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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Modulation of Saharan dust export by the North African dipole" *by* S. Rodríguez et al.

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Thank you for your detailed review and constitutive comments that definitively contributes to improve the analysis of the results of this study.

Reply to questions and comments.

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 °N –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 20°N – 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).

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.

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).

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).

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.

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.

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 μgÂům-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 μgÂům-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.

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).

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.

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.

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.

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.

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 26689, 2014.

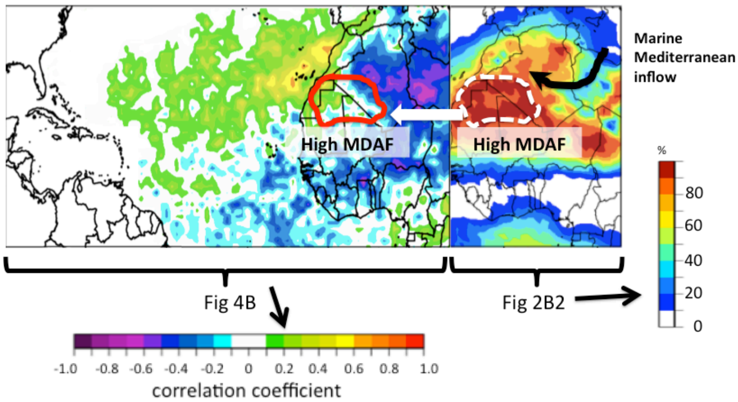

Fig Q3.2. Composite of the plot shown in Fig 4B and 2B2 of the ACPD paper.

Fig. 1.