Santa Cruz de Tenerife
23 April 2014

Dear Dr. Chuang

By taking into account the comments of both referees we have prepared a revised version of the manuscript. As you can see in their reports, both referees agree with the publication of the manuscript in ACP. They raised a set of questions and suggestions that, in our opinion, have definitively contributed to improve the manuscript (in some cases because more explanations were needed and in other cases because some part were not enough clear).

Please, find attached to this letter (i) the <Authors Response Report> which includes the reply to each question raised by the referees and a short description of the changes introduced in the manuscript as consequence of each referee comment, and (ii) a copy of the revised version of the Manuscript and of the Supplement where the changes performed (with respect to the ACPD version) are highlighted.

The revised version of the manuscript does not include changes of concept or interpretations, with respect to the ACPD version. The abstract and the conclusions were slightly reworded to include the comments of the referees. We have also update the data to 2014 (2012 in the ACPD version). The attached version with changes highlighted will allow tracing the modifications of the manuscript.

Referee 1 suggested change of title for avoiding the term dipole (referee 2 did not raised any comment about this). We (authors) have been discussing about this; because of the reasons described below (see comment Q1 of referee 1, section CHANGES IN THE MANUSCRIPT point (iv)) we have - in principle - decided to change keep the same title. We want, however, to avoid any potential rejection simply because of the title, so we kindly ask you to let us know for your opinion. In case we consider that other title could me more suitable we could modify it. Please, let us know.

The latex file will be uploaded in a further step once we have information about the acceptance of the article.

Thanks
Sergio Rodriguez

Authors Response Report

Referee 1 (Dr. Perez)

Changes in the manuscript due to comments and suggestions of referee 1 are indicated with the symbol R1#Qi (i=1,2….n) in the copy of the revised version of the manuscript where the changes are highlighted.

Q1) About the term North African dipole.

REPLY:
Thanks for this comment. We agree that the NAFDI is a measure of the geostrophic flow, in fact we did that description in section 4.1 of the paper (pg 26700, lines 9-11): <The NAFDI (Eq. 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>.

The term dipole is used to refer to the <subtropical Saharan high> with respect to the <tropical low> pressures during the monsoon, and not to the cases shown in Fig 2 (low (-) and high (+) NAFDI summers).

As said in the introduction of your review, a important result of this study is that inter-annual variability in dust export in the last decades have been modulated by variability in the intensity of winds. Although this is a relevant result, our purpose is to give a further step, and understand what is the relationship between the observed variability in winds and large-scale meteorology in North Africa. We initially did a year-to-year analysis, and observed that inter-annual variability in wind, dust export (Izaña and satellite observations), monsoon inflow and north-south shifts in the tropical rain band were connected through (and to) the variability in large scale meteorological patterns. We built the NAFDI as a tool for having an approximate description of the large-scale synoptic meteorological patterns in western North Africa with a simple number (note: the southern point was selected at 10-13 ºN –Bamako- in order the NAFDI be sensitive to the tropical region; if the objective would had been only sensitivity to geostrophic wind at the north of the ITCZ, then a southern point located in central Sahara 20ºN – rather than in the tropic - would have been enough). With the NAFDI we can have an approximate characterization of the large scale meteorological scenario in North Africa with just a number; for example, the overall results show that summers with a high values of NAFDI (e.g. > + 1.2) are associated with the reinforcement of the North African high at 700hPa over the Sahara, high wind speeds in the at the north of the ITCZ, a northern shift of the tropical rain band, high dust concentrations at Izaña and a northern shift in the Saharan Air Layer over the Atlantic. The correlation analysis presented in the study (between NAFDI and other variables, e.g. Fig 1, 3, 4 and 5) allowed quantifying the strength of the associations. It is important to highlight that, in general, we simply aim to describe the associations we observe between large scale synoptic meteorology and other variables, avoiding to establish casual relationships. Even if the NAFDI was determined between two regions 2300 km distant (Bamako and central-Morocco regions) – i.e. a distance is not very different to that used in other indexes such as the NAO (Lisbon and Reykjavík 2900 km, or Azores and Reykjavík: 2900 km) - we never used the term teleconnection index for referring to the NAFDI (the tele- connection was only used once for referring to other indexes such as MEI, pg 26703, line 16-17 < We also compared the NAFDI with a set of teleconnection indexes and found that the Multivariate ENSO (El Niño Southern Oscillation) Index (MEI)>).

Thanks again for this comment, which we really consider very useful; following your suggestion, we will consider to remove the term dipole from the title. We will also do more emphasis on what is the usefulness of the NAFDI (an approximate description of the meteorological scenario in the summer time in a given period).

CHANGES IN THE MANUSCRIPT:
Changes due to this comment are indicated with symbol R1#Q1, page 8:
(i) we did a more clear explanation on what how are we using the term dipole
(ii) we also included a new Fig 2 showing the meteorological scenario to which we referee as North African Dipole
(iii) the term Index was removed, now NAFDI is the acronym of North African Dipole Intensity
(iv) **About the use of the term dipole**.
Referee 1 said: The use of the term North African Dipole can be confused with a leading mode of variability in North Africa, particularly if it is announced in the title of the paper. This does not seem to be the case, or at least it is not shown in the paper. Therefore, I suggest the term North African dipole is avoided, at least in the title, as it can be misleading
Reply: we have introduced additional information that supports the use of the term dipole. A new Fig. 2 which shows the summer meteorological scenario of North Africa, characterised by low pressure in the tropic and high pressure in the subtropical Sahara (low-to-high dipole like pattern we referee as North African Dipole (NAFD) at the 850hPa has been added. Another new Fig. 7S which shows how this low-to-high pattern change in years with low and with high NAFDI values as also added. In our study it is shown how from 1987 to 2014 (28-years) the <summer dust concentrations at Izaña> and the <Wet Sahel Portion> (two processes not connected by causal-effect relationship) exhibits a high a correlation coefficient r=0.74 (Fig. 3d of the revised version of the manuscript). This demonstrates that variability in the large scale meteorology, as described by the NAFD, is a leading mode of variability in North Africa. We agree with the referee in the fact that a geopotential gradient anomaly between the subtropic and tropic is associated with winds and dust emissions. Our study gives a further step and shows how the variability in the geopotential gradient anomalies between the subtropic and tropic (NAFDI) is associated with shifts in the subtropical Sahara high with respect to the tropical low : (i) see meteorological scenario in low and high NAFDI summers are shown at the 850hPa level in Fig.7S (online Supplement) and at the 700hPa level in Fig.4 and (ii) observed the correlation between the 1987 to 2014 summer dust at Izaña (subtropics, Fig. 3a) and the Wet Sahel Portion (in the tropics Fig. 3d) which demonstrate the leading mode represented by the low-to-high dipole like patter. This is now clearly said in the section 4.4: <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>. We consider that to find this link between long term dust export and the variability in the large scale meteorology pattern in North Africa (as represented by the NAFD) is the key finding of this study.

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Q2) Comparison with results obtained by Doherty et al. (2008, J. Geophys. Res., 113, D07211, Saharan mineral dust transport into the Caribbean: Observed atmospheric controls and trends).

REPLY:

Thanks for this proposal. We didn't know about this study that is really very interesting and useful for us. Doherty et al. (2008) analysed how the variability in the pressure and latitudinal and longitudinal shifts of the Azores and Hawaiian anticyclone may have influenced the long-term (1979-1993) impacts of dust on the Caribbean.

The subtropical belt is expose to the high pressures linked to the descending branch of the Hadley cell. A set of concatenated anticyclones occurs along the subtropical belts. Doherty et al. (2008) focused on the Hawaiian and Azores high, whereas we focused on the North African high (described in the book <UK Meteorological Office, 1962. Weather in the Mediterranean, Vol. I,2nd Edition. General Meteorology HM Stat. Office, London>, and by < Rodriguez et al., 2001, Saharan dust contributions to PM10 and TSP levels in Southern and Eastern Spain, Atmos Environ 35, 2433-2447> and by other studies cited in the ACPD manuscript).

Meteorological processes affecting impacts of North African (Saharan & Sahelian) dust to the Caribbean can be split in two:

1) processes affecting dust export off the coast of North Africa. This is the subject of our study, on the basis of the variability of the typical meteorological scenario of North Africa (North African high, trade – Harmattan – winds, monsoon, etc…).

2) processes affecting trans-Atlantic transport of dust (from the coast of North Africa to the Caribbean). This is the subject studied by Doherty et al. (2008), on the basis of the variability of the Azores and Hawaiian highs and some tele-connection indexes (NAO and ENSO).

The study of Doherty et al. (2008) focused on the trans-Atlantic transport; they did not studied (neither described) meteorological processes in the North Africa continent. This is the reason because Doherty et al. (2008) and our study are complementary.

Even if we focused on different aspects of dust transport (export vs trans-Atlatnic transport), the conclusions and some of the proposals of Doherty et al. (2008) are consistent with our results, e.g. about how shifts in the subtropical anticyclones and the implications on trade winds may influence on dust transport. We will definitely include a comparison with the results of Doherty et al. (2008), which will contribute to have a broader view. Thanks again for this suggestion.

CHANGES IN THE MANUSCRIPT:
Changes due to this comment are indicated with symbol R1#Q2:
-Introduction
-section 4.4
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Q3) About the interpretation of the dipole in section 4.4.

Q3.1. Page 26703 line 2: "This suggests that NAFD may also influence Sahelian dust emissions and consequently dust impacts in the tropical North Atlantic".
It is not clear here how it can be derived that the NAFD may influence Sahelian dust emissions.

REPLY:
Thanks for this comment. The reason to think in <emissions> was based on:

1) Prospero and Lamb 2003 (see reference list of the ACPD manuscript) showed that during 4 decades, the amount of dust transported to the Caribbean was negatively correlated with the precipitation in the Sahel. Although this not necessary means a causal relationship, it has contributed to support the idea that inter-annual variability in the wetting of soil may influence of dust emissions (e.g. the paper of Doherty et al. (2008) you suggested above).

2) Our results show that the NADFI is correlated with the Wet Sahel Portion (portion -%- of the Sahel that received a precipitation rate > 3mm/day), i.e. high NAFDI summers are associated with a northern shift in the tropical rain band, prompting rains at the south of Sahel (Fig 1A and 1E).

Although it is true that it may influence on Sahelian dust emissions, it would only affect to the southern part of the Sahel (max value of Wet Sahel Portion is 15% Fig 1B), and consequently may not necessary be as significant to influence on Sahelian dust impacts on the Atlantic. (i) The negative correlations we observe between NAFDI and MDFA (Major Dust Frequent Activity) in Southern Sahel and the tropic (Fig. 4B) and (ii) the low MDAF in high NAFDI summers (associated with a high Wet Sahel Portion) may also be interpreted as caused by enhanced scavenging link to rains (as described in lines 5-9, page 26703). For this reason, we will revise this reference to the emissions (remove or to nuance it).

CHANGES IN THE MANUSCRIPT:
Changes due to this comment are indicated with symbol R1#Q3.1:
-Section 4.4
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Q3.2. Line 3: "The low MDAF in the Sahel and in the tropical rain band during high NAFDI summers supports this (Fig. 2b2). The association of NAFDI with the monsoon rains (Fig. 4c) and the implications for dust emissions and scavenging, accounts for the negative correlation of NAFDI with the MDAF over the Sahel and tropical North Africa (Fig. 4b),"
Figure 2 shows larger MDAF for high NAFDI summers than for low NAFDI summers.

Yet, there is a negative correlation in the Sahel (Figure 4b). Also a bit surprising is the negative correlation between the NAFDI and MDAF in the main source areas in Algeria (in contrast to the high MDAF for high NAFDI summers and the lower MDAF for low NAFDI summers in Figures 2B1 and 2B2).

REPLY:
The reason of low MDAF (Major Dust Activity Frequency) in high NAFDI summers in the Sahel and tropical rain band was described above.
About Algeria. In general, the data analysis shown in Fig 2B2 may (potentially) be affected by the mixing (when calculating the average in each pixel for the 1988, 2008 and 2012) the signal linked to different dust sources that can be activated with different strength in different years. A quick comparison between Fig 2B2 and Fig 4B suggests that results in Central Algeria could be inconsistent; however, if we compare the two figures in detail we can clearly see that they are consistent. Please, see Fig Q3.2 (attached to this document), in which we have merged F4B (correlation coefficient between NAFDI and MDFA) and Fig 2B2 (MDFA in high NAFDI summers). The region of high MDFA in high NAFDI summers is highlighted in Fig. 2B2 and projected in Fig 4B. In the composite shown in part 4B (of Fig Q3.2), it can clearly be observed how the region of <negative correlation between NAFDI and MDFA> (blue and violet) occurs at the north of the <High MDAF in high NAFDI summers> region (red line). The negative correlation between NAFDI and MDFA is probably linked to the entry of the Mediterranean marine inflow by Libya (a well know airstream, e.g. Fig. 2C).

CHANGES IN THE MANUSCRIPT:
This comment does not require modifications in the paper.
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Q3.3. Line 12: "This modulation of dust export and monsoon rains by the NAFDI may account for the results obtained: : :"
This sentence implies that the NAFDI modulates monsoon rains and this is not shown.
Correlation doesn't mean causation.

REPLY:
We agree with this criticism. This sentence will be reworded to avoid establishing causal relationships.

CHANGES IN THE MANUSCRIPT:
Text reworded. Change indicated with R1#Q3.3
Section 4.4
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Q3.4. Line 21: "This suggests that variability in MEI and in the NAFDI may be connected to global climate oscillations in the subtropics, e.g. intensity in the global trade winds belt, as also suggested by the correlation between NAFDI and the zonal component of trade winds (Fig. 4a)."
This sentence is difficult to understand. How the correlation of the NAFDI and the zonal component suggest that the NAFDI may be connected to global climate oscillations in the subtropics? More detail is needed to support this suggestion.

REPLY:
We mean that:
(i) low NAFDI years are frequently associated with high MEI years (El Niño) and vice versa (high NAFDI with La Niña events),
(ii) during El Niño – high MEI years – trade winds over the Pacific weakens (as part of the well known phenomena),
(iii) low NAFDI years are associated with low winds at the north of the ITCZ over Central Algeria (as demonstrated in the paper, e.g. Fig 2C1 and Fig 4A) and this is consistent with the simultaneous weakens of trade winds (ii) during El Niño years (as part of the phenomena, not shown by us)

Variability in the strength (pressure) and position (latitudinal and meridional shifts) of the subtropical highs (Pacific, Atlantic and North Africa) may influence on the strength of trade winds; because of these anticyclones are concatenated along the subtropical belt, variability in the intensity and/or location of one of these anticyclones may influence on adjacent regions. For example, according to Doherty et al. (2008) - paper you suggested above - variations in the Hawaiian High pressure system control the strength and the position of the trade winds, and this is highly correlated with fluctuations in the SOI (El Niño – Southern Oscillation Index); they conclude that transport of dust to the Caribbean by the Gulf of Guinea is teleconnected with the strength and longitudinal shifts of the Hawaiian high. This is just an example of the relationship we are referring. We will rewrite this part of the revised version of the manuscript to clarify this.

CHANGES IN THE MANUSCRIPT:
Change indicated with R1#Q3.4
-Section 4.4. Text reworded. The sentence < This suggests that variability in MEI and in the NAFDI may be connected to global climate oscillations in the subtropics, e.g. intensity in the global trade winds belt, as also suggested by the correlation between NAFDI and the zonal component of trade winds (Fig. 4a).”> was removed.
-We also included wind in the Fig. 3B and 3C.
-We have included Fig. 5 C ad 5D (also by a comment of referee 2) which illustrate the connection to both NAFDI and MEI.
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Q3.5. Line 3: "The increase in dust concentrations recorded in the tropical North Atlantic at Barbados [: : :] since the mid 1970s has been linked to Sahelian droughts (Prospero and Lamb, 2003). Have similar changes occurred at subtropical Saharan latitudes? To address this issue we assumed that the "dustT vs. NAFDI relationship found for the period 1987–2012 period" is also valid for preceding decades, and used regression equation shown in Fig. 3a for estimating summer dustT at Izaña using the NAFDI from 1950 to 2012. We estimate persistent high dust concentrations (68 to 10 120 μg·m-3) at Izaña's subtropical latitude (Fig. 1c) from the mid-1950s to mid-1960s and relatively low dust concentrations from mid-1970s to mid-1980s (16 to 81 μg·m-3) (Fig. 1c). This NAFDI-based record at Izaña is markedly different from that based on measurements in Barbados which showed low dust concentrations prior to the onset of Sahelian drought in the early 1970s and high concentrations since then (Prospero and 15 Lamb, 2003). This suggests that multidecadal changes in the NAFDI may have modulated the latitudinal transport pathways of North African dust across the Atlantic. This is supported by our overall results which show that high values of the NAFDI enhance dust transport at subtropical latitudes and rainfall in the Sahel"

Q3.5.A. How can we respond to the first question using the NAFDI? The trends in Barbados where linked to drought and not to the strength of the winds.

REPLY: We do not attempt explain dust at Babados, but to Izaña-subtropical latitudes. Our results have shown that dust impacts in the subtropics are correlated with winds and with NAFDI. So, NAFDI is used for estimating dust at Izaña.

CHANGES IN THE MANUSCRIPT:
Text reworded [R1#Q5] and new plot in Fig. 8B and 9.
We removed the estimation of dust at Izaña since 1950.
The text was smoothed. Now it is said that the reanalaysis data suggest that the changes observed since the 1970s did not only affected the Sahel (drought), but also subtropical Sahara and that future research is needed to study how the enhanced wind speeds in the subtropical Sahara observed prior to the drought affected dust export to the subtropic. Changes in wind speed in the subtropical Saharan Stripe can be observed in the new plot (Fig. 8B) and Fig.9
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Q3.5.B. The last suggestion on the multidecadal changes in the NAFDI seems a bit speculative. In any case, the trends in the NAFDI can be explored using the reanalysis. Is there any trend?

REPLY: we do not understand this comment. We have already explored the evolution of NAFDI from 1950 to 2012 in Fig 1C. It can be observed how from ending 1950s to ending 1960s the NAFDI showed high values (mean value 1957 to 1967 = + 1.56; Fig 1C) whereas from ending 1970s to ending 1980s the NAFDI showed low value (mean value 1977 to 1987= - 1.33; Fig 1C). This illustrates that the decadal changes are not speculative. This has been done by using the reanalysis (as you suggest; details in the methodology section).

CHANGES IN THE MANUSCRIPT:
Time serie of NAFDI from 1950 to 2014 is included in Fig 8A and discussed in at the end of section 4.4. This is part of the previous modification [R1#Q5]
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Q3.5.C. The last sentence states that the NAFDI enhances rainfall in the Sahel. This causation hasn't been shown.

REPLY: we agree with this comment. This will be reworded, e.g. by replacing the term modulation by association.

CHANGES IN THE MANUSCRIPT:
That sentence was removed.

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Q3.5.D. It is not clear how you relate Barbados and Izana. Is the Barbados variability in August related to the NAFDI?

REPLY: A detailed analysis of dust impacts in Barbados is out of the scope of this study, in fact we simply did reference to other study on Barbados (Prospero and Lamb, 2003). As already stated above (reply to Q2), dust impacts in the Caribbean (Barbados) are affected by processes affecting <dust export from North Africa> and by processes occurring during <trans-Atlantic transport>, and in this study we just focused on processes affecting dust export. The comparison between the behaviour of dust at Barbados (Prospero and Lamb, 2003) and that we estimated in Izaña (Fig 1C) is done through the NAFDI. In the 1987-2012 period we observed that:

(i) high NAFDI summers are associated with intense winds in the subtropical Sahara, high dust export to subtropical latitudes, enhanced rains and low dust loads in the tropics.

(ii) low NAFDI summers are associated with low wind speeds in the subtropical Sahara, low dust export to subtropical latitudes, lower rains in the Sahel due to a southern shift in the rain band and high dust loads in the tropics.

Because of this (i+ii), the Saharan Air Layer is shifted to north in high NAFDI summer with respect to low NAFDI summers (Fig 4C).

The low dust impacts at Barbados in the 1950s-1960s (according to Prospero and Lamb, 2003), when the NAFDI exhibited the highest decadal values (mean value 1957 to 1967 = + 1.56; Fig 1C), are consistent with the behaviour we observed in high NAFDI summers (i). This would imply a high dust load in the subtropics in that period (Fig 1C). This is a new idea we propose here due to the high interest of the scientific community on the increased in dust impacts on Barbados since the 1970s. This will require future studies.

CHANGES IN THE MANUSCRIPT:
This part was removed.

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Q3.5.E. This paragraph and more generally section 4.4 needs more detail and discussion in the context of previous studies (Including those related to summer dust variability in Barbados). In particular, the results may be compared with those obtained by Doherty and co-authors. Nothing is said in the paper about the Azores High displacement, which seems to be a central aspect partly explaining the enhanced easterlies resulting in high dust years.

REPLY:
Thanks, this is a good suggestion. As already said above (Q2) the paper of Doherty et al. (2008) is complementary to ours. We focused on how the variability of the meteorological scenarios in North Africa influence on dust export, whereas the results of Doherty et al. (2008) have implications on transport across the North Atlantic (they did not analysed what was happened in North Africa). This comparison will be included in the revised version.

CHANGES IN THE MANUSCRIPT:
We have add more details to seccion 4.4, including references to Doherty et al.

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Q4) About transfer of material from Supplement to Main text.

REPLY: We agree with these suggestions. Part of Supplement will be moved to main text according to these recommendations and those raised by referee 2 as well.

CHANGES IN THE MANUSCRIPT:
Plots of wind speed were transferred from the Supplement to the paper.
Fig. S7 was modified, repeated material was removed (now it only includes geopotential height at 850hPa, which is not included in the paper).

Referee 2

Changes in the manuscript due to comments and sugestions of referee 2 are indicated with the symbol R2#Ci (i=1,2….n) in the copy of the revised version of the manuscript where the changes are highlighted.

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C1) About description data included in the supplement and data management.
1. Although the authors provide additional information of the dust surface concentrations in the supplement I consider that important information should be provided in the text. The authors mention daily data in the text but the analysis is done in terms of monthly data. How is the monthly average computed, more specifically how is the NAFDI computed, taking only days with surface concentration data or taking all days?

Same is valid with respect to the satellite data. Furthermore, the authors mention that two databases of dust surface concentration exist for the analysed period, which one was used for the study? This should be clarified.

REPLY:
We agree with this suggestion and part of the methodology of dust measurements will be transferred to the text of the article. Aerosol samples for chemical analysis have been collected every day, so dust records in our database have a daily time resolution. Time series of dust presented and analysed in the article (Fig.1A-1B) is based on monthly averages calculated with the daily data available for the month. The requested details on the measurements, used databases and calculation of the monthly averages of dust and satellite information will be included in the main text (not supplement) of the final version of the manuscript.

CHANGES IN THE MANUSCRIPT:
This change has been introduced in the text as the referee suggest. Changes are indicated with the symbol R2#C1:
-section 2.1, part of the methodology used in the measurements was transferred from the sumplement to the manuscript.
-Fig. 1 was transferred from the supplement to the manuscript.
-section 4.1 about NAFDI

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C2) About high and low NAFDI summers.
2. Although the high and low NAFDI summers are defined in caption of Figure 2, this should be made explicit in the text. In addition, the authors should explain why the define high and low NAFDI summers only taking 3 years. Why were the years 1994 (high NAFDI) and 2002 (low NAFDI) excluded?

REPLY:
We agree with this comment. A detailed description will be added in the text. We selected the three years with the three highest and three lowest NAFDI for which dust data at Izaña and satellite AI and reanalysis. These details will be added in the text. We will increase from 3 to 5 the number of years used in each group with the highest and lowest NAFDI values (we have already checked the results and there are no relevant changes when using 5 year in each group rather than 3 years).

CHANGES IN THE MANUSCRIPT:
This change has been introduced in the text as the referee suggest, including an explanation of why some years were not included in the selection Changes are indicated with the symbol R2#C2:
-section 4.1

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C3) About back-trajectories.
3. Section 2.3 mentions that back trajectories were analyzed but no mention is made of this analysis neither in section 4 presenting the results nor in the conclusions. Either include some of the results in the text or remove this analysis completely from the manuscript. The supplement is made to provide additional information or to support the results presented in the study. If the back trajectories is not linked somehow to the results and is not even mentioned then I don't see the point of having it in the supplement at al.

REPLY:
We also agree with this comment, the back trajectories analysis will be transferred to the main document (removed from the supplement).

CHANGES IN THE MANUSCRIPT:
When reading this comment we thought in move the trajectory analysis from the supplement to the manuscript. However, we now consider that release that such Figure is not really necessary into the manuscript. For this reason, we let the trajectory analysis in the Supplement and moved the reference to the trajectories calculation from section 2.3 to the Supplement.

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C4) About surface dust concentrations movement.
4. Section 2.4 describes how the dust surface concentrations are processed. I suggest moving this paragraph to section 2.1 where the surface concentrations are presented.

REPLY:
We agree, it will be transferred.

CHANGES IN THE MANUSCRIPT:
In the revised version of the manuscript, the description of how dust data were obtained and processes is included in Section 2.1 [R2#C4]. Section 4.1 is focused on described the scientific interest on August, it includes a description of the meteorological and dust data analysed in the paper. All aspects of August (the study month) need to be included in this section.

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C5) About surface dust concentrations.
5. The authors make references to the supplement throughout the text but without specifying which figure, table and/or section they refer. The authors should facilitate the task to search the information in the supplement to the reader and specify which part is meant each time the supplement is referenced.

REPLY:
Thanks for this comment. References to the specific figures of the supplement will be included in the main text.

CHANGES IN THE MANUSCRIPT:
Throughout the manuscript we have add reference to the specific sections, figures and tables of the supplement [R2#C5].

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C6) Correlation of NAFDI with other parameters.
6. Figure 4 presents correlations between the NAFD with different parameters (zonal wind, MDAF and precipitation). Is this done for all summers, high NAFDI summers or Low NAFDI summers? I'm surprised by the negative correlations over ocean and continent in the subtropical band. From Figure 2 we see that low NAFDI summers we have weaker winds than summers with high NAFDI, shouldn't that give a positive correlation? A negative correlation between NAFDI and zonal wind tells me that while one increases the other one decreases. Doesn't a negative correlation contradict the result that enhanced

dust transport is linked to the NAFDI and is associated to stronger easterly zonal winds? Please clarify. How exactly is this figure produced?

REPLY:
Fig 4 was calculated using all summer-averaged data (1987-2012). The negative correlation is due to the direction of the zonal component of wind vector is indicated with a sing: negative for westward wind (e.g. - 1 m/s) and positive for eastward wind (e.g. + 1 m/s). The very negative correlation between NAFDI and zonal wind in Central Algeria means that in high NAFDI summers there are strong westward winds over Central Algeria, and this is in agreement with the results plotted in Fig 2. Similar for winds over the ocean and the other regions included in the plot. That is the reason because arrows highlighting the wind direction pointed by the resulted of the correlation were included in fig 4A. Thanks for this comments, this will be explicitly described in the text.

CHANGES IN THE MANUSCRIPT:
This has been explicitly introduced in the text, section 4.2 [R2#C6].

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C7) Correlation of NAFDI with other parameters.

7. The results show that in general, enhanced dust surface concentrations in the summer coincide with and increase in the NAFDI. This is illustrate in Figure 5a and is seen for most of the years in Figure 1a. The authors then analyze the meteorological largescale condition and link the enhanced surface concentration to increase of zonal wind in the subtropics. Only three summers are used to define the high NAFDI summers and three for the low NAFDI summers. Yet, years exists where low dust surface concentration is not matched with low NAFDI (1991 and 1994), in particular for the year 1994 with a NAFDI equivalent to the year 1987. The latter was defined as a high NAFDI year and used in the analysis. The authors should explain or at least discuss why

REPLY:

This is an interesting comment; I guess you meant to 1988 (which has a high NAFDI similar to 1991 and 1994) and not to 1987 (low NAFDI). Yes, effectively, in 1991 and 1994 the NAFDI was rather high whereas dust concentrations were not as high as expected for these NAFDI values (compared to other summers). There are many factors that may have prompted this, e.g. vertical distribution of dust, dust deposition processes, meteorological processes that may have a scale rather low to be studies with the resolution of the re-analysis data. The correlation coefficient between the times series of summer mean values of NAFDI and dust at Izaña is +0.74, this means that the processes explained by the NAFDI accounts for most of the variability of dust, whereas other processes not properly described by NAFDI accounts for a rather low variability of dust (~25%). Thanks for this comment which will be included in the text.

CHANGES IN THE MANUSCRIPT:

The fact that some (just a few) high dust summers have not be associated with NAFDI values is now described in the text together with the association of MEI in section 4.4 [R2#C7].

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Specific comments

S1. Page 26691, lines 15-18: I suggest reformulating these lines with parenthesis within parenthesis.

REPLY: thanks, will be considered.

CHANGES IN THE MANUSCRIPT:

Brackets removed and a coma added [R2#S1].

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S2. Page 26693, lines 10-16: I suggested reformulating these lines, too long and unclear.

REPLY: agree, thanks.

CHANGES IN THE MANUSCRIPT:

We add (i) and (ii) for separating the data sets [R2#S2].

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S3. Page 26693, line 18: remove “the” in “in the summertime”.
REPLY: thanks.
CHANGES IN THE MANUSCRIPT:
removed.

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S4. Page 26696, line 6: include “the” after “studying”.
REPLY: thanks.

CHANGES IN THE MANUSCRIPT:
Added [R2#S4].

================================

S5. Page 26699, Eq 1: why is there a 0.1 in the equation? Please clarify.
REPLY: thanks.

CHANGES IN THE MANUSCRIPT:
Clarified in the text , section 4.1 [R2#S5] - It is just a scaling factor by which NAFDI has an order of magnitude of 1, and it varies between -4 and +4.

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S6. Page 26704, line 6: replace “latutudes” with “latitudes”.
REPLY: thanks.

CHANGES IN THE MANUSCRIPT:
That sentence was removed, so the correction is not needed.

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S7. Page 26715, Figure 2: Although the latitudes are provided in Figure 2d, please include them again in Figure 2a and 2b, it makes it easier to read them.
REPLY: thanks.

CHANGES IN THE MANUSCRIPT:
I guess referee meant longitude (rather than latitude). They were included.

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END

Copy of the manuscript with changes highlighted in green colour

Brackets indicate the comment or suggestion that prompted the change [R1Q….and R2C….]

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. [R2#S1] 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 [R1#Q2].

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) [R2#S2] 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) [R2#S2] 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 [R2#C1 and R2#C5].

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) [R2#C1, R2#C4 and R2#C5]. 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 [R2#C1] and [R2#C4]).

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) [R2#C5].

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 [R2#S4] 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 [R2#C5]). The maximum frequency of dust events occurs in August (52% of the August-days as average; Fig. 1 [R2#C1]). 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 [R2#C5]). 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[R2#C1]) averaged in all (dust and no-dust) days of August (shown in Fig. 3a and analyzed below [R2#C1]). We refer to August as summer. Results are presented in section 4; additional analysis is presented in section S3 of the online Supplement [R2#C5].

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 [R1#Q1]. 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) [R2#C1]:

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

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 [R2#S5].

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) [R2#C1 and R2#C2].

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 [R2#C5]). 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 [R2#C6]). 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 [R1#Q3.1] 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) [R1#Q3.1]. 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 [R1#Q1]. 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 [R1#Q3.3] 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 [R2#C5]). 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)[R1#Q3.4 and R2#C7]. 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 [R1#Q2]. 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. [R1#Q5]

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 µg/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. [R2#C1]

Figure 2. Mean height of the 850 hPa geopotential over North Africa in summer (August) [R1#Q1].

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). [R1#Q5]

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. [R1#Q5]

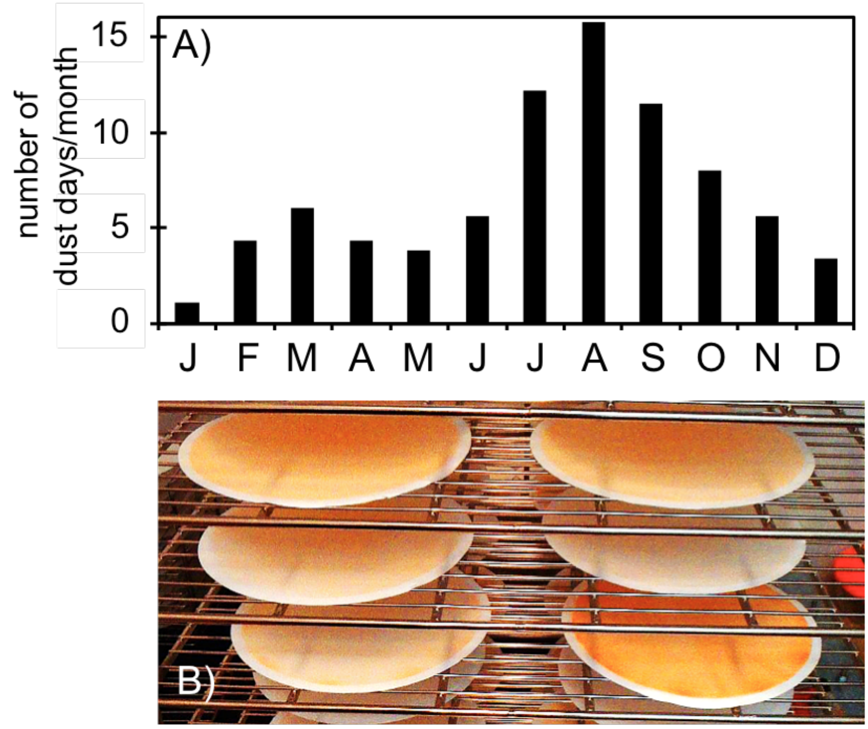
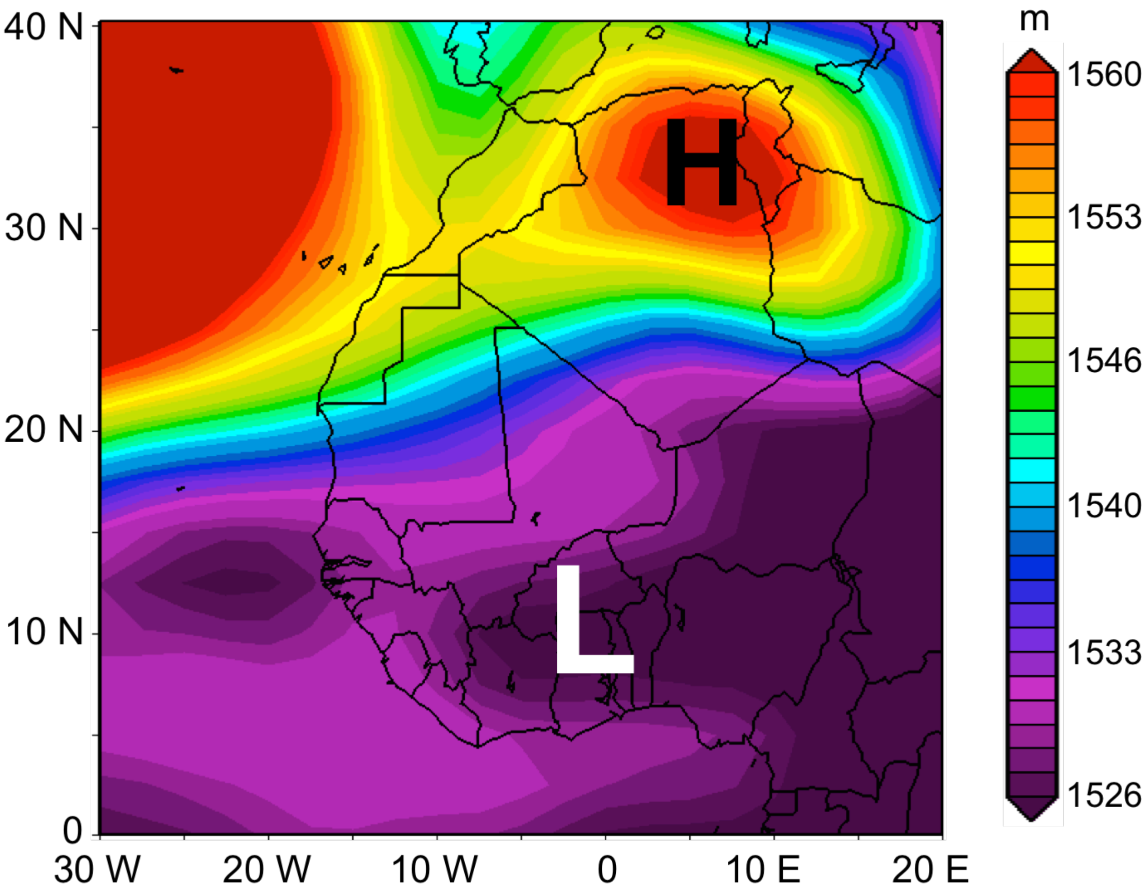


Figure 1.



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.

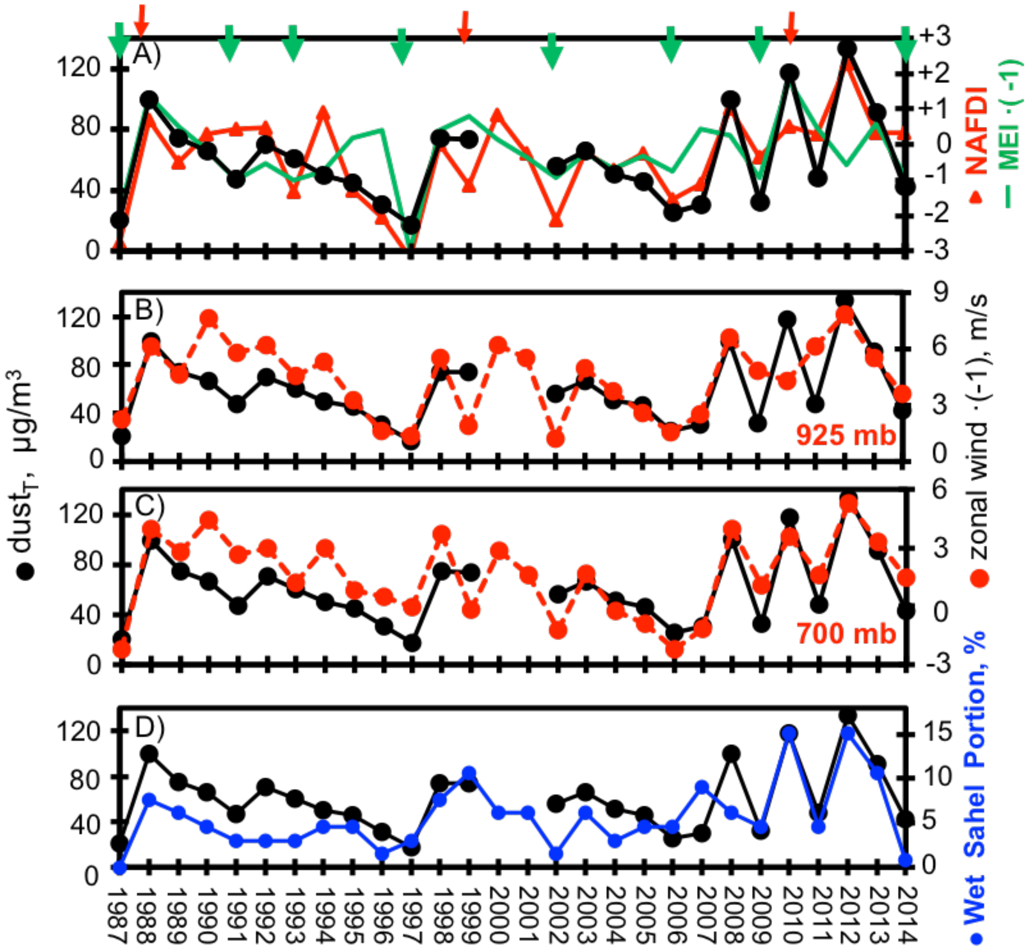

A)
B)
C)
D)
925 mb
700 mb
dust$_T$, μg/m^3
NAFDI
MEI ·(-1)
zonal wind ·(-1), m/s
Wet Sahel Portion, %
0
40
80
120
+3
+2
+1
0
-1
-2
-3
9
6
3
0
6
3
0
-3
15
10
5
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

Figure 3

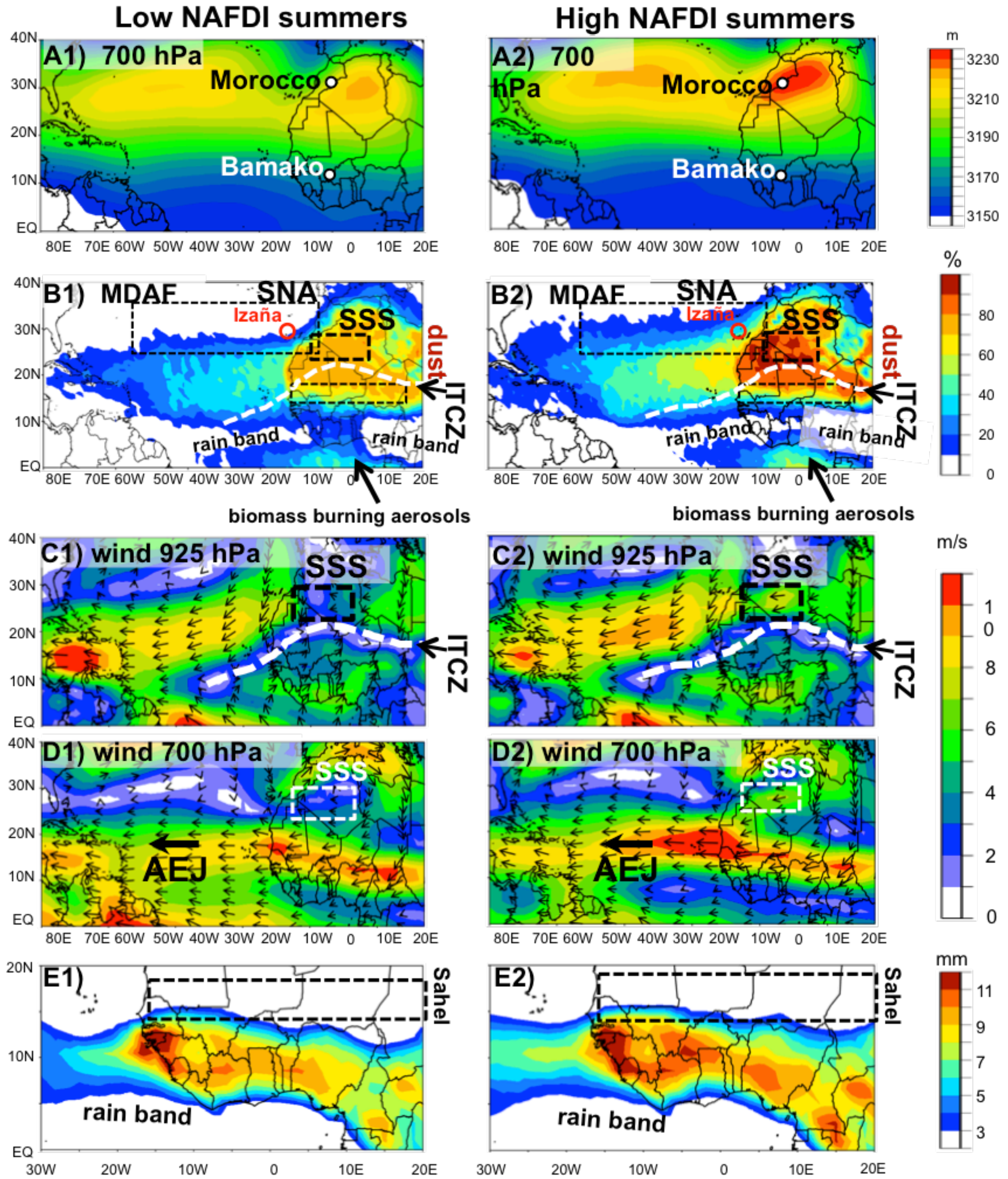

Low NAFDI summers
High NAFDI summers
A1) 700 hPa
A2) 700 hPa
Morocco
Bamako
m
3230
3210
3190
3170
3150
B1) MDAF
B2) MDAF
SNA
Izaña
SSS
dust
ITCZ
rain band
biomass burning aerosols
%
80
60
40
20
0
C1) wind 925 hPa
C2) wind 925 hPa
D1) wind 700 hPa
D2) wind 700 hPa
AEJ
m/s
10
8
6
4
2
0
E1)
E2)
Sahel
mm
11
9
7
5
3
40N
30N
20N
10N
EQ
80E 70E 60W 50W 40W 30W 20W 10W 0 10E 20E
30W 20W 10W 0 10E 20E

Figure 4.

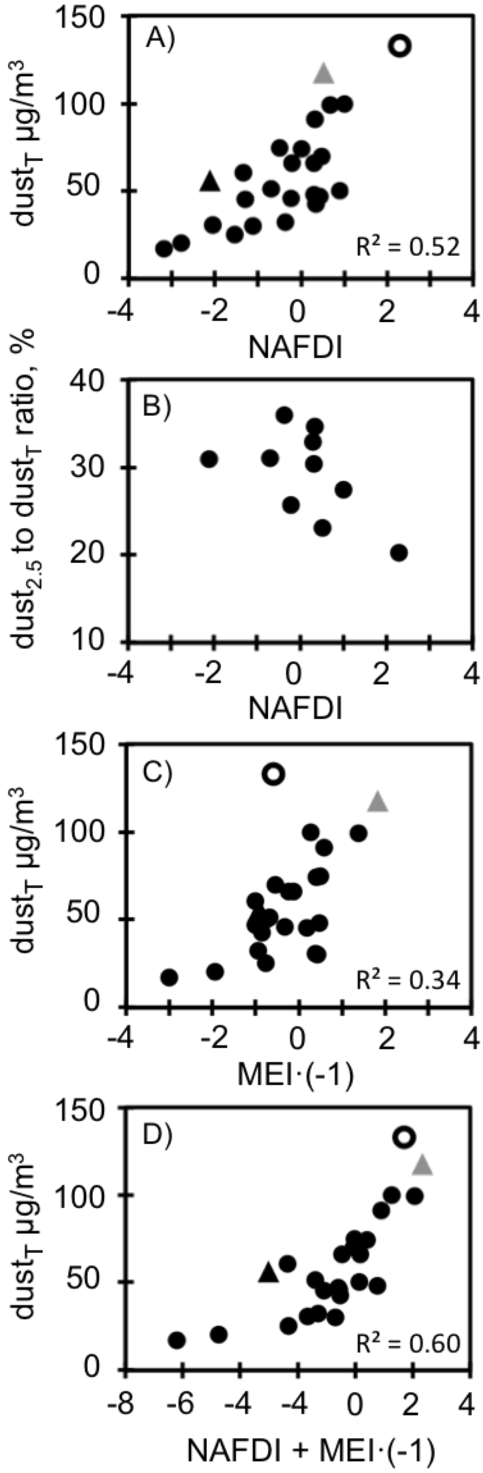
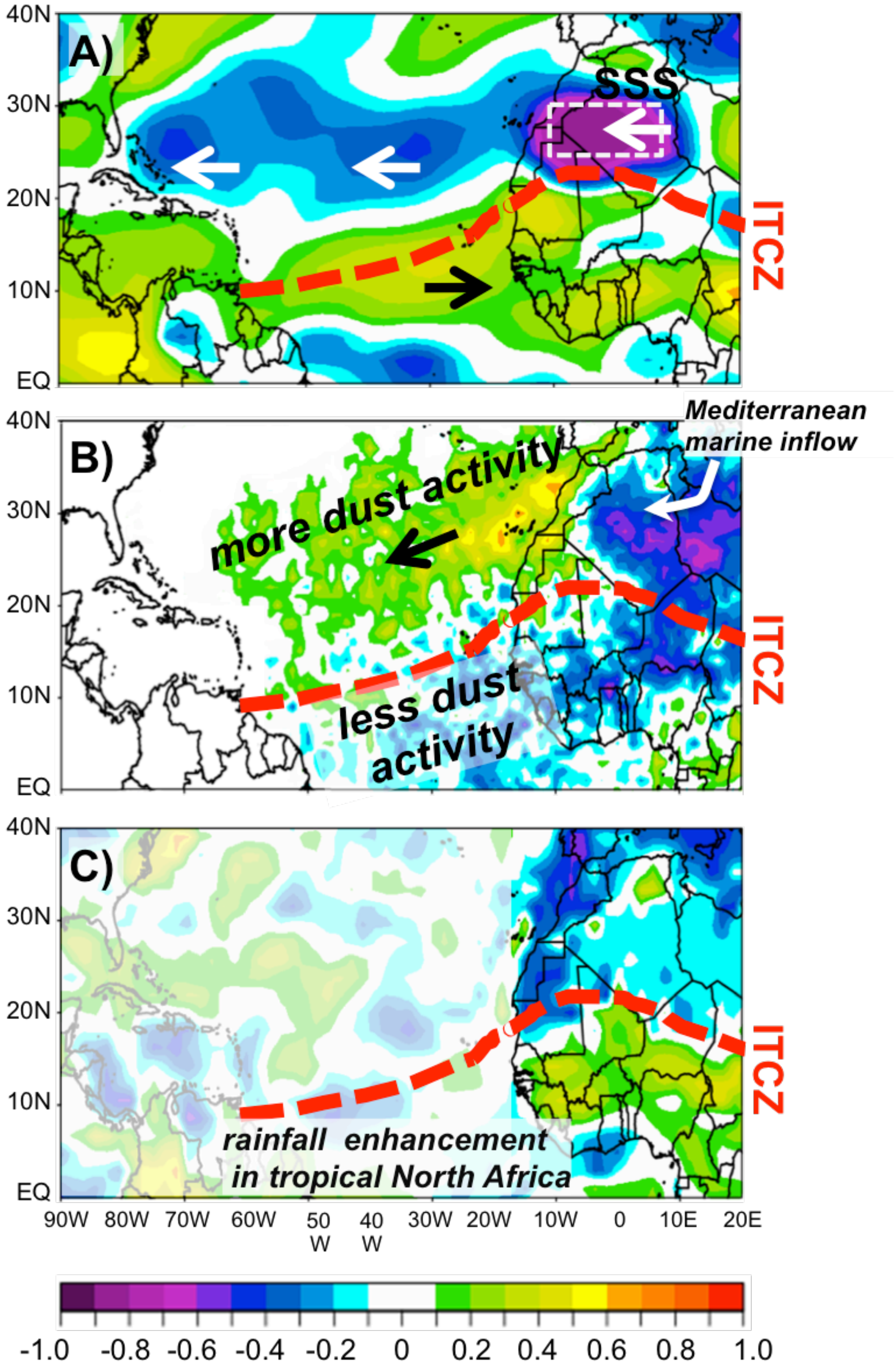

A)
$dust_T$ µg/m³
NAFDI
R^2 = 0.52
B)
$dust_{2.5}$ to $dust_T$ ratio, %
NAFDI
C)
$dust_T$ µg/m³
MEI·(-1)
R^2 = 0.34
D)
$dust_T$ µg/m³
NAFDI + MEI·(-1)
R^2 = 0.60

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.

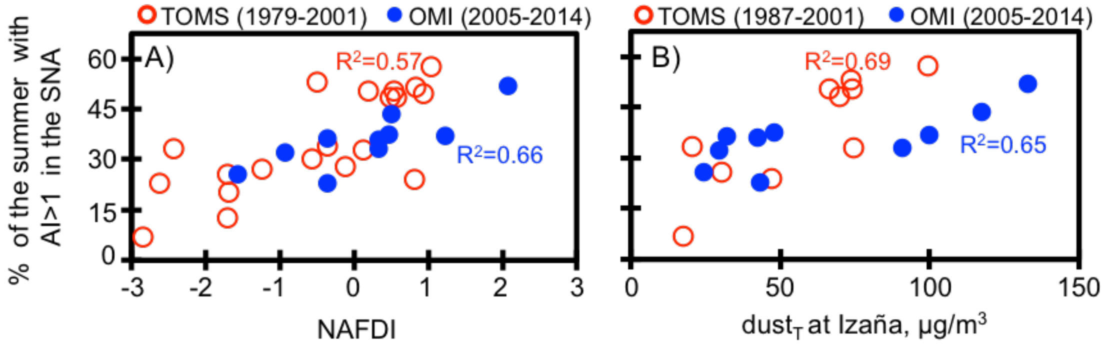


Figure 7.

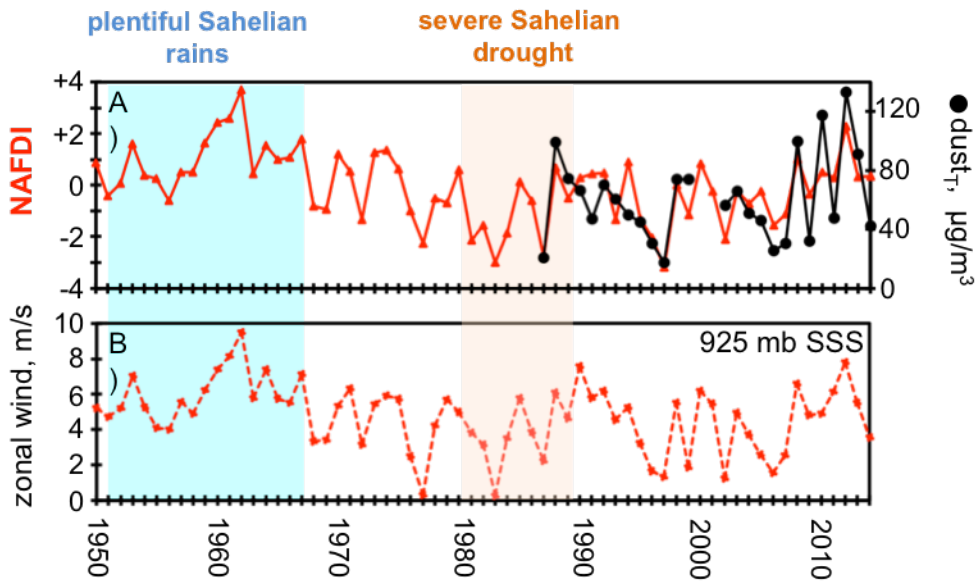


Figure 8.

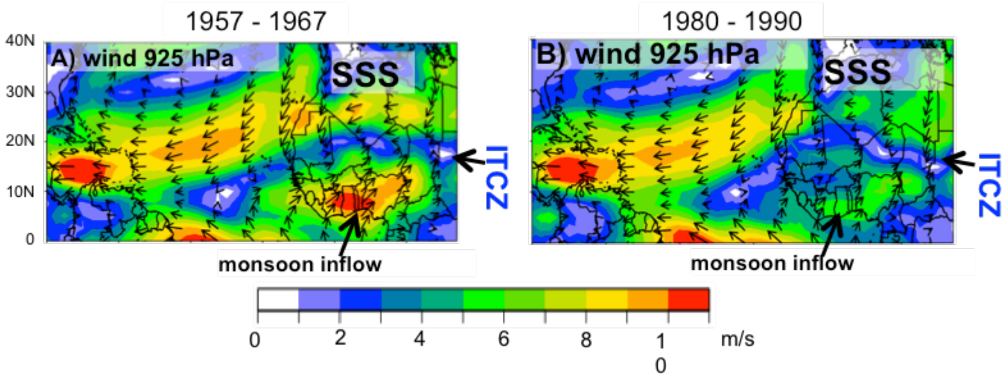

1957 - 1967
A) wind 925 hPa
SSS
ITCZ
monsoon inflow
40N
30N
20N
10N
0
1980 - 1990
B) wind 925 hPa
SSS
ITCZ
monsoon inflow
0
2
4
6
8
1
0
m/s

Figure 9.

Copy of the Supplement with changes highlighted in green colour

Supplement of

"Modulation of Saharan dust export by the North African Dipole"

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S1. Dust measurements

Measurements of in-situ aerosol dust concentrations have been performed at the Izaña Global Atmospheric Watch (GAW) observatory since 1987 (http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html). These measurements are part of the in-situ aerosols GAW program in operation at Izaña, which also include long term measurements of other aerosol properties (chemical composition, size distribution and optical properties) (http://www.wmo.int/pages/prog/arep/gaw/aerosol.html).

The Izaña observatory is located on Tenerife island (28°18'N, 16°29'W; the Canary Islands) at 2367 meters above the sea level. The site is normally above the marine stratocumulus associated with the trade winds inversion layer, typical of the subtropics. At night, when upslope winds cease, Izaña is exposed to the free troposphere airflows.

Samples of atmospheric aerosols are collected by drawing the ambient air through a filter mounted in a sampler whose pump operates at a controlled (constant) airflow. Subsequently, these samples are subject to chemical analysis for determining the concentrations of dust and other aerosol species (Table S1). These analyses have been performed in several size fractions of ambient aerosols:

- Total Particulate Matter (PM_T). A sampler with a whole air inlet operating at 30 to 50 m^3/h airflow, depending on the period, was used.
- Particulate Matter with an aerodynamic diameter smaller than 10 microns (PM_{10}). The sampling was performed at 30 m^3/h flow-rate placing an impactor, equivalent to the EN-12341 standard, in the inlet of the sampler.
- Particulate Matter with an aerodynamic diameter smaller than 2.5 microns ($PM_{2.5}$). The sampling was performed at 30 m^3/h flow-rate placing an impactor, designed according to EN-14907 standard, in the inlet of the sampler.

Dust concentrations are extracted from the chemical composition dataset (Table S1) in three size fractions:

- Concentrations of total dust ($dust_T$), obtained by chemical analysis of the PM_T samples.
- Concentrations of dust particles with an aerodynamic diameter smaller than 10 microns ($dust_{10}$), obtained by chemical analysis of PM_{10} samples.
- Concentrations of dust particles with an aerodynamic diameter smaller than 2.5 microns ($dust_{2.5}$), obtained by chemical analysis of $PM_{2.5}$ samples.

The long term observations of size segregated dust concentrations at Izaña have been based on the following measurements:

- 1987-1999: based on $dust_T$.
- 2000-2001: no measurements available.
- 2002-2004: based on $dust_T$ and $dust_{2.5}$.
- 2005-2014: based on $dust_{10}$, $dust_{2.5}$ and $dust_T$ (the latter only in August, the month in which dust events occur with the highest frequency).

In order to avoid a large volume of data in the plots, in the Article we only presented data of $dust_T$ and $dust_{2.5}$.

During the 1987-1999 period, sampling was performed almost every day. In the 2002-2014 period, sampling was performed at the rate of 1 sample collection every 3 to 4 days in two size fractions, except in August, when the sampling was performed every day in the three size fractions.

Complementary size distributions measurements were performed with an Optical Particle Counter (GRIMM™, 1108) since 2002 and an Aerodynamic Particle Sizer (TSI™, model 3321) since 2006 in the size range 0.5 to 20 microns. We used these data for estimating the bulk aerosol mass concentrations in several size factions with an hourly resolution. Volume aerosol concentrations (determined from the number size distributions) were converted to mass aerosol concentrations using standard methods (Rodríguez et al., 2012). We used a volume to mass conversion factor (effective density equivalent) obtained by correlating and fitting by regression of the aerosol dust concentrations obtained by chemical methods versus aerosol volume concentrations. This method was applied in the three size fractions: total particles and particles smaller than 10 μm and 2.5 μm.

The differences in the daily average dust concentrations data obtained with these two methods (based on chemical analysis and on size distributions) is within the range 3-8%. The good agreement between these two methods (high linearity and low mean bias) is due to the very low aerosol volume concentrations in the free troposphere during no dust events (typically < 1 to 2 $\mu m^3/cm^3$; 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 sampled filters (Fig.S1). As part of the quality control in data analysis, we used monthly mean concentrations data obtained with the two methods for assessing the consistency of the monthly mean variations of dust concentrations.

During the whole measurement period (25 July 1987 –31 December 2014, excluding the none-measurement period 11 October 1999 - 13 February 2002), dust concentrations records are available during 8001 days, which lead to a data availability of 87.3%. Data collected at Izaña in different periods have been analyzed in individual studies, e.g. 1987-1999 (Chiapello et al., 1999), 2002 (Alastuey et al., 2005) and 2005 to 2008 (Rodríguez et al., 2011). All data were joined for the first time for this study.

The Quality Assurance/Quality Control activities of the Izaña aerosol program include periodic checks of airflows and zeros in all devices, collection of blank field filters and instrument inter-comparisons. The latter are typically performed during the summer dust season, when each sampling of PM_T, PM_{10} and $PM_{2.5}$ is simultaneously performed with two samplers. PM_x concentrations obtained with the two samplers typically differs 2-9% for PM_T, and 3% for PM_{10} and $PM_{2.5}$.

S2. Summer dust time series

At Izaña, the summer dust season (impacts of the Saharan Air Layer) typically starts in the second half of July and ends at the beginning of September (Fig.S2). The maximum frequency of dust events occurs in August (Fig.S2a). We used dust averaged in August (excluding July and September) for studying the long term summer dust variability for the following reasons:

1. this is the only month when $dust_T$ concentrations were measured after 2004,
2. this is the only month when simultaneous $dust_T$, $dust_{10}$ and $dust_{2.5}$ measurements are available,

In August, the Inter-Tropical Convergence Zone (ITCZ) is shifted to the North and (i) the Saharan Air Layer is exported at the northern most latitude, as evidenced by the highest frequency of dust impacts at Izaña (Fig.S2a), and (ii) maximum rainfall occurs in tropical North Africa (Nicholson et al., 2009).

The high correlation of August mean dust concentrations with the July to September dust mean concentrations evidences that summer mean dust concentrations are mainly weighted by August (Fig.S3a). This is also true for dust annual mean (Fig.S3b). 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).

S3. Supplementary data analysis

Table S2 shows the summer mean dust concentrations at Izaña from 1987 to 2014. For analyzing the large scale processes influencing the inter-annual dust variability we used the following complementary data sets:

1. 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).

2. Back-trajectories calculated with the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler et al., 2010) developed by the NOAA Air Resources Laboratory (http://www.arl.noaa.gov/). Ten-day back trajectories were calculated using National Center for Atmospheric Research (NCEP) data.

3. Gridded meteorological National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) re-analysis data (Kalnay et al., 1996) were used for determining the North AFrican Dipole Intensity (NAFDI), equation 1.

4. Teleconnection index data downloaded from the NOAA-ERSL web (http://www.esrl.noaa.gov/psd/data/climateindices/).

These four data sets were subject to the following analysis.

We first analyzed the consistency between dust detection by the satellite AI signal and the in-situ dust measurements at Izaña. Previous studies found a high consistency between the variability in daily in-situ dust concentrations at Izaña and the daily AI signal at the lat-lon of Izaña (Chiapello et al., 1999). We found that there is also a high correlation between the long term (1987-2014) in-situ $dust_T$ concentrations at Izaña and AI signal which supports the consistency between the two complementary dust observations techniques (Pearson correlation coefficient r=0.82; Fig. S4). We also assessed how the change of the TOMS to the OMI sensor may have influenced the assessment of the spatial variability of dust that was performed in Fig.2b of the Article. For this reason we performed the same analysis but only using data from the TOMS period (1979-2001). The main features of dust distribution during low and high NAFDI years observed with TOMS and OMI data (Fig.3b of the Article) are also observed when only using TOMS data (Fig.S5). This is in agreement with the previously described consistency of the TOMS and OMI AI data already demonstrated by Li and co-workers (Li et al., 2009).

As a second step, we used the back-trajectories for identifying the North African regions that are potential dust sources and/or within the transport pathways of the dust recorded at Izaña. Fig. S6a shows the back-trajectories associated with the dust events > 10 μg/m^3 at Izaña from 1987 to 2014. The frequency of the back-trajectory passes (only considering points below 3000 m.a.s.l.) in shown in Fig S6b (see Rodríguez et al., 2011 for methodology). This trajectory analysis shows that dust at Izaña, and consequently the northern Saharan Air Layer, is sensitive to dust mobilization in a region that extends from Central Algeria through Northern Mauritian and Western Sahara, where important dust sources are located (Prospero et al., 2002).

Thirdly, we used the NCEP/NCAR re-analysis data and the NAFDI for studying the variability in the large scale processes that influence long term dust variability. The NAFDI typically exhibits values between -3 and +3 (Table S2). The implications of the variation of this index on the North African meteorological scenarios were described in the Article. As complement, we present the average height of the 850hPa geopotential field (Fig. S7); plots were created in the NOAA-ESRL - Monthly/Seasonal Climate Composites web (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl). The intensification of the anticyclone in northern Sahara and the lower height of geopotential fields in all standard pressure levels in tropical North Africa result in the airflows characteristic of the high NAFDI summers described in the Article.

We correlated the NAFDI with several meteorological fields (zonal and meridional component of wind in standard levels, precipitation rates, temperature and sea surface temperature –SST-, among others) during the 1987 to 2014 period. This was done in the NOAA-ESRL - Linear Correlations in Atmospheric Seasonal/Monthly Averages web (http://www.esrl.noaa.gov/psd/data/correlation/). Only relevant results for understanding dust inter-annual variability are shown. The NAFDI shows a high correlation (r > 0.8) with the zonal component of wind at the north of the ITCZ, in the Subtropical Saharan Stripe (SSS) region, which extends from Central Algeria through Northern Mauritania to Western Saharan between 24 and 30 °N (Fig. 6a of the Article). Long term summer mean $dust_T$ at Izaña also showed a high correlation with the zonal component of wind at 925hPa (r=0.65; Fig.2b of the Article) and at 700 hPa in the SSS (r=0.79; Fig.2c of the Article; mean winds 1987-2014 in the SSS were calculated in the NOAA-ESRL web ; http//www.esrl.noaa.gov/psd/data/timeseries/). These results are consistent with the back-trajectories analysis described above, which also indicate that dust mobilization in the SSS exerts an important influence on dust records at Izaña (Fig. S6b).

The correlation analysis was also performed to assess the influence of NAFDI on rainfall in tropical North Africa. The NAFDI shows a positive correlation with gridded precipitation rates over the tropical North African and part of the Sahel (Fig. 6c of the Article). Although the correlation coefficient values are not very high (0.2 to 0.5, Fig. 6c), it is remarkable that this correlation is observed over an extension of thousands of square kilometers. Because of this, we then quantified the area of the Sahel was wet during the monsoon season. We defined "Wet Sahel Portion" as the area of the Sahel (14-18°N to 17°W-22.5°E) which received a mean precipitation rate ≥ 3 mm/day. Data of mean precipitation rates were downloaded from the NOAA-ESRL web. The Wet Sahel Portion showed a significant variability, from less than 5% in dry periods up to 15% in wet periods (Fig. 2d of the Article).

In a fourth step, we correlated the NAFDI and $dust_T$ at Izaña with other teleconnection indexes (Table S3). The NAFDI only shows a significant correlation with the Multivariate ENSO Index (MEI), which, in turn, is negatively correlated with dust at Izaña and with Sahel rainfall.

In a fifth and final step, we used AI data for assessing how the NAFDI influenced the spatial distribution of dust in the North Atlantic. We found that increases in the values of the NAFDI enhance dust export at subtropical latitudes. This is clearly observed in the plots of the 'correlation coefficient between NAFDI and MDAF and $dust_T$ at Izaña (Fig.7 of the Article).

S4. Supporting References

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Figure S1. Saharan dust samples. Examples of batch of filters with aerosol samples collected at Izaña for illustrating their typical ochre colour due to dust.

Figure S2. Statistics of dust events at Izaña from 1987 to 2012. A) Frequency of dust (> 10 μg/m^3) events; B) Average dust concentrations per month.

Figure S3. Scatter plots of summer and annual versus August dust means. A) Jul-Sept and (B) Jan-Dec versus Aug average dust concentrations at Izaña. Data corresponds to the period 1987-2012, based on $dust_T$ from 1987 to 2004, and on $dust_{10}$ from 2005 to 2012.

Figure S4. **In-situ and satellite-AI dust signal over Izaña**. Times series of summer mean $dust_T$ at Izaña and AI at the lat-lon of Izaña. The Pearson correlation coefficient (r) is shown in the plot.

Figure S5. Spatial distribution of dust**.** MDAF studied using only TOMS data in summers of (A) low NAFDI (1981 = -1.7, 1983 = -2.6 and 1997 = -2.8) and (B) high NAFDI (1980 = +0.9, 1988 = +1.0 and 2000 = +0.8).

Figure S6. Transport pathways of dust. A) back-trajectories at Izaña during the dust events > 10 μg/m^3 registered in August from 1987 to 2012. B) frequency by which the points of the back trajectories passes (in total counts).

Figure S7. Meteorological scenario in low NAFDI summers compared to high NAFDI summers**.** Height of the 850hPa geopotential. "Images produced at the NOAA/ESRL Physical Sciences Division web, Boulder Colorado from their Web" (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl). The high NAFDI (1988, 2000, 2008 and 2012) and low NAFDI (1987, 1996, 1997 and 2006) summer groups are those used in Fig 3 of the Article.

Figure S1.

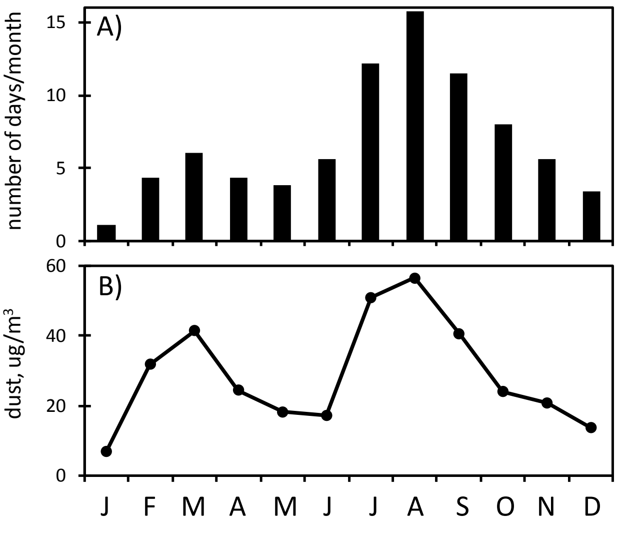


Figure S2.

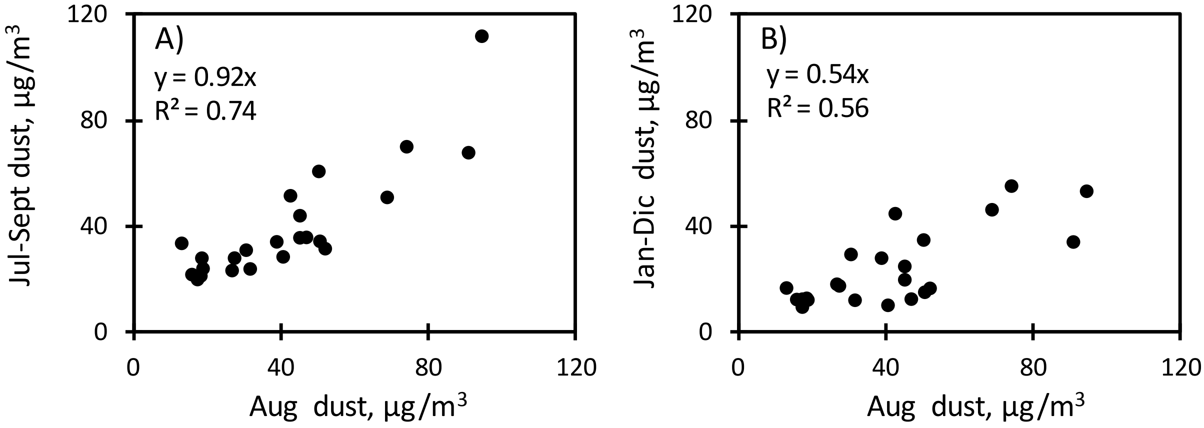


Figure S3.

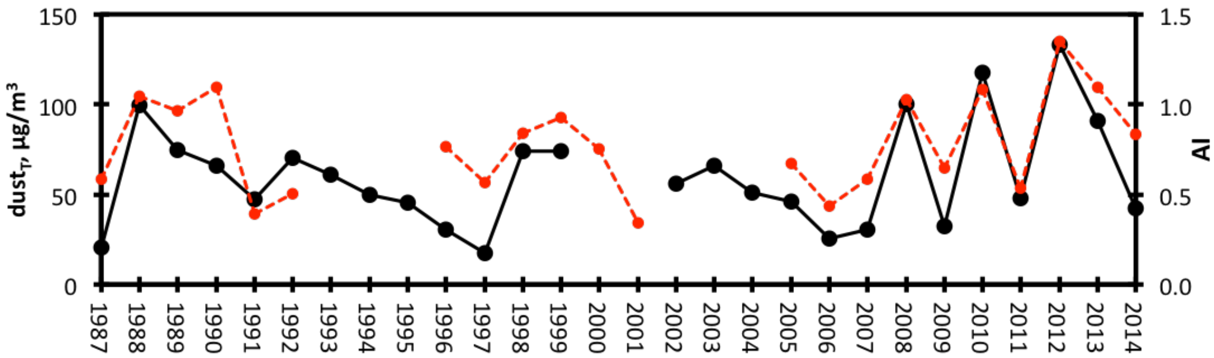


Figure S4.

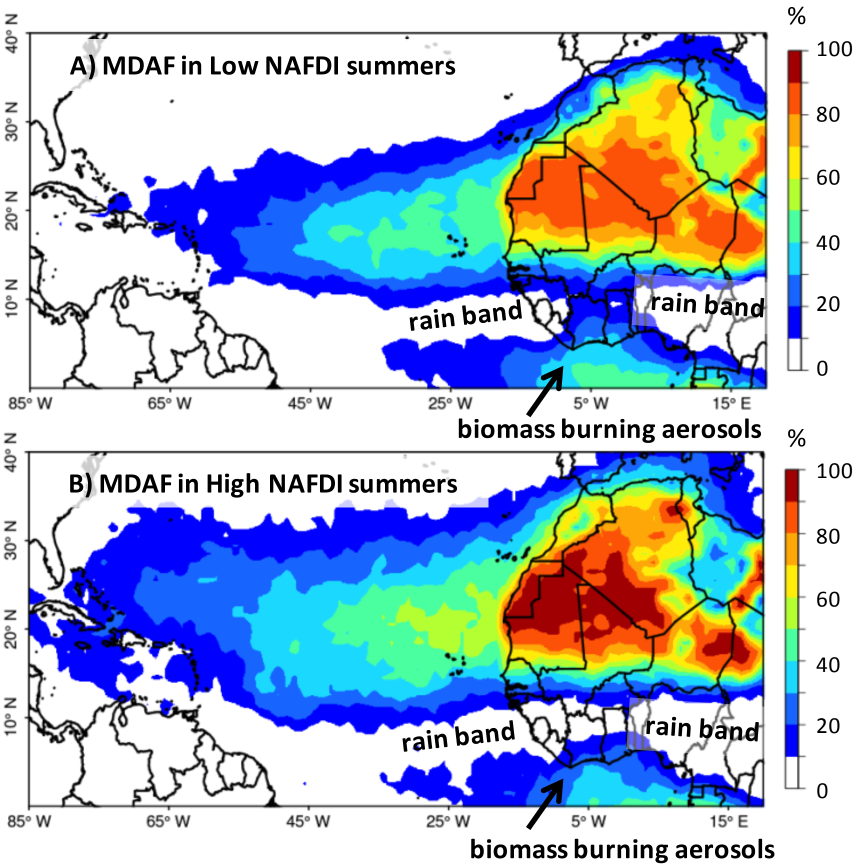

A) MDAF in Low NAFDI summers
rain band
rain band
biomass burning aerosols
B) MDAF in High NAFDI summers
rain band
rain band
biomass burning aerosols
%
100
80
60
40
20
0
85° W
65° W
45° W
25° W
5° W
15° E
40° N
30° N
20° N
10° N

Figure S5.

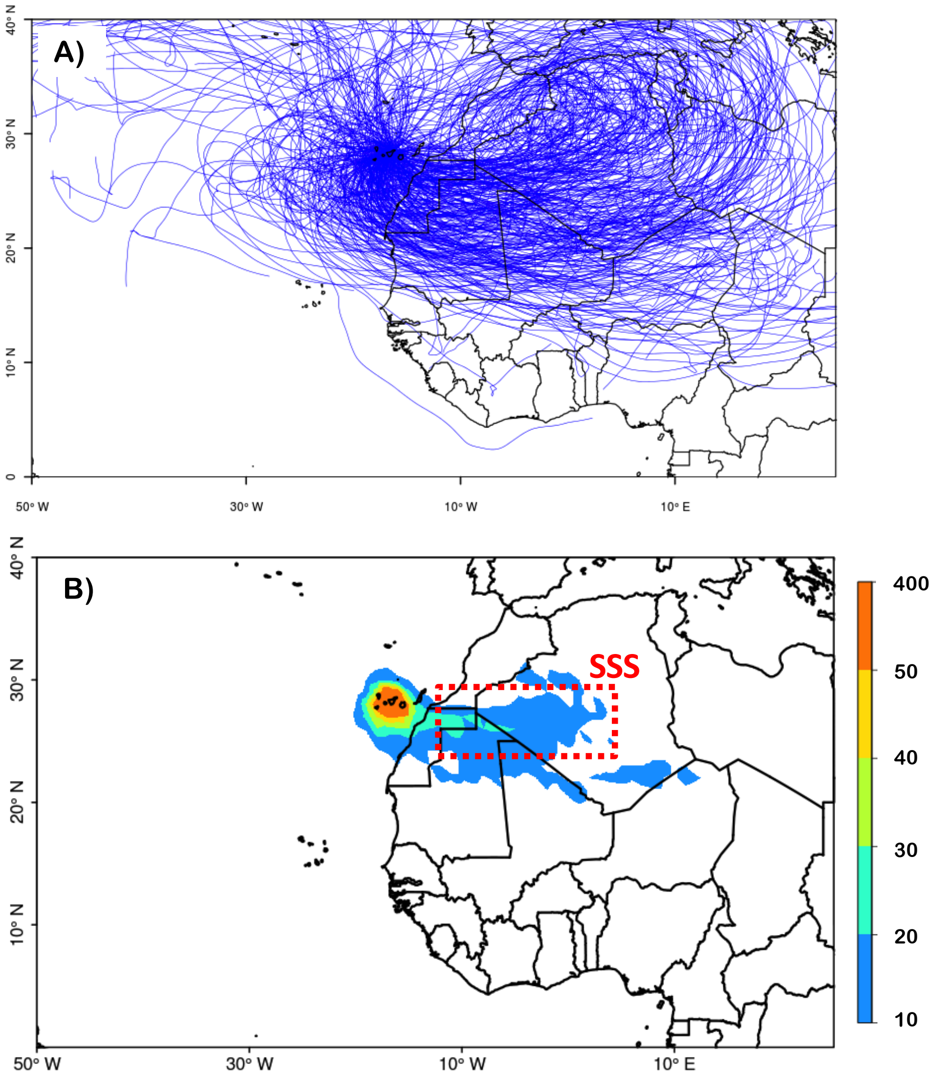
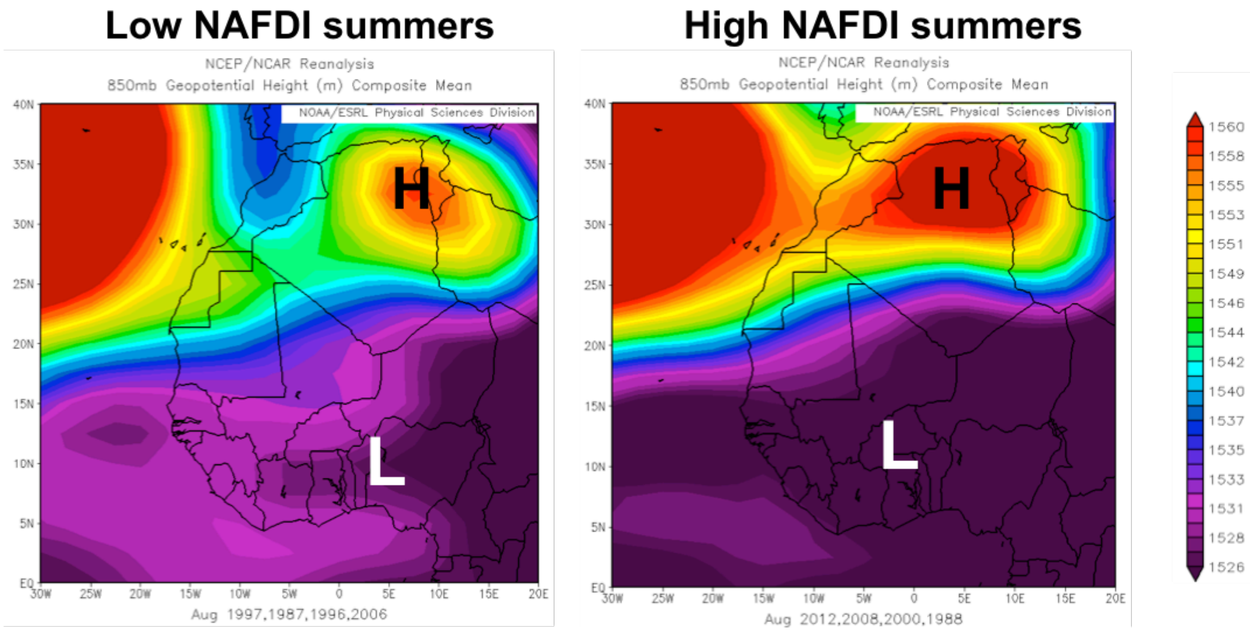

A)
40° N
30° N
20° N
10° N
0
50° W
30° W
10° W
10° E
B)
SSS
40° N
30° N
20° N
10° N
50° W
30° W
10° W
10° E
400
50
40
30
20
10

Figure S6.


Low NAFDI summers
NCEP/NCAR Reanalysis
850mb Geopotential Height (m) Composite Mean
NOAA/ESRL Physical Sciences Division
H
L
Aug 1997,1987,1996,2006
High NAFDI summers
NCEP/NCAR Reanalysis
850mb Geopotential Height (m) Composite Mean
NOAA/ESRL Physical Sciences Division
H
L
Aug 2012,2008,2000,1988
1560
1558
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1551
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Figure S7.

Table S1. Description of the sampling and chemical analysis of the aerosol samples.

1987 to 1999. Samples of total suspended particles PM_T were collected on 20 cm by 25 cm Whatman 41 paper filters at a nominal flow rate of about 35 $m^3\ h^{-1}$. In 1994 the airflow was modified to 50 $m^3\ h^{-1}$. Samples were stored and sent periodically to the University of Miami. Blank field filters were also chemically analyzed. Dust concentrations records with the following method are available for 4460 days.

- Concentrations of soluble species were determined by extraction with de-ionized water subsequent analysis by flame atomic absorption (Na^+), ion chromatography (Cl^-, NO_3^- and $SO_4^{=}$) and colorimetry (NH_4^+).
- Concentrations of aluminium were analyzed by Instrumental Neutron Activation Analysis.
- Dust concentrations. The extracted filters were placed in a muffle furnace for 14-h (overnight) at 500 ºC. After blank removal, the ash residue weight divided by the sampled volume is the mineral dust concentration. Because the scatter plot of Al versus dust typically shows a slope of 10.4%, which is somewhat higher than the mean content of Al in soils (8%), a normalization factor of 1.3 was used (Arimoto et al., 1995). Standard error is considered ±0.1 $\mu g/m^3$ for concentrations <1 $\mu g/m^3$, and about 10% for higher concentrations.

2002 to 2014. Aerosol samples in several size fractions were collected at the flow rate of 30 m^3/h in micro quartz fibre filter Schleicher & Schuell™ QF20 (2002–2006) and Munktell™ MK360 (2007–2012). Filters were weighed before and after sampling following the EN-14907 procedure (except for relative humidity, which was set to 30-35% in the weighing room). Samples were stored and sent periodically to the Research Council of Spain (CSIC) in Barcelona for chemical analysis. Chemical composition data obtained with the following method is available during 652 days. Blank field filters were also chemically analyzed.

- Concentrations of soluble species were determined by extraction in de-ionized water subsequent analysis by ion chromatography (Cl^-, NO_3^- and $SO_4^{=}$) and FIA colorimetry (NH_4^+).
- Concentrations of major elements (Al, Ca, K, Na, Mg and Fe) and trace elements were determined by acid digestion (HF:$HClO_4$:HNO_3) and subsequent Inductively Coupled Plasma Atomic Emission Spectrometry, (ICP-AES, IRIS Advantage TJA Solutions, THERMO), and Inductively Coupled Plasma Mass Spectrometry, (ICP-MS, X Series II, THERMO), respectively. Detection limit and accuracy were estimated as 0.4 ng m^{-3} and 2% for ICP-AES and 0.02 ng m^{-3} and 3% for ICP-MS.
- Dust concentrations were determined as the sum of $Al_2O_3 + SiO_2 + Fe + CaCO_3 + K + Na + P + Ti + Sr$. The following indirect determinations were used: (a) CO_2^{-3}, calculated from the amount of Ca not present as Ca-sulphate and Ca-nitrate, and then assuming this fraction of Ca is present as calcite ($CaCO_3$; $CO_3^{=}$ =1.5*Ca; S3); (b) SiO_2, determined from the Al content on the basis of prior experimental equations (SiO_2 =3*Al_2O_3, see Querol et al., 2001). Data were normalized in order that the mean Al content in the aerosol dust be 8%, as also performed in the 1987-1999 dataset.
- Carbonaceous aerosols were characterized in terms of total carbon (TC) and organic carbon (OC) and elemental carbon (EC). Concentrations of TC were determined with a Total Carbon Analyser (LECO) from 2002 to 2007. Concentrations of OC and EC were analyzed since 2007 by a thermal-optical transmission technique (Birch et al., 1996) using a Sunset Laboratory OC-EC analyzer.

Table S2. Summer mean dust concentrations from 1987 to 2012 in three size fractions at Izaña observatory, and NAFDI index. Dust concentrations are normalized to 1013 hPa.

	$dust_T$ µg/m³ average	$dust_{2.5}$ µg/m³ average	$dust_T$ µg/m³ Std Dev.	$dust_{2.5}$ µg/m³ Std Dev.	NAFDI
1987	20.63		24.49		-2.79
1988	99.28		101.81		0.68
1989	74.52		60.34		-0.51
1990	66.23		51.81		0.30
1991	47.27		71.02		0.43
1992	70.05		90.43		0.48
1993	60.75		162.41		-1.34
1994	49.99		85.69		0.89
1995	45.15		43.17		-1.30
1996	30.54		43.33		-2.05
1997	17.36		21.24		-3.20
1998	74.14		88.89		0.00
1999	73.76		82.31		-1.14
2000					0.84
2001					-0.24
2002	56.01	19.32	47.28	8.28	-2.11
2003	66.15	15.71	24.03	5.18	-0.20
2004	51.10	15.87	44.91	8.64	-0.71
2005	43.41	14.17	48.32	13.02	-0.24
2006	24.48	9.96	23.67	8.63	-1.55
2007	29.34	9.61	31.52	9.71	-1.12
2008	99.84	23.43	64.55	16.49	1.02
2009	32.18	11.55	35.48	9.74	-0.36
2010	117.56	27.11	98.22	21.25	0.52
2011	47.83	15.74	57.37	13.53	0.30
2012	133.00	25.05	93.22	15.31	2.29
2013	90.91	27.63	59.92	28.64	0.33
2014	42.41	14.67	45.20	19.00	0.34

Table S3. Correlation coefficient between $dust_T$ at Izaña and NAFDI with a set of selected climate indexes. Data: mean values of August from 1987 to 2014. Bold: absolute values ≥ 0.5. Data source: Sahel Rainfall downloaded from the website of the Joint Institute for the Study of the Atmosphere and Ocean of the University of Washington (http://jisao.washington.edu/data/sahel/#values) NAO, TNA, MEI, SOI, El Niño 4, El Niño 3.4, El Niño 3 and El Niño 1+2 downloaded from the NOAA-ERSL web (http://www.esrl.noaa.gov/psd/data/climateindices/)

phenomenon	**index name**	**$dust_T$ Izaña 1987-2014**	**NAFDI 1987-2014**	**NAFDI 1950-2014**
North African Dipole	NAFDI	**0.72**		
Sahel rainfall	Wet Sahel Portion	**0.74**	**0.54**	
Sahel rainfall	Sahel Rainfall	**0.58**	**0.55**	0.43
North Atlantic Oscillation	NAO	-0.24	-0.14	-0.19
Tropical North Atlantic	TNA	-0.37	-0.30	-0.24
Multivariate ENSO Index	MEI	**-0.59**	**-0.50**	-0.44
ENSO	SOI	**0.59**	0.45	0.38
ENSO	El Niño 4	**-0.60**	-0.35	-0.31
ENSO	El Niño 3.4	**-0.56**	-0.44	-0.33
ENSO	El Niño 3	-0.44	-0.46	-0.42
ENSO	El Niño 1+2	-0.35	-0.43	-0.45

Physical meaning:

NAFDI	differences of 700hPa geopotential anomalies between central Morocco and Bamako region
Wet Sahel Portion	Proportion (%) of Sahel that received a precipitation rate ≥ 3 mm/d
Sahel Rainfall	precipitation anomaly with respect to 1950-79.
NAO	normalized pressure differences between Azores and Iceland
TNA	anomaly of the average of the monthly SST from 5.5N to 23.5N and 15W to 57.5W
MEI	based on six variables over the tropical Pacific: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky.
SOI	(Stand Tahiti - Stand Darwin) Sea Level Pressure
El Niño 4	Central Tropical Pacific SST *(5N-5S) (160E-150W)
El Niño 3.4	East Central Tropical Pacific SST* (5N-5S)(170-120W)
El Niño 3	Eastern Tropical Pacific SST (5N-5S,150W-90W)
El Niño 1+2	Extreme Eastern Tropical Pacific SST *(0-10S, 90W-80W)