2013), and also by modulating ocean-atmosphere CO_2 exchange through the deposition of dust which supplies iron, a micronutrient for marine biota (Jickells et al., 2005). Ice core records show increased dust activity during glacial periods when CO_2 was low (Martínez-García et al., 2009). Dense dust hazes often occur between tropical and mid-latitudes over the North Atlantic (Tanaka and Chiba, 2006), with implications also on air quality (Rodríguez et al., 2001; Pérez et al., 2008; Mallone et al., 2011; Díaz et al., 2012). Consequently, there is considerable interest in climate variability, the global distribution of dust (Adams et al., 2012; Ginoux et al., 2012) and dust microphysical properties including particle size which modulates dust impacts (Mahowald et al., 2014), e.g. the interaction with radiation (Otto et al., 2007), iron solubility and supply to the ocean (Baker et al., 2006), its role as cloud and ice nuclei (Welti et al., 2009), and health effects due to dust exposure (Pérez et al., 2008; Mallone et al., 2011; Díaz et al., 2012; Pérez et al., 2014). During atmospheric transport, dust is removed by precipitation and by dry deposition, the latter a process that is strongly size dependent. Dust size variability is observed over time scales of individual dust events (~ days) (Ryder et al., 2013) and in ice cores, over thousands of years, linked to changes in wind speeds, transport pathways and dust sources attributed to climate variability (Delmonte et al., 2004).

North Africa is the largest and most active dust source in the world (Ginoux et al., 2004; Huneeus et al., 2011; Ginoux et al., 2012). Dust mobilization experiences a marked seasonality. In winter, sources located in southern Sahara and the Sahel (<20ºN) are especially active linked to north-easterly dry (Harmattan – trade) winds which prompt dust export across the North African tropical coast (<15ºN) (Engelstaedter and Washington, 2007; Haywood et al., 2008; Menut et al., 2009; Marticorena et al., 2010). In summer, the north-east trade winds and the Inter-Tropical Convergence Zone (ITCZ) shift northward, enhancing emissions from Saharan sources and increasing dust export at subtropical latitudes (20-30°N), concurrently the northward shift in the monsoon rain band to southern Sahel tends to decrease Sahelian dust emissions (Engelstaedter and Washington, 2007; Knippertz and Todd, 2010; Ashpole and Washington, 2013, and references therein).

There is a major scientific interest in understanding the links between long term variability in North African dust export and climate. Dust sources in part of the Sahel have a hydrological nature (Ginoux et al., 2012); their emissions are affected by the summer variability in rainfalls and also by the North Atlantic Oscillation in winter, and this has had consequences on dust impacts on the tropical North Atlantic detected during, at least, four decades (Prospero and Lamb, 2003; Chiapello et al., 2005). In addition, the increase in commercial agriculture over the last two centuries coupled with droughts has had an impact on Sahelian dust emissions (Mulitza et al., 2010). In contrast the Sahara is a hyper-arid environment (< 200 mm/yr) where natural non hydrological dust sources (i.e. not associated with annual hydrological cycles) prevail (Ginoux et al., 2012), and dust emission variability is mainly controlled by winds (Engelstaedter and Washington, 2007; Ridley et al., 2014). Conceptual model explaining interannual variability in Saharan dust export have been proposed for the winter (e.g. North Atlantic Oscillation by Ginoux et al., 2004; Chiapello et al., 2005), but not for summertime when the highest dust emissions occur in North Africa due to the enhanced activation of the subtropical Saharan sources (Prospero et al., 2003; Ginoux et al., 2004; Chiapello et al., 2005; Tanaka and Chiba, 2006; Engelstaedter and Washington, 2007; Mulitza et al., 2010; Knippertz et al., 2012; Ridley et al., 2014). Doherty et al. (2008) found that the trans-Atlantic dust transport of North African dust to the Caribbean is influenced by displacements in the Azores and Hawaiian anticyclones. In this study we have focused on the links between North African meteorology and dust export.

Starting in 1987 we have measured aerosols at the Izaña -Global Atmospheric Watch (GAW) - World Meteorological Organization (WMO) - high-mountain observatory (28°18'N, 16°29'E, 2367 m. a.s.l.) on Tenerife Island, which frequently lies under the main path of the high altitude Saharan dust outbreaks. At night, when mountain upslope winds cease, Izaña is within the free troposphere airflows, frequently within the dust-laden Saharan Air Layer (SAL) which in summer is typically located at altitudes between ≈1 to 5 km a.s.l. (Adams et al., 2012, Nicholson et al., 2013; Tsamalis et al., 2013). Here we report on long term measurements of summertime concentrations of total dust ($dust_T$) (1987-2014) and of dust particles < 2.5 µm ($dust_{2.5}$) (2002-2014). Our 28 years observation evidence that there is a significant interannual variability in Saharan dust export in summer. Our research focuses on one key question: *What is the relationship between long term inter-annual variability in Saharan dust export in summer and large scale meteorology in North Africa?* For addressing this issue we also used (i) the UV Aerosol Index determined by the Total Ozone Mapping Spectrometer and Ozone Monitor Instrument satellite-borne spectrometers (Herman et al., 1997) for studying long-term and inter-annual spatial distribution of dust and (ii) gridded meteorological National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) re-analysis data (Kalnay et al., 1996) for studying the variability of large scale meteorological processes.

In this article, we first perform a brief description of the typical meteorological scenario in western North Africa in the summertime. Then, the concept of the North African dipole is introduced as an approach to characterize how variability in large scale meteorology may influence Saharan dust export. We then assessed how the long term variability in the intensity of the North African dipole has influenced long term Saharan dust export to the free troposphere during 28-years and particle size distribution during 13-years. Finally, we assess whether the North African dipole intensity can be used to connect Saharan dust export with climate variability. Here we present connections between dust export and large scale meteorology; further studies will be necessary for understanding the involved meteorological and dust processes.

2. Methods

2.1 In-situ dust measurements

We used in-situ dust concentrations data recorded between 1987 and 2014 at Izaña observatory. Here we present a brief description of the methods, details are included in section S1 of the online Supplement.

Dust concentrations were obtained by chemical analysis of aerosol samples collected on filter at the flow rate of 30 m^3/h. Throughout the almost three decades of observations, several analytical methods have been used for determining soluble species ($SO_4^{=}$, NO_3^{-}, NH_4^{+} by ion chromatography and colorimetry), organic and elemental carbon (by TOT), elemental composition (INAA, IPC-AES and IPC-MS) and the content of dust (by the 'weight of the ash residue after 14-h heating at 500ºC' method and by using the elemental composition data) in the aerosol samples; details of these methods and their use throughout the measurement period are included in Table S1 of the online Supplement. In order to facilitate data comparison with other studies, dust concentrations are reported to mean pressure at sea level (1013 hPa) and normalized in such a way that aluminum accounts for 8% dust (mean content of Al in soils). Here we report on dust concentrations in two size fractions: concentrations of total dust ($dust_T$) from 1987 to 2014 and of dust particles with an aerodynamic diameter ≤ 2.5 μm ($dust_{2.5}$) from 2002 to 2014 (Rodríguez et al., 2012).

Dust concentrations were also calculated with a secondary complementary method based on number size distributions measurements (0.5 to 20 μm) performed with an Optical Particle Counter and an Aerodynamic Particle Sizer. These data were used for determining the aerosol volume concentrations and convert then to bulk aerosol mass concentrations using standard methods (Rodríguez et al., 2012). The good agreement (high linearity and low mean bias, 3-8%) between these two methods (based on chemical analysis and on size distributions) is due to the very low aerosol volume concentrations in the free troposphere during no dust events (typically < 1 to < 3 μg/m^3; Rodríguez et al., 2009) and to the fact that the aerosol volume concentrations during dust events are by far dominated by dust, as evidenced by the chemical analysis (Rodríguez et al., 2011) and the ochre color of the aerosol samples (Fig. 1b).

These two dust databases (based on chemical and on size distribution methods) were used to assess the consistency of the observed year-to-year variability of dust. During the whole measurement period (25 July 1987 –31 December 2014, excluding the non-measurement period 11 October 1999 - 13 February 2002), dust concentrations records are available for 8001 days, which lead to a data availability of 87.3%. This record of aerosol dust concentration is among the longest in the world (after Barbados –

started in 1965, Miami – 1972 and American Samoa - 1983) and probably the longest in several aerosol size fractions downwind of a dust large source (Rodríguez et al., 2012).

2.2 Satellite dust observations

We used UV Aerosol Index (AI) data from the Total Ozone Mapping Spectrometer –TOMS- (1979-2001) and from the Ozone Monitor Instrument –OMI- (2005-2014) spectrometers onboard the satellites Nimbus 7 (TOMS 1979-1993), Earth Probe (TOMS 1996-2001) and Aura (OMI 2005-2014) for studying the spatial and temporal variability of dust. Because of the UV absorption by some minerals (e.g. hematite, goethite), AI has been widely used in dust studies. This is a semi-quantitative parameter; AI values > 1 are considered representative of an important dust load and the frequency of daily AI values > 1 has been used for dust climatology (Prospero et al., 2002). In North Africa, the AI signal at the north of the summer tropical rain band is due to dust, whereas biomass burning aerosols transported from South Africa contribute to AI signal at the south of the tropical rain band (Prospero et al., 2002). We only analyzed and interpreted the variability in the frequency of daily AI > 1 at the north of the summer tropical rain band. The following data were used:

- Level 3 TOMS data of the period 1979-2001. TOMS data for the period 2002-2005 were not used due to calibration problems (http://disc.sci.gsfc.nasa.gov/guides/legacy-guides/tomsl3_dataset.gd.shtml).
- Level 3 OMI data of the period 2005-2014. Although this instrument has experienced the so called "row anomalies" since 2007 (http://www.knmi.nl/omi/research/product/rowanomaly-background.php), the affected data is not included in the level 3 datasets (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/index.shtml#info)

Level 3 daily AI data of TOMS and OMI of summer (August) were downloaded from the Giovanni online data system of the NASA Goddard Earth Sciences Data and Information Services Centre (GES DISC) (http://disc.sci.gsfc.nasa.gov/). The consistency of the TOMS and OMI AI data set has already been shown (Li et al., 2009). Consistency between TOMS, OMI and our in situ dust measurements is analyzed in section S3 of the online Supplement (including Fig.S4 and S5).

2.3 Meteorological reanalysis data

We used gridded meteorological National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) re-analysis data (Kalnay, et al., 1996) for studying the relationship between dust variability and large scale meteorological processes in summer (August). This analysis included geopotential heights, winds and rains used in equation 1 (shown below) and Fig.2, 4 and 9.

2.4 Summer dust season

At Izaña, the summer dust season (impacts of the SAL) typically starts in the second half of July and ends at the beginning of September (section S2 of the online Supplement). The maximum frequency of dust events occurs in August (52% of the August-days as average; Fig. 1). This month is of high interest given that (i) the ITCZ is shifted to the North and consequently (ii) the SAL is exported at the northern most latitude (as evidence the highest frequency of dust impacts at Izaña; Tsamalis et al., 2013) and the maximum rainfall occurs in tropical North Africa (Nicholson et al., 2009). For this reason, we used the August dust averages for studying summer long term dust evolution in the boreal subtropic (Fig. 1a). The study of the central month (August) of the summer dust season (excluding July and September) allows characterizing long term evolution in terms of intensity of dust export, avoiding the variability that could be linked to (i) shifts in the beginning (July) or end (September) dates of the dust season or (ii) variability in the location of the ITCZ from July to September. Our data analysis shows that the July to September dust average is dominated by the dust events occurring in August (Fig S3 of the online Supplement). In August 1987-2014, daily dust data were available during 761 days, i.e. a data availability of 94% (excluding the no-measurements period 11 October 1999 - 13 February 2002). In this study we analyze 1987-2014 time series of in-situ dust concentration at Izaña (determined by chemical methods) averaged in all (dust and no-dust) days of August (shown in Fig. 3a and analyzed below). We refer to August as summer. Results are presented in section 4; additional analysis is presented in section S3 of the online Supplement.

3. North African summer meteorological scenario

Meteorological scenario throughout western North Africa is influenced by the high pressures typical of the subtropical deserts and the so-called western African monsoon (Lafore et al., 2010). Additionally, the formation of the summer Saharan heat low (Lavaysse et al., 2009) in central western Sahara has also implications on meteorological processes, not only related to the development of the wet western African monsoon season in tropical North Africa (Lafore et al., 2009), but also on mobilization, upward transport and export of dust to the North Atlantic at subtropical latitudes (Jones et al., 2003; Flamant et al., 2007; Knippertz and Todd, 2010).

In summer, the vertical structure of the atmosphere over the Sahara is characterized by the Saharan heat low at low levels (surface to 925Pa standard level at ~20ºN) with a confluence of surface 'northern dry desert Harmattan' and 'southern humid monsoon' winds at its southern margin (Nicholson et al., 2013) in the so-called ITCZ, which in central western Sahara occurs between 18-20ºN (Lafore et al., 2010; Pospichal et al., 2010; ITCZ also known as Inter-Tropical-Discontinuity ITD). Monsoon rainfalls occur at southern latitudes (<15ºN), in a region we will refer as rain band (Nicholson et al., 2009). The Saharan heat low, as a shallow hot depression, enhances subsidence processes due to compensatory downward movement in upper levels (Spengler and Smith, 2008; Canut et al., 2010). The African Easterly Jet (AEJ) forms at altitude between 2 and 6 km between 15 and 20ºN due to the thermal wind in the baroclinic zone between the 'northern hot desert air' and the 'cool monsoonal southern airflow' (Nicholson, 2009, 2013).

Emissions, upward transport and export of dust to the North Atlantic occur in this summer scenario. Dust emission processes occur in a range of scales (Knippertz and Martin, 2012) from (i) synoptic scale (e.g. Harmattan - trade winds, African easterly waves; Jones et al., 2003; Knippertz and Todd, 2010), through (ii) strong winds, convergence and high turbulence associated to the ITCZ (Flamant et al., 2007; Ashpole and Washington, 2013), low-level jets (Knippertz, 2008; Fiedler et al., 2013) and cold pools of mesoscale dry convective systems (particularly over the Sahel; Engelstaedter and Washington, 2007; Lavaysse et al., 2010a, and references therein) including 'haboob' storms (Marsham et al., 2008), to (iii) microscale dust devils and dusty plumes (Allen and Washington, 2013). As a consequence of convergence processes close to the ITCZ (Ashpole and Washington, 2013) and because of the convective boundary layer, huge amounts of dust are lifted up to ~ 5 km altitude (Cuesta et al., 2009; Guirado et al., 2014). The easterly subtropical circulation at the south of the North African anticyclone typically present at the altitude of the 700 hPa level and aloft (Font-Tullot, 1950; UK Meteorological Office, 1962), coupled with the divergence linked to the Saharan heat low, and the AEJ (Lavaysse et al., 2010a) expands this dry dusty air mass over the North Atlantic free troposphere resulting in the previously described SAL (Prospero and Carlson, 1972; Tsalamis et al., 2013). Off the coast of North Africa, the summer SAL is found at altitudes between 1 and 5 km (Karyampudi et al., 1999; Immler and Schrems, 2003; Tsamalis et al., 2013; Andrey et al., 2014) due to the westward dust export occurs above the so-called 'Atlantic inflow', a layer of cool and stable sea-breeze like inflow present along the subtropical North African coast (Lafore et al., 2010).

This brief description illustrates how the presence of the dusty SAL over the North Atlantic is the net result of a set of complex and coupled processes which occur in a wide range of scales and which may also involve (i) feedback mechanisms (e.g. radiative, cloud and rain processes triggered by dust; Lau et al., 2009), (ii) interconnections between processes (e.g. influence of the AEJ-convection-monsoon connections on dust described by Hosseinpour and Wilcox, 2014), (iii) variability in dust emissions due to meteorologically driven variability in soil features (Prospero and Lamb, 2003) and (iv) dust microphysical processes (e.g. size dependent deposition and cloud and radiation interactions; Mahowald et al., 2014).

4. Results and discussion

4.1 The North African dipole

We aim to find a simple conceptual model for linking long term variability in Saharan dust export with variability in the large scale meteorology in western North Africa. Because it resemble a dipole, we will referee to the summer meteorological scenario of North Africa - characterized by high pressure in subtropical Sahara (27 - 32 °N over Algeria; Font-Tullot, 1950; UK Meteorological Office, 1962) and low pressure in tropical North Africa (< 15 °N) - the North AFrican Dipole (NAFD). The NAFD is illustrated in the height of the 850 hPa summer average geopotential in Fig. 2. The intensity of this dipole can be measured as the difference of the anomalies of the geopotential height over the subtropic and that over the tropic in North Africa. Because summer dust export to the Atlantic occurs between 1 and 5 km altitude (Prospero and Carlson, 1972; Immler and Schrems, 2003; Tsalamis et al., 2013), with a frequent maximum dust load between 2 and 3 km (Teschen et al., 2009; Cuevas et al., 2014), we paid special attention to the 700 hPa standard level (Nicholson, 2013) at 5 – 8 ºW longitude (i.e. close to the Atlantic coast). Thus, in this study we measured the intensity of the NAFD as the difference of the anomalies of the 700hPa geopotential height averaged over central Morocco (30-32°N, 5-7°W) and that over Bamako region in Mali (10-13°N, 6-8°W) by equation 1. Other parameterisations of the NAFD are plausible depending on the study subject. We calculated the NAFD Intensity (NAFDI) with equation 1 using the average values of the 700 hPa geopotential heights in every month of August (31 days average) from 1948 to 2014 obtained from the NCEP/NCAR re-analysis (Kalnay, et al., 1996):

$$NAFDI \quad = \frac{1}{10}((\emptyset_{Mo}^{y} - < \emptyset >_{Mo}) - (\emptyset_{Ba}^{y} - < \emptyset >_{Ba})) \qquad \text{Equation 1}$$

where,

- $\emptyset_{Mo}^{y}$ is the mean geopotential height at 700hPa averaged in central Morocco region (30-32°N, 5-7°W) in August of year 'y'.
- $< \emptyset >_{Mo}$ is the mean geopotential height at 700hPa averaged in central Morocco region (30-32°N, 5-7°W) averaged in August months from 1948 to 2012.
- $\emptyset_{Ba}^{y}$ is the mean geopotential height at 700hPa averaged in Bamako region (10-13°N, 6-8°W) in August of year 'y'.
- $< \emptyset >_{Ba}$ is the mean geopotential height at 700hPa averaged in Bamako region (10-13°N, 6-8°W) averaged in all August months from 1948 to 2012.
- $\frac{1}{10}$ is a scale factor.

The NAFDI (equation 1) is a measure of the inter-annual variability of the dipole intensity and, because of its relationship with the geopotential gradient, it is related with the intensity of the geostrophic North African outflow.

Fig 3a shows the time series of the summertime NAFDI values from 1987 to 2014, when it showed values between -3.19 and +2.29. In order to assess how large-scale meteorology changes with NAFDI values, we averaged some meteorological fields during high NAFDI summers and low NAFDI summers (Fig.4a and 4c-4e). The low NAFDI group includes the summers with the four lowest NAFDI values in the period 1987-2014: 1997 (NAFDI = -3.19), 1987 (-2.79), 1996 (-2.04) and 2006 (-1.54). The high NAFDI group includes the summers with the four highest NAFDI values in the period 1987-2014: 2012 (+2.29), 2008 (+1.01), 2000 (+0.83) and 1988 (NAFDI= +0.68). Only summers for which satellite AI data are available were considered (i.e. 1993-1995 and 2002-2004 periods were not included in the selection). The spatial distribution of dust was assessed by determining the metric Major Dust Activity Frequency (MDAF): the number of days with AI values > 1 divided by the total number of days with available AI data in % (Fig.4b).

The NAFD is illustrated in Fig. 4a with the mean 700hPa geopotential height field during summers of low and of high NAFDI. The core of the northern Saharan anticyclone reinforces over the western Atlas Mountains (~30ºN) in high NAFDI summers (Fig.4a2), whereas it weakens and shifts southward to central Algeria (~28ºN) in low NAFDI summers (Fig.4a1). Conversely, at the tropical latitude of Bamako (~12N) geopotentials heights are higher during low NAFDI summers (Fig.4a1) than during high NAFDI summers (Fig.4a2).

4.2. Long term variability of Saharan dust export

At Izaña we observe a strong interannual variability in dust concentrations (Fig. 3a). In low dust years - 1987, 1997, 2006 and 2007 – mean concentrations were within the range 17 – 30 μg/m^3; in high dust years - 1988, 2008, 2010 and 2012 – the range was 100 - 140 μg/m^3. We associate this variability to the spatial variability of meteorological conditions over North Africa, specifically to the NAFD (Fig.4). The high value of the Pearson correlation coefficient (r) of mean summer $dust_T$ at Izaña with the NAFDI from 1987 to 2014 (r=0.72, Fig. 3a) indicates that the dust export is highly sensitive to the dipole intensity (Fig. 5a).

The mean wind fields and precipitation rates are shown along with MDAF for low and high NAFDI summers in Fig. 4. There is a significant variability in the spatial distribution of dust over the North Atlantic in high with respect to low NAFDI periods. Increases in the NAFDI are associated with a strengthening of the zonal (easterly) component of continental trade winds north of the ITCZ in a region we define as the subtropical Saharan Stripe (Fig.4c-4d). This strengthening of easterly winds was observed in all standard levels (only shown at 925 and 700 hPa for the sake of brevity) and is associated with a reinforcement of the tropical low to subtropical Saharan high pattern represented by the NAFD (e.g. at the level of 850 hPa, Fig S7 of the online Supplement). The subtropical Saharan Stripe region, which extends from Central Algeria to Western Saharan between 24 and 30 °N, includes important dust sources (Prospero et al., 2002; Schepanski et al., 2009; Rodríguez et al., 2011; Ginoux et al., 2012) which clearly exhibit a greater MDAF during summers with high NAFDI (Fig. 4b2). Long-term (1987-2014) summer mean values of NAFDI and of $dust_T$ at Izaña are highly correlated with the zonal wind in the subtropical Saharan Stripe (r= 0.6 to 0.9, Fig. 6a, where negative correlation indicates reinforcement of westward winds). These correlations reflect the net result of a wide range of dust-related processes (emission, vertical transport, advection to the Atlantic and size dependent deposition during transport). These results are consistent with those of the back-trajectories analysis (Fig. S6 of the online Supplement)

The portion of the SAL with a MDAF during more than 40% of the summertime extends from North Africa to 30°W during summers with a low NAFDI (Fig. 4b1); in contrast the region extends to 55°W during high NAFDI summers (Fig. 4b2). In high NAFDI summers the SAL also expands northward over the subtropical North Atlantic domain (24 – 35 °N, 9 - 60 °W; Fig. 4b); because of this, the MDAF over the subtropical North Atlantic shows a significant correlation with the NAFDI (1979-2014 r = 0.73; Fig. 7a) and with dust records at Izaña (Fig.7b). The positive correlation of NAFDI with the MDAF in the North Atlantic subtropical band (24 – 35 ºN, Fig 6b) points to an association between summer-to-summer variability in zonal winds in the subtropical Saharan Stripe (Fig. 4c and 6a) and dust export at subtropical latitudes. Reinforcement of easterly winds during high NAFDI summers is also observed in the AEJ (Fig. 4d), which plays a role in the trans-Atlantic dust transport (Jones et al., 2003).

4.3. Long term variability of dust size distribution

Our dust record in two size fractions was used to assess long term variability in dust size distribution. We found that the NAFDI is correlated with the interannual variability of dust size distribution. Our measurements show pronounced changes in the size distribution of dust particles that are apparently related to wind interannual variability driven by the NAFDI (Fig. 5b). Dust tends to be coarser during high NAFDI years than during low NAFDI years. Observe how the $dust_{2.5}$ to $dust_T$ ratio tends to decrease with the NAFDI increase: ~ 30% in summers with a NAFDI < 0 and down to ~ 20% in summers with a NAFDI > 2 (Fig. 5b). The high amount of coarse (> 2.5 μm) dust during high NAFDI summers may be linked to the activation of dust sources closer to the Atlantic coast and/or faster atmospheric transport due to higher wind speeds. Both processes will reduce the loss rate of larger-size particles due to gravitational deposition during transport (Ryder et al., 2013).

4.4. Connection of NAFD to climate variability

In this section we assess if the NAFDI could be used for linking long term export of Saharan dust with climate variability during the last decades. Here we present some associations between NAFDI, tropical rains and ENSO that will require future investigations.

South of the ITCZ, NAFD is associated with the variability in the tropical monsoon rains. We found that from 1987 to 2014 the interannual variability of the NAFDI is moderately correlated with the precipitation rates over tropical North Africa (Fig. 6c) and with what we defined as Wet Sahel Portion (r=0.54, Fig.3d), i.e. the portion of the Sahel region (14-18°N to 17°W-22°E; Fig. 4e) that experienced a precipitation rate ≥ 3 mm/day. High NAFDI summers tend to be associated with enhanced precipitation rates in tropical North Africa and northern shifts in the rain bands that may affect southern Sahel (Fig.4e1, 4e2 and 6c). Enhanced dust scavenging in high NAFDI summers may accounts for the negative correlation we observe between the 1987 to 2014 summer mean values of the NAFDI and the MDAF over the Sahel and tropical North Africa (Fig.6b), in a region where rainfall and mixing between the inland monsoon flow and the SAL may have an influence on spatial and temporal distribution of dust (Canut et al., 2010). The low MDAF in the Sahel and in the tropical rain band during high NAFDI summers, with respect to high NAFDI summers, is also clear in Fig. 4b1 and 4b2. This is consistent with the negative correlations between Sahelian rains and dust impacts in the Caribbean found by Prospero and Lamb (2003). The long term (1987-2014) correlation of $dust_T$ at Izaña with the Wet Sahel Portion (r=0.74, Fig. 3d) suggests that variability in the Saharan dust export in the subtropic and monsoon tropical rains have been influenced by a common meteorological / climatic mechanism. Observe how high $dust_T$ summers at Izaña have been associated with high Wet Sahel Portion in the last three decades (e.g. 1988, 1999, 2010, 2012 and 2013, $dust_T$= 75 – 140 µg/m^3 and Wet Sahel Portions = 7-15%; Fig 3d) and vice versa (e.g. 1996, 1997, 2006, 2009, 2011, 2014, $dust_T$= 17 – 45 µg/m^3 and Wet Sahel Portions = 0.8 - 4.5 %; Fig 3b). In a shorter time scale (days-to-weeks), this connection of dust export and monsoon rains was also observed by Wilcox et al. (2010), who found that the tropical rain band shifted northward by 1 to 4 degrees latitude during westward dust outbreak events accompanied by an acceleration of winds in the northern edge of the EAJ.

We also compared the variability of the NAFDI with that of a set of teleconnection indexes and found that the Multivariate ENSO (El Niño Southern Oscillation) Index (MEI), -calculated with sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky over the tropical Pacific Ocean - is moderately correlated with the NAFDI (r=-0.50) and with $dust_T$ at Izaña (-0.59) (Fig. 1a) (Table S2 of the online Supplement). Because variability in NAFDI is connected to wind at the north of the ITCZ (Fig.6a), these correlations suggest that MEI may be teleconnected to winds over the subtropical Sahara and this would have implications on Saharan dust export. In five of the eight intense ENSO years recorded from 1987 to 2014 (green arrows on the top of Fig 3) $dust_T$ concentrations at Izaña were low (1987, 1997, 2006, 2009 and 2014, 17-32 µg/m^3; Fig.3a) coupled with rather low zonal winds at 925 mb and 700 mb along the Subtropical Saharan stripe (Fig. 3b and 3c), whereas in the other three intense ENSO years $dust_T$ concentrations were moderate (1991, 1993 and 2002, 47-61 µg/m^3; Fig.3a). In the 1987 - 2014 time series, we can observe that many of the peak $dust_T$ summers are associated with correlated increases in NAFDI and MEI·(-1) (e.g. 1988, 1998 and 2008); however we also observe some peak $dust_T$ summers associated with MEI peaks but rather low NAFDI values (e.g. 2002 and 2010, Fig 3a) and vice versa, i.e. peak $dust_T$ summers associated with NAFDI peaks but rather low MEI values (e.g. 2012). This suggests that NAFDI and MEI may be tracing the dependence of different processes involved in dust export on climate variability (e.g. regional variability in source activation, spatial distribution of dust or altitudinal and latitudinal shifts of the SAL). Observe how long term summer mean $dust_T$ at Izaña exhibits higher linearity with NAFDI + MEI·(-1) (Fig. 5d, R^2=0.60) than with either NAFDI (Fig. 5a, R^2=0.52) or MEI (Fig. 5c, R^2=0.34). The 1987 - 2014 summer mean $dust_T$ at Izaña exhibited a higher correlation with NAFDI + MEI·(-1) (r=0.77) than with NAFDI (r=0.72) or MEI·(-1) (r= 0.50). Teleconnections of dust with several large scale systems were also observed by Doherty et al. (2008), who found that trans-

Atlantic transport of dust was teleconnected to displacement of both the Azores and Hawaiian anticyclones. Deficits in the North African tropical rains have also been linked to ENSO (including summer Palmer, 1986; Bhatt, 1989; Janicot et al., 1996; Rowell, 2001), consistent with the correlation found between NAFDI and precipitation rates over tropical North Africa (Fig. 6c) and with the low Wet Sahel Portions we observe in low NAFDI and MEI·(-1) summers (Fig. 3a and 3d). Interannual variability in dust transport in subtropical Asia (Abish and Mohanakumar, 2014) and dust mobilization in sources affected by land use and ephemeral lakes (Ginoux et al., 2012) has also been linked to ENSO.

The increase in the concentrations of dust transported to the tropical North Atlantic - at Barbados - since the mid 1970s has been linked to Sahelian droughts (Prospero and Lamb, 2003). Fig. 8a shows the summer NAFDI values from 1950 to 2014. Values of NAFDI were persistently higher prior to the onset of the Sahelian drought – from 1950s to mid 1960s - than since mid 1970s, with the lowest values observed during the most severe part of the drought - from 1980 to 1990 (Fig. 8a). Similarly, summer mean values of zonal wind at 925 mb in the subtropical Saharan Stripe were persistently higher prior to the Sahelian drought (Fig. 8b). This suggests that the meteorological change which occurred in the mid 1970s, did not only occur in the Sahel, but also in the subtropical Sahara. Particularly, the high wind speeds in the subtropical Saharan Stripe between mid 1950s and mid 1960s (Fig. 9a) – e.g. compared to the 1980-1990 period (Fig.9b) - may have enhanced dust mobilization in central Sahara (north of the ITCZ, including the subtropical Saharan Stripe). Further studies should address what have been the implications on dust transport paths and impacts over the North Atlantic of such meteorological changes.

5. Conclusions

The analysis of the 1987 to 2014 summer mean values of dust concentrations at Izaña observatory (~2400 m.a.s.l. in Tenerife), satellite and meteorological reanalysis data shows that summer Saharan dust export is highly dependent on the variability of the large scale meteorology in North Africa, which is characterised by a high over the subtropical Sahara and a low over tropic linked to the monsoon (at 850 hPa and aloft). We referred to this high-low dipole like pattern as North AFrican Dipole (NAFDI) and, in this study, we parameterized its variability in terms of the NAFD Intensity (NAFDI): the difference of geopotential heights anomalies averaged over the subtropic (30-32ºN, Morocco) and the tropic (10-13ºN, Bamako region) close to the Atlantic coast (at 5-8ºW longitude). Because summer dust export off the coast of North Africa tends to occur between 1 and 5 km.a.s.l., we determined the NAFDI at 700 hPa standard level. Other parameterisations of the NAFD are plausible depending on the study subject.

We observe significant summer-to-summer variability in the NAFDI, which is associated with shifts in the Saharan high that have implications on winds over the Sahara and on the outflow from North Africa and dust export. Increases in the NAFDI values (i) results in higher wind speeds at the north of the

Inter-Tropical Convergence Zone which are associated with enhanced dust export over the subtropical North Atlantic, (ii) influences the size distribution of exported dust particles (increasing the load of coarse dust) and (iii) are associated with enhanced rain in the tropic and northern shifts of the tropical rain band that may affect southern Sahel. Variability in NAFDI is also connected to spatial distribution of dust over the North Atlantic; high NAFDI summers are associated with major winds and dust export in the subtropic and minor dust presence in the tropic (linked to rainfall scavenging), and vice versa.

We found connections of NAFDI and dust at Izaña to climate variability. El Niño periods (e.g. 1987, 1997, 2006, 2009 and 2014) are generally associated with moderate to low summer mean values of the NAFDI, wind speed at the north of the ITCZ and dust at Izaña, and vice versa during La Niña summers (e.g. 1988, 1998, 1999 and 2010). The 1987 - 2014 summer mean dust records at Izaña showed a higher correlation with NAFDI + MEI·(-1) (r=0.77) than with either NAFDI (r=0.72) or MEI·(-1) (r= 0.50). These correlations evidence the need of understanding the processes that links dust with climate variability in the subtropics and tropics.

Further studies are necessary to understand how the variability of the summer NAFDI since 1950 to present days - associated with high wind speeds over subtropical Saharan dust sources prior to the Sahelian drought and low wind speeds over the subtropical Saharan during the severe part of the drought – may have influenced on the multi-decadal evolution of the dust export paths.

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Figure 1. Saharan dust observations in Izaña. A) Frequency of dust events (> 10 $\mu g/m^3$) in Izaña in the period 1987-2014. B) Batch of filters with aerosol samples collected at Izaña for illustrating their typical ochre colour due to dust.

Figure 2. Mean height of the 850 hPa geopotential over North Africa in summer (August).

Figure 3. Long term evolution (1987-2014) of summer dust and meteorology. Summer mean values of $dust_T$ concentrations at Izaña (black dot, A-D), MEI (green line, A), NAFDI (red triangle, A), zonal wind at 925 mb in the Subtropical Saharan stripe (25-28 ºN, 7ºW - 2ºE, B), zonal wind at 700 mb averaged in the Subtropical Saharan stripe to Tenerife corridor (25-28 ºN, 16ºW - 2ºE, C) and Wet Sahel Portion (blue dot) from 1987 to 2014. Green and red arrows highlight moderate and intense ENSO and La Niña summers, respectively (http://www.cpc.ncep.noaa.gov).

Figure 4. North African dipole and spatial distribution of dust and meteorological fields averaged in low and high NAFDI summers. Low NAFDI group includes the summers with the four lowest NAFDI values in the period 1987-2014 (1987, 1996, 1997 and 2006 = -2.79, -2.04, -3.19 and -1.54, respectively). High NAFDI group includes the summers with the four highest NAFDI values in the period 1987-2014 (1988, 2000, 2008 and 2012 = +0.68, +0.83, +1.01 and +2.29, respectively). Only summers for which satellite AI data are available were considered for this Low and High NAFDI summers selection (i.e. 1993-1995 and 2002-2004 were not included). A) height of 700hPa geopotential highlighting the location of the two regions used for determining the NAFDI. B) MDAF at the north of the rain band (data at the south of the tropical rain band is due to biomass burning aerosols from Southern Africa) (Prospero et al., 2002). Mean winds at (C) 925hPa (≈800 m.a.s.l.) and (D) 700hPa (≈3000 m.a.s.l.). E) mean precipitation rates. The location of the Inter-Tropical Convergence Zone (ITCZ), the Subtropical Saharan Stripe (SSS), the African Easterly Jet (AEJ) and the Subtropical North Atlantic (SNA) are highlighted.

Figure 5. Scatter plot of dust versus NAFDI and MEI. Summer mean $dust_T$ at Izaña (1987-2014) versus NAFDI (A), MEI (C) and NAFDI + MEI(-1) (D), and summer mean $dust_{2.5}$-to-$dust_T$ ratio (B, 2002-2014) versus NAFDI. Different symbols are used for the summer mean data of 2002 (black triangle), 2010 (grey triangle) and 2012 (white filled symbol) for exampling how some data may have different associations with NAFDI and MEI.

Figure 6. Influence of the NAFD strengthening on zonal winds, spatial distribution of dust and precipitation rate**.** Correlation coefficient between long term (1987-2012) summer NAFDI and (A) zonal wind (B) MDAF and (C) precipitation rate. The Inter-Tropical Convergence Zone (ITCZ) and the subtropical Saharan Stripe (SSS) are highlighted. Arrows indicate (A) zonal wind direction and (B) relevant airflows for dust mobilization.

Figure 7. Scatter plot of summer dust activity in the subtropical North Atlantic versus the NAFDI. MDAF in the Subtropical North Atlantic (SNA) versus the NAFDI (A) and versus $dust_T$ at Izaña (B).

Measurements of the TOMS (red circle) and OMI (blue dot) satellite borne sensors were used. The R^2 coefficient of the linear fitting is included.

Figure 8. Summer mean values of NAFDI (red triangle, A), $dust_T$ at Izaña (black dot, A) and zonal wind at 925 mb in the Subtropical Saharan stripe (25-28 ºN, 7ºW - 2ºE, B). Period of plentiful rains and severe drought in the Sahel are highlighted according to Lucio et al. (2012).

Figure 9. Mean winds at 925hPa (≈800 m.a.s.l.) in the 1957-1967 (plentiful rains in the Sahel) and the 1980-1990 (severe Sahelian drought) decades

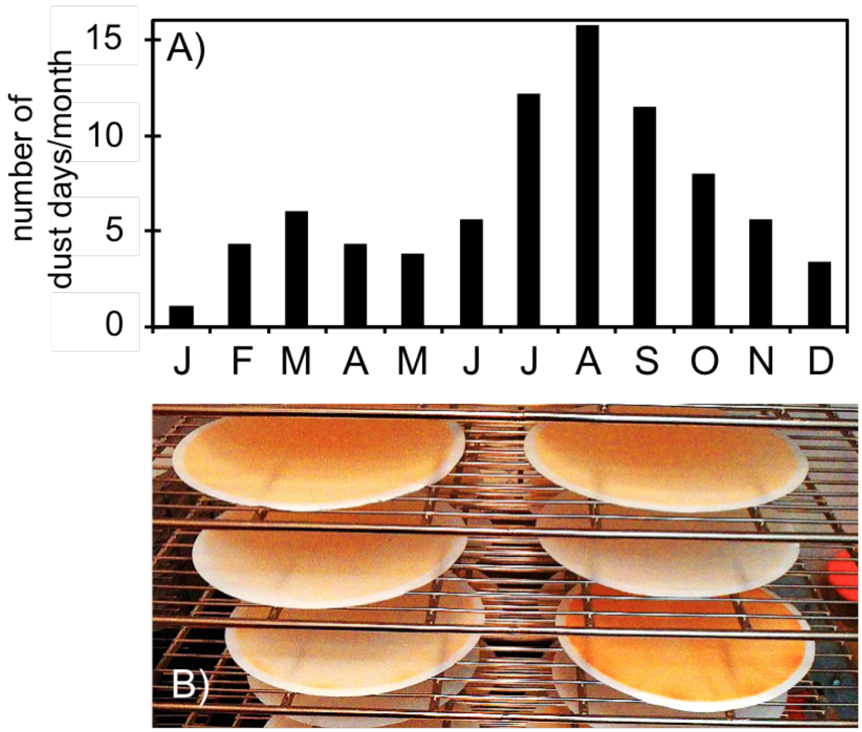


Figure 1.

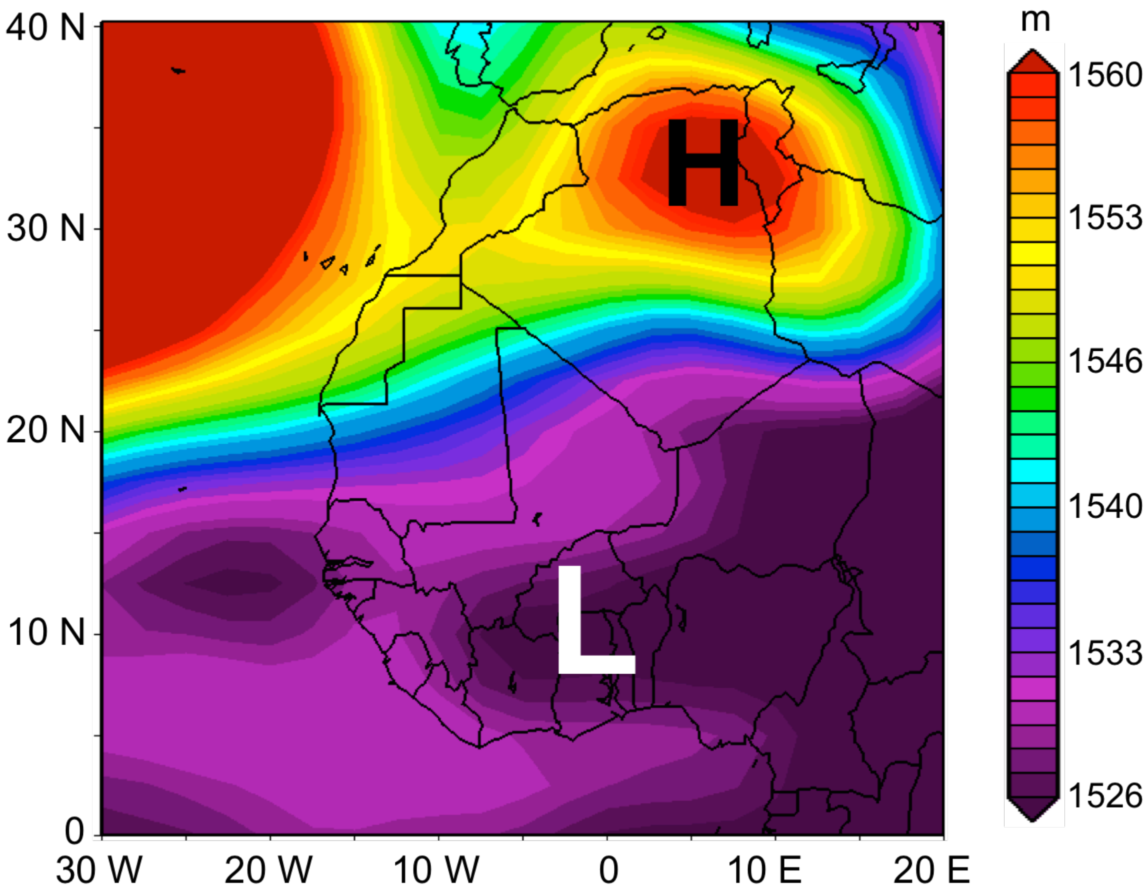
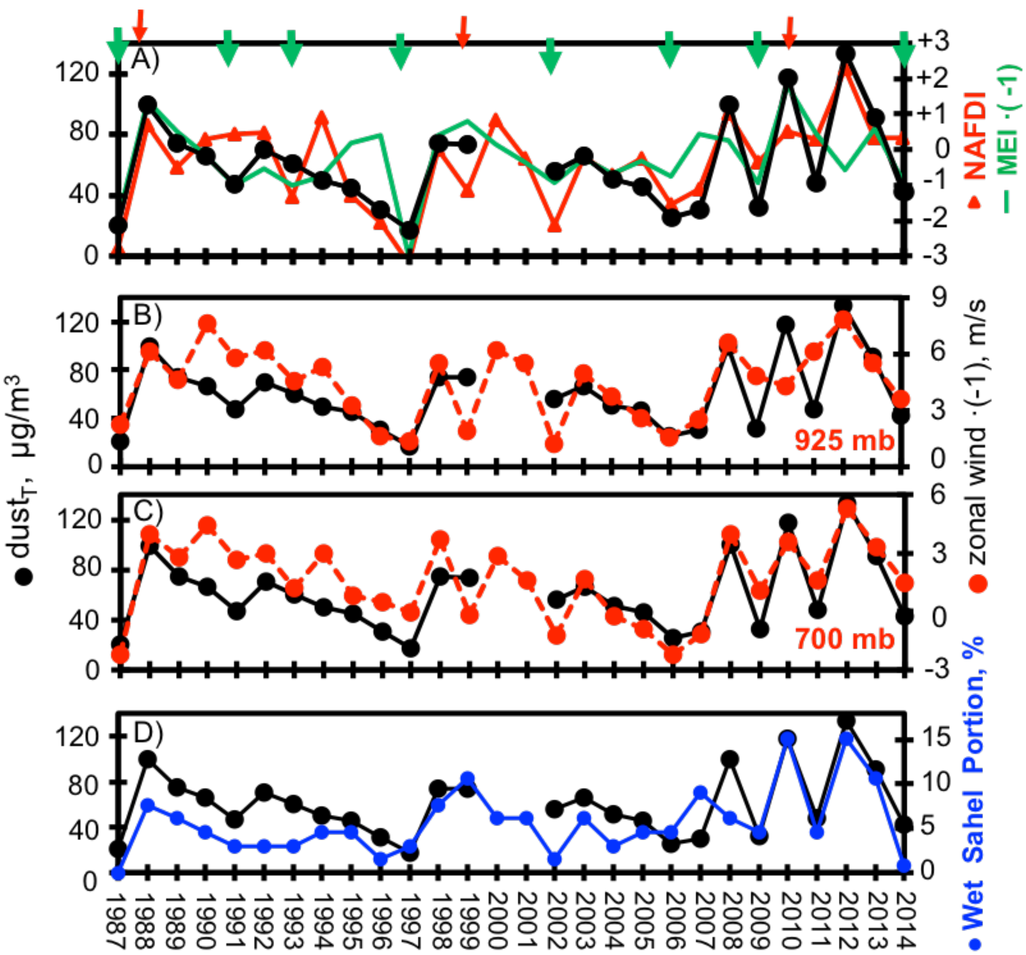

40 N
30 N
20 N
10 N
0
30 W
20 W
10 W
0
10 E
20 E
H
L
m
1560
1553
1546
1540
1533
1526

Figure 2.


A)
B)
C)
D)
NAFDI
MEI ·(-1)
dust_T, μg/m3
zonal wind ·(-1), m/s
925 mb
700 mb
Wet Sahel Portion, %
120
80
40
0
+3
+2
+1
0
-1
-2
-3
9
6
3
0
6
3
0
-3
15
10
5
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
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2001
2002
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2004
2005
2006
2007
2008
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2011
2012
2013
2014

Figure 3

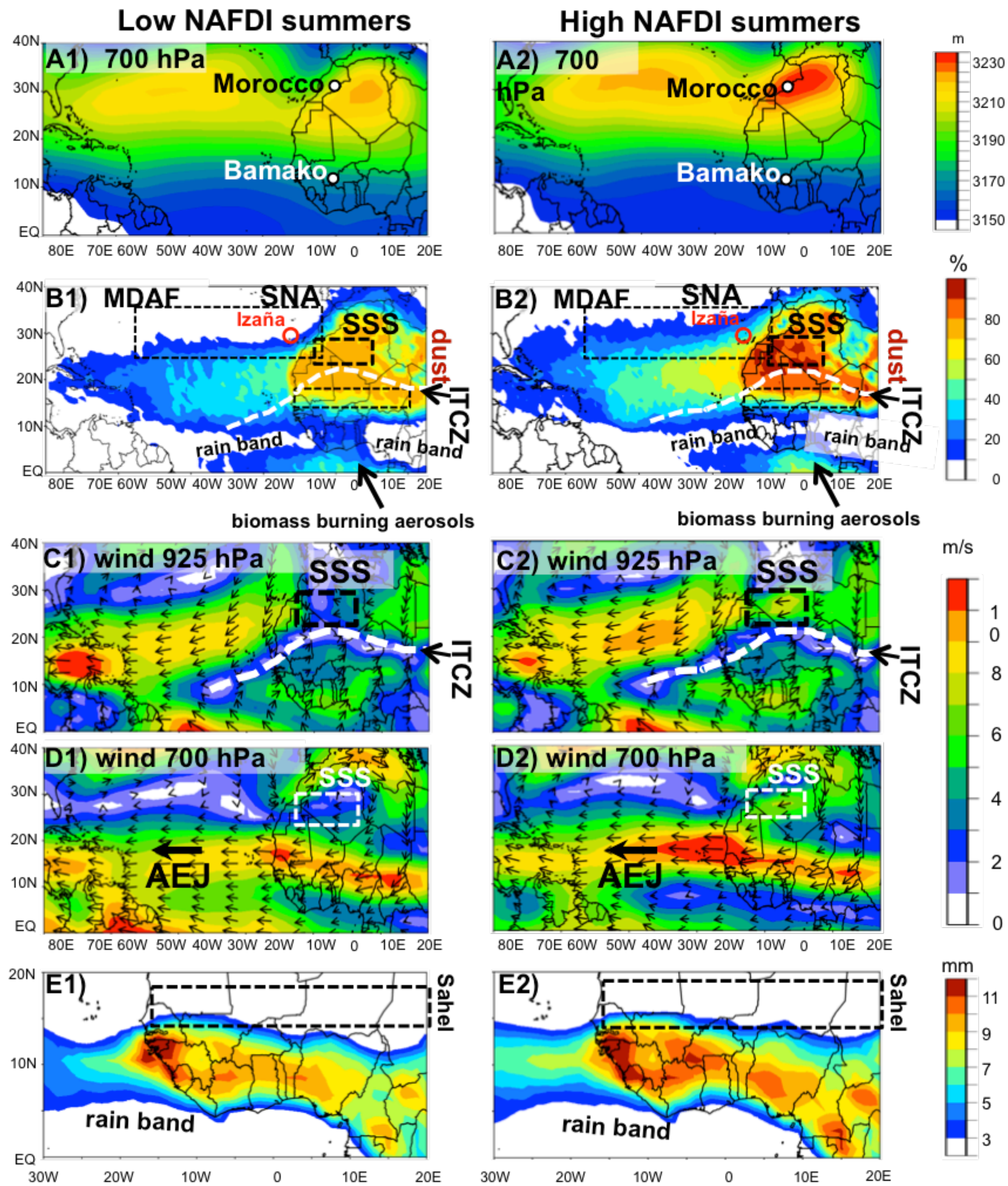

Low NAFDI summers
High NAFDI summers
A1) 700 hPa
A2) 700 hPa
Morocco
Bamako
B1) MDAF
B2) MDAF
SNA
SSS
Izaña
dust
ITCZ
rain band
biomass burning aerosols
C1) wind 925 hPa
C2) wind 925 hPa
D1) wind 700 hPa
D2) wind 700 hPa
AEJ
E1)
E2)
Sahel
m
%
m/s
mm

Figure 4.

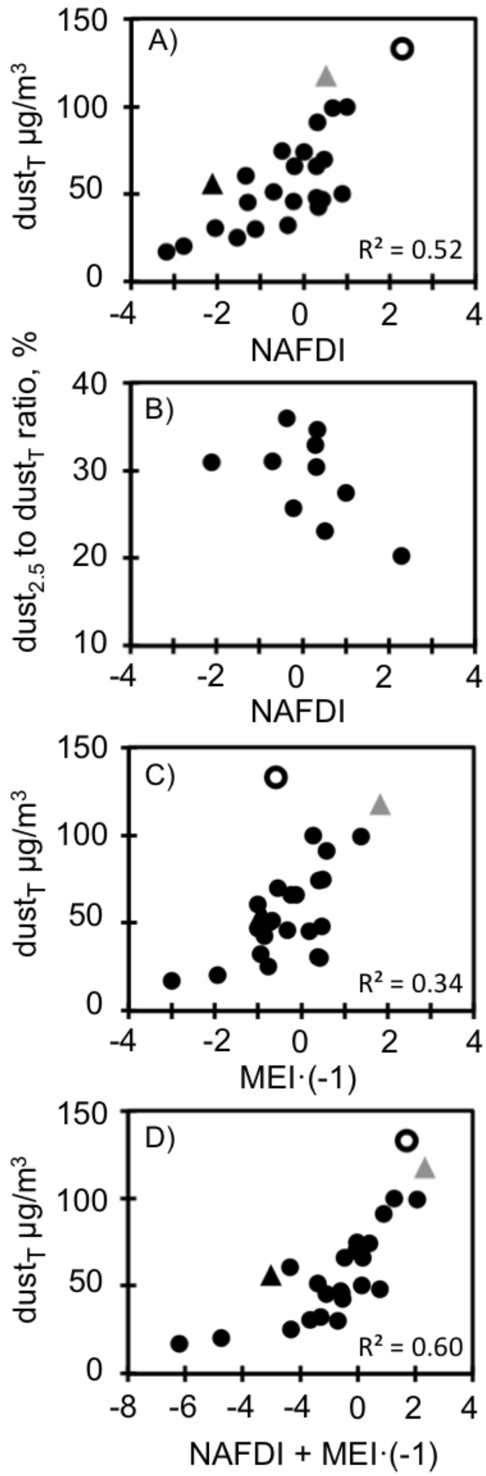
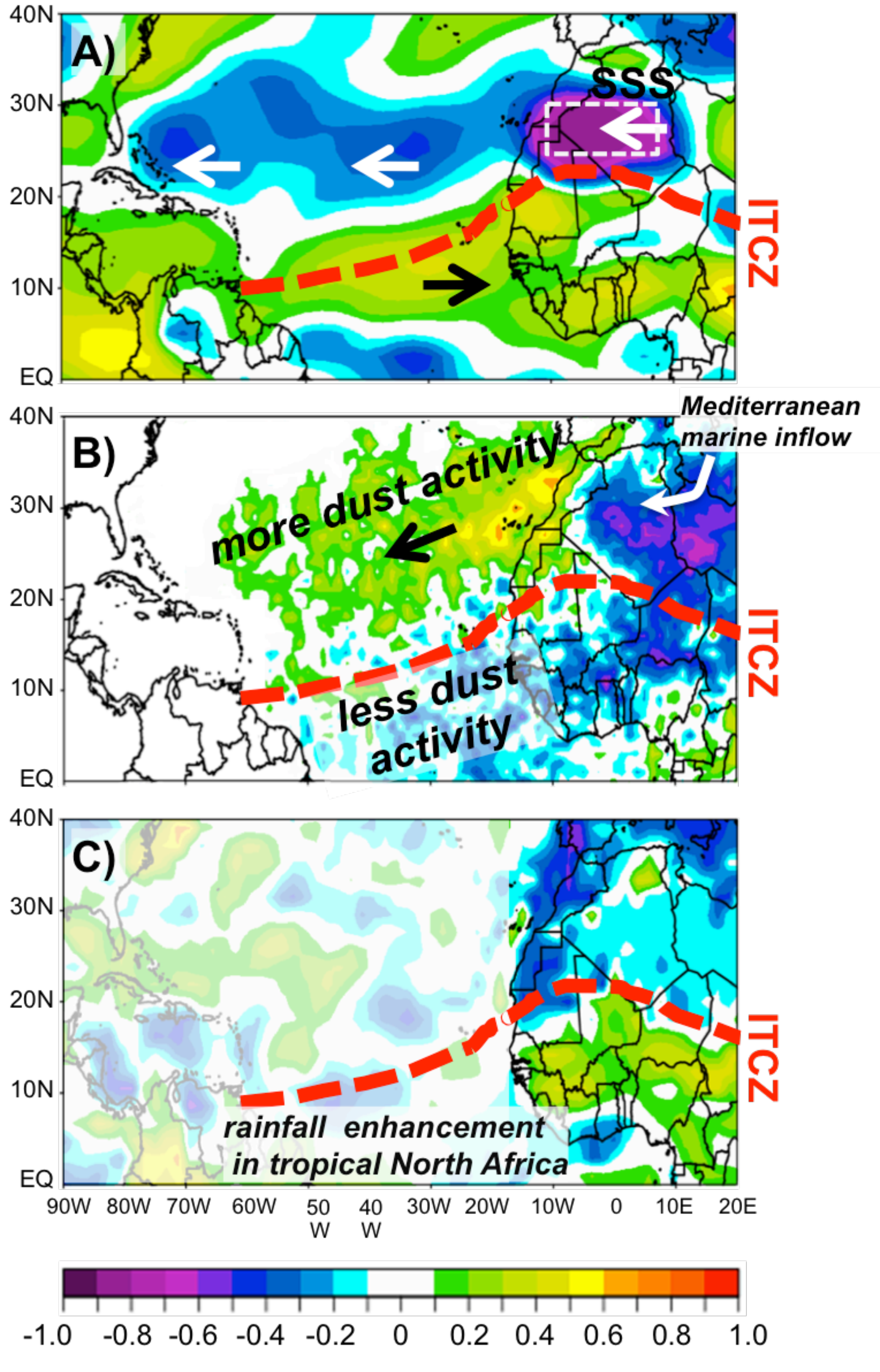

A)
dust$_T$ µg/m^3
NAFDI
R^2 = 0.52
B)
dust$_{2.5}$ to dust$_T$ ratio, %
NAFDI
C)
dust$_T$ µg/m^3
MEI·(-1)
R^2 = 0.34
D)
dust$_T$ µg/m^3
NAFDI + MEI·(-1)
R^2 = 0.60

Figure 5.



A)
SSS
ITCZ
B)
more dust activity
less dust activity
Mediterranean marine inflow
ITCZ
C)
rainfall enhancement in tropical North Africa
ITCZ
40N
30N
20N
10N
EQ
90W 80W 70W 60W 50 W 40 W 30W 20W 10W 0 10E 20E
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0

Figure 6.

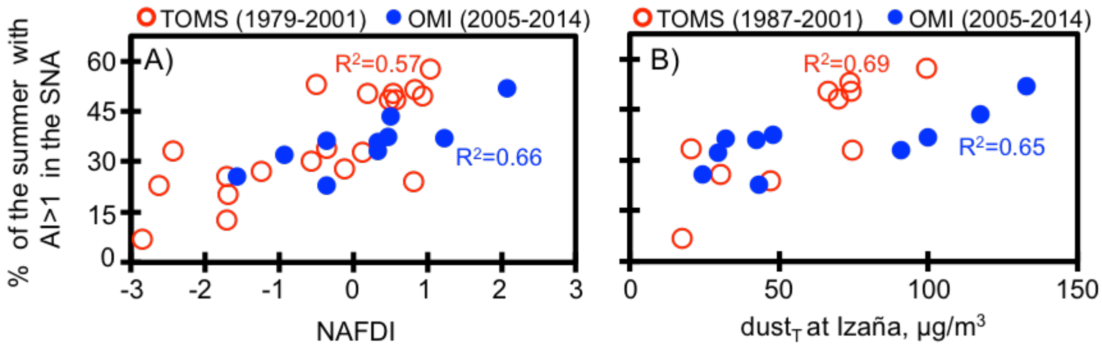


Figure 7.

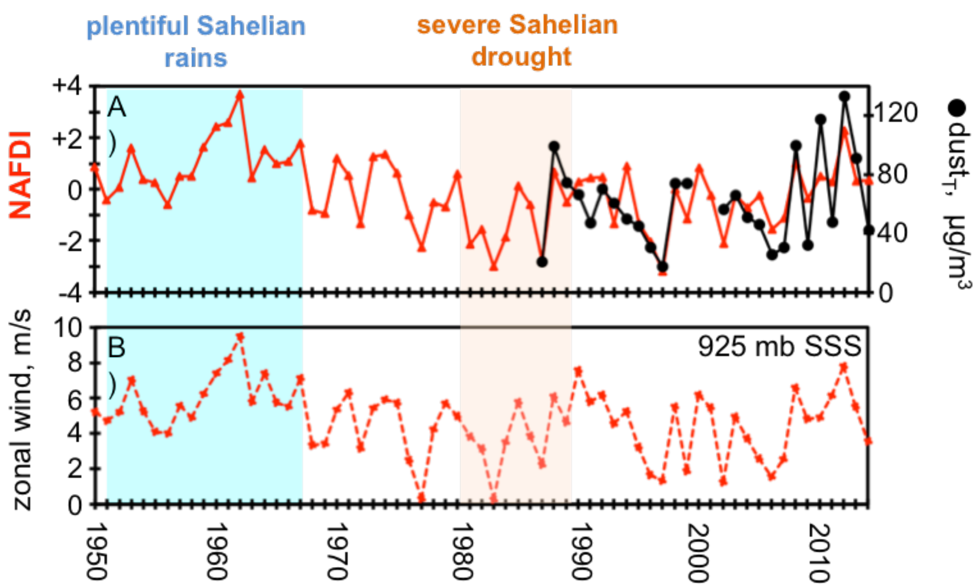


Figure 8.

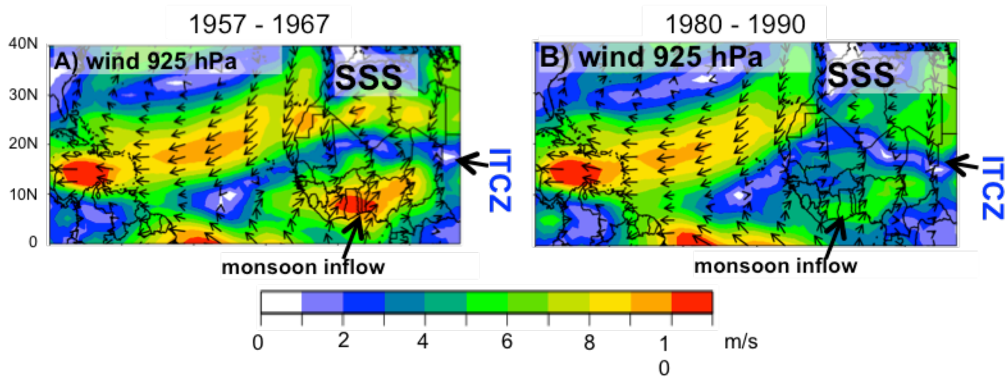

1957 - 1967
A) wind 925 hPa
SSS
ITCZ
monsoon inflow
40N
30N
20N
10N
0
1980 - 1990
B) wind 925 hPa
SSS
ITCZ
monsoon inflow
0
2
4
6
8
1
0
m/s

Figure 9.