REPLY TO REVIEWER #1

We thank the reviewer, Prof. Jérôme Brioude, for the constructive comments and suggestions, which have helped us to improve our manuscript. We have provided responses to the comments; the comments appear in *red italics*, our response in **bold face** below the respective comments and we have used *green italics* to quote the changes in the revised manuscript.

General comment: the paper presents new results on large scale processes that control the interannual variability of the dust concentration above the South Asia. The authors used satellite measurements from 2001 to 2018 to analyse the frequency of days (over a month, called $DA_{\%}$) when the dust optical depth above South Asia is high. Using NCEP/NCAR reanalysis, they found that an increase in $DA_{\%}$ was associated to an increase in SST in the mid-latitude North Atlantic, and a cooling in the Subtropical North Atlantic between 2011 and 2018. The authors presented a detailed analysis, based on NCEP reanalysis and CEMS simulations, of anomalies in the wind fields and SST to explain the link between the SST variability in the Atlantic Ocean and the dust emission over South Asia. The correlation was linked to large scale transport pattern anomalies and a weakening of the South Asia monsoon.

The paper is well written and the results are of interest for the community. I will accept this paper for publication after addressing the following comments:

We thank the reviewer for the summary evaluation and positive recommendation. Our responses to the specific comments follow.

Specific comment:

1) Section 3.3 is a bit long and probably needs some reorganisation. Figures 6 and 7 discuss the capabilities of CESM to simulate dust and precipitation in South Asia, and not so much the mechanisms that link dust activity to North Atlantic SST. I'm wondering if figure 6 and 7 should go in section 2.2 instead, and leave figures 8 and 9 in section 3.3. That way you will only discuss anomalies in section 3.3, which will help to follow the arguments of section 3.2.

This is indeed a helpful suggestion. We have now taken out Figures 6 and 7 from the original manuscript, along with the accompanying texts, from Section 3.3 and have placed them under a separate Section 2.3 titled as "Model Validation". We have modified all the figure numbers throughout the manuscript accordingly. The following sentences are added in the beginning of Section 3.4 of the revised manuscript to link it with the new Section 2.3:

As discussed in Section 2.3, although there are certain limitations, CESM can reproduce the main aspects of atmospheric circulation and the spatial and temporal characteristics of dust over South Asia quite well. This gives us confidence in using the model for our present study.

Please see L469-471 in the modified manuscript.

2) introduction: you don't mention the impact of the indian ocean dipole (IOD) and its impact on the monsoon and potentially on the dust emission. Please add references and comments.

Thanks for this suggestion. We have now added the following sentences in the introduction to elucidate the possible role of Indian Ocean Dipole on monsoon and dust:

The Indian Ocean Dipole (IOD) is the other teleconnection that influences atmospheric circulation over this region, with the positive phase of IODs counteracting the impact of El Nino on precipitation over South and Southwest Asia (Ashok et al., 2001; 2004). This can reduce the magnitude of anomalies of dust over Southwest Asia due to an El Nino event (Banerjee and Prasanna Kumar, 2016).

Please see L49-52 in the revised manuscript.

Technical comments:

figure 5 top: the coast lines need to be enhanced.

Complied with. Please note that the Figure number has been changed in the revised manuscript to Figure 8.

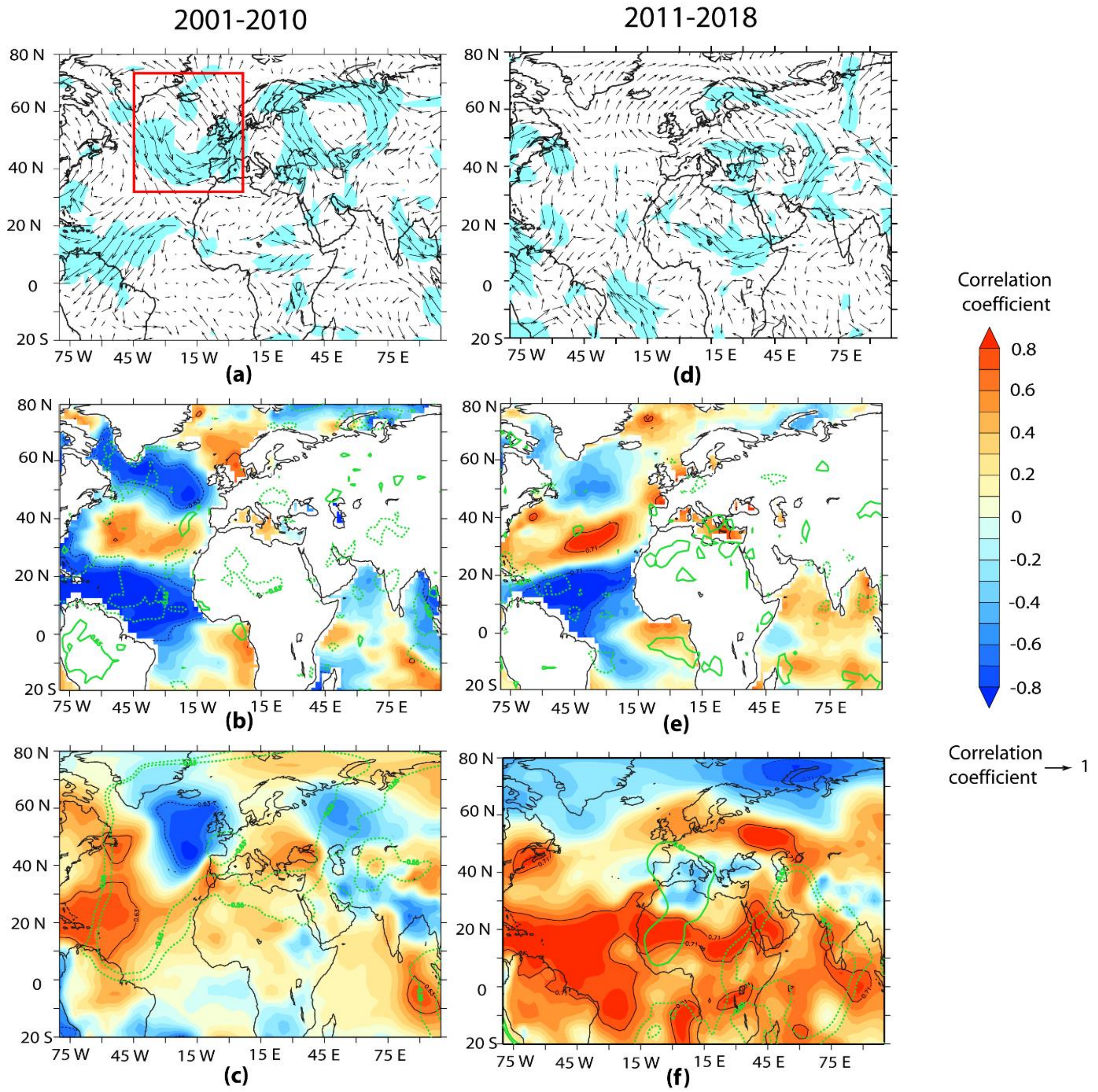

Figure 8: *Correlation between the April-June North Atlantic Difference Index (NADI) and different meteorological parameters from NCEP/NCAR Reanalysis averaged for May-September for (left panels) 2001-2010 and for (right panels) 2011-2018. (a) and (d) Arrows show correlation between NADI and wind vectors averaged between 850 and 700 hPa pressure levels. Light blue shade highlights the regions where one of the components of the wind vector is significantly (95% confidence level) correlated with NADI. (b) and (e) Shading shows correlation between NADI and SST and the green contours enclose the regions where significant correlation (at 95% level) exists between NADI and precipitation. Black contours indicate the regions where correlation between NADI and SST are significant at 95%. (c) and (f) Shading shows correlation between NADI and sea level pressure and the green contours enclose the regions where significant correlation exists between NADI and velocity potential at 850 hPa pressure level: inner and outer contours indicate 95% and 90% confidence levels respectively. Black contours indicate the regions where correlation between NADI and sea level pressure are significant at 95% level. For all the panels continuous and dashed contours are indicative of significant positive and negative correlations respectively.*

abstract: you should rephrase lines 22-23 to better explain what you mean by 10% (20%) and 30% (50%).

We have rephrased these lines as follows to make the meaning clearer:

Simulations with an earth system model show that the positive phase of the North Atlantic SST tripole pattern is responsible for 10% increase in dust optical depth over South Asia during May-September; with increases as much as 30% during the month of June. This increase is mainly due to transport by the westerlies at 800 hPa pressure level, which on average increases dust concentration at this pressure level by 20% during May-September and up to 50% during June.

Please see L21-25 of the revised manuscript.

References

Ashok, K., Guan, Z., and Yamagata, T.: Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO, Geophys. Res. Lett., 28, 4499–4502, https://doi.org/10.1029/2001GL013294, 2001.

Ashok, K., Guan, Z., Saji, N. H., and Yamagata, T.: Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian Summer Monsoon, J. Climate, 17, 3141–3155, https://doi.org/10.1175/1520-0442(2004)017<3141:IACIOE>2.0.CO;2, 2004.

Banerjee, P., and Kumar, S. P.: ENSO Modulation of Interannual Variability of Dust Aerosols over the Northwest Indian Ocean, J. Climate, **29**, 1287–1303, https://doi.org/10.1175/JCLI-D-15-0039.1, 2016.

REPLY TO REVIEWER #2

Review Comments

On "Is the Atlantic Ocean driving the recent variability in South Asian dust?" by Priyanka Banerjee, Sreedharan Krishnakumari Satheesh, Krishnaswamy Krishna Moorthy.

Recommendation: major revision

General comments: The study of the impact of dust on the South Asian region Asian monsoon is important to the environmental improvement. The study conducted by Banerjee et al. indicated the impact of the interannual variability of dust aerosols over the South Asia has been experienced shift from Pacific Ocean SSTs to the North Atlantic SSTs in recent years. The authors further found that the NAO is the crucial factor to impact the North Atlantic tripole pattern, then leading to associated atmospheric large circulation change, therefore affecting the dust over the South Asia. However, the logical of the mechanisms is not clear, lots of parts confused me, so, I recommend it be accepted for publication after major revisions.

We appreciate the summary comments, the favourable recommendation, and the valuable feedbacks from the reviewer, which have helped us to improve the work. We have provided responses to the comments; the comments appear in *red italics*, our response in **bold face** below the respective comments and we have used *green italics* to quote the changes in the revised manuscript. Please note that, unless otherwise mentioned, all line numbers and figure numbers in our response are with respect to those of the revised manuscript.

Specific comments:

1. *Write all the EL Niño/La Niña words correctly in this article, such as Line 38, 42, 53, etc.*

We have complied with throughout the manuscript.

2. *Line 118-119, "The SD is low indicating that high dust activities persist over these regions." In the Fig1a, this SD of this region is the biggest than other regions, the value is between 4-8.*

Thanks for pointing this out. We have checked and corrected the text accordingly to:

The SD is high indicating that these dust source regions experience significant interannual variability of $DA_{\%}$.

Please see L122-123 of the revised manuscript.

3. *Line 178, the reference of the data "monthly SST and sea ice from Hadley Centre (1870-1981)" is missed.*

We have now added the reference Rayner et al., 2003 for Hadley Centre SST. Please see L187-188 and L796-798 in the revised manuscript.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, J. Geophys. Res.-Atmos., 108, 4407, https://doi.org/10.1029/2002JD002670, 2003.

4. *Line 179-181. About the "NAtl" simulation, I don't know the specific region of the North Atlantic Ocean, is the south two areas of the North Atlantic tripole SST?*

In L190 of the revised manuscript we have explicitly mentioned the domain over which the SST trend has been imposed for the "Natl" simulation:

.... the "NAtl" simulation, where the month-by-month observed trend in SST during 2011-2018 were imposed over the climatological SST only over the North Atlantic Ocean, that is, over the region 5°-80°N latitude and 5°W-85°W longitude.

5. *Line 197-198, why you divided two periods from 2010, what is the basis?*

We have conducted several correlation analyses between $DA_{\%}$ and SST by shifting the time window one year at a time. That is: 2001-2010, 2002-2011 and so on. This showed that the periods 2001-2010 and 2011-2018 have the most prominent signals of Pacific and Atlantic SST influence on dust, respectively. Hence, we followed this division of period.

6. *Line 203, shifted north-eastwards, is that corrected? Not the westward?*

Thanks for pointing this out. We have corrected to "north-westward". Please see L276 of the revised manuscript.

7. *Line 223, the partial correlation method, you not mentioned in the methods, please introduce it.*

Complied with. We have added the following sentences in L149-153 of the revised manuscript to explain how partial correlation is calculated:

To separate the impact of the Atlantic Ocean on dust from the Pacific, partial correlations between SST and $DA_{\%}$ have been calculated using the following relation:

$$r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1-r_{13}^2)(1-r_{23}^2)}} \qquad (1)$$

where, $r_{12,3}$ is the correlation between variables 1 and 2 after removing the impact of variable 3. In equation (1), r_{ij} refers to correlation between variables i and j.

8. *Since the NADI index from April to June is well correlated with the dust index, and the NADI index from April to June is also analyzed in the article, why is the annual SST field given here?*

Dust aerosol over South Asia is remotely modulated by SST over different regions during different seasons. In this study we are interested in the regions which are important in controlling dust at an annual timescale, which is why we have started with annual SST field before introducing the specific months when the SST

signals over the North Atlantic is magnified. For the reference of the reviewer, we are providing below the correlation between DA% and SST during April-June as an example.

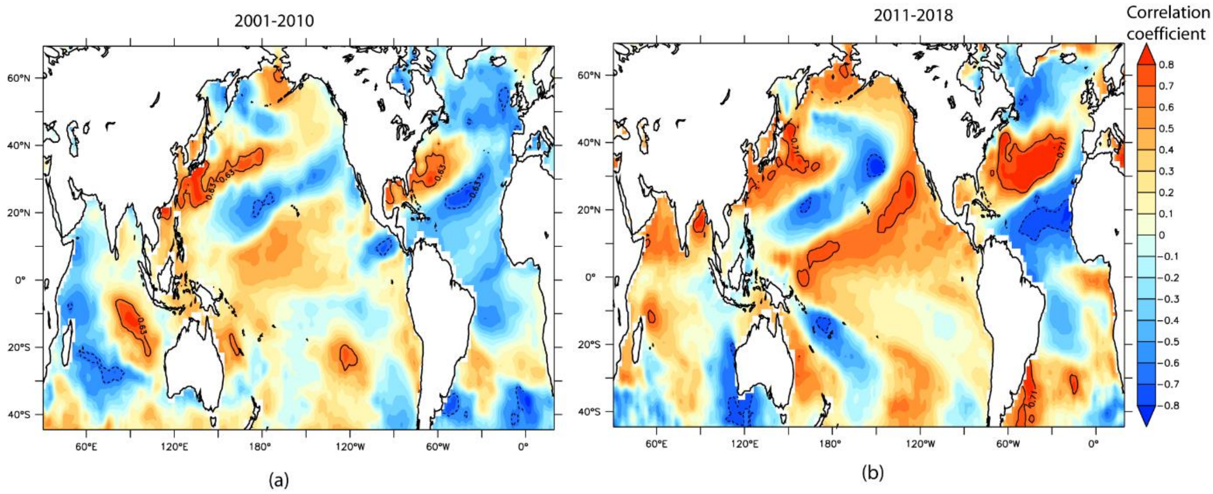

Figure: Correlation between annual DA% over South Asia and April-June SST for (a) 2001-2010 and (b) 2011-2018. The black contours enclose the regions where correlation coefficient is significant at 95%.

As it can be seen from the above diagram that there are other regions (example western part of the North Pacific) that appear when we take April-June SST, which are not important at annual timescale. We would therefore like to retain correlation with annual SST to convey the main message clearly.

9. *Line 241-234. The signal of the Pacific SST is weak, only is a small region shown the 90% confidence level, how does it affect the dust? What is the physical process?*

The equatorial central Pacific is a region well-known to impact circulation over South Asia, with SST warming in the former leading to dry conditions over the latter region. We see a strong signature of Pacific SST at annual scale influencing dust during 2001-2010 in Figure 4a (2a) of the revised (original) manuscript. We want to convey that during this period the Pacific underwent either slight cooling over a small region or no warming over a large stretch, which has intensified the Walker circulation. This slight cooling/no trend is opposed to the warming that the Pacific Ocean has been experiencing historically.

We have now explained the physical process of Pacific SST impacting dust by including a new Section 3.2 entitled "Reduced influence of the Pacific Ocean on South Asian dust" in the revised manuscript. Please also see our response to Comment 12 for details.

Instead, the signals are stronger in the north Pacific and tropical Atlantic Ocean, did you analyze the process?

We have analyzed month-by-month correlation between DA% and SST. Correlation between DA% and north Pacific SST is prominent during January-April of 2011-2018, while that with south tropical Atlantic appears during January-February of 2001-2010 (negative correlation) and over a small region during June-

October of 2011-2018 (positive correlation). None of these regions appear significant when we consider annual average SSTs, which is relevant to this study. Thus, we do not consider these regions in our present study.

10. Line 254-256. NAO is the seesaw pattern of the relationship between the Icelandic Low and the Azores High, which is the atmospheric circulation pattern, not the SST pattern. The Icelandic Low is located over the north of 60 degrees, and your two signifant regions are both over the south of 50 degrees, which is not the NAO, but two south branches of the North Atlantic tripole.

We agree with the reviewer. Indeed, what we see is the impact of the sea level pressure seesaw due to NAO on the North Atlantic SST pattern. As Figure 7 in the revised manuscript shows that it is the winter NAO which impacts the SST south of 50ºN latitude during the following spring-to-summer months. We have updated this part to make the meaning clearer:

The spatial pattern of correlation between $DA_{\%}$ and SST for 2011-2018 in Fig. 4b shows resemblance to SST tripole pattern resulting from surface heat exchanges during the positive phase of NAO

Please see L324-326 in the revised manuscript.

11. *Line 301-303, What is the linkage with the NAO and the North Atlantic tripole?*

The linkage between NAO and the North Atlantic tripole has been discussed in several previous works (e.g., Visbeck et al., 2001; Peng et al., 2002; Pan et al., 2005). Briefly, positive phase of NAO leads to a cold phase of North Atlantic tripole mainly via turbulent heat exchanges, which in turn, can also feedback into the atmosphere. During summer, SST tripole can trigger an East Atlantic Pattern, while during winter SST tripole can result in NAO pattern in the atmosphere (Gastineau and Frankignoul, 2015). It is beyond the scope of this work to discuss the linkage in detail.

With all the wind fields, SST, pressure fields and precipitation fields introduced above, it is completely impossible to see the process how the Atlantic SST influences NADI?

We have now improved the clarity of the figure by deleting contours for 90% significant levels (except for velocity potential) and only retaining those pertaining to 95% significant levels. Please note that the new Figure number in the revised manuscript is Figure 8.

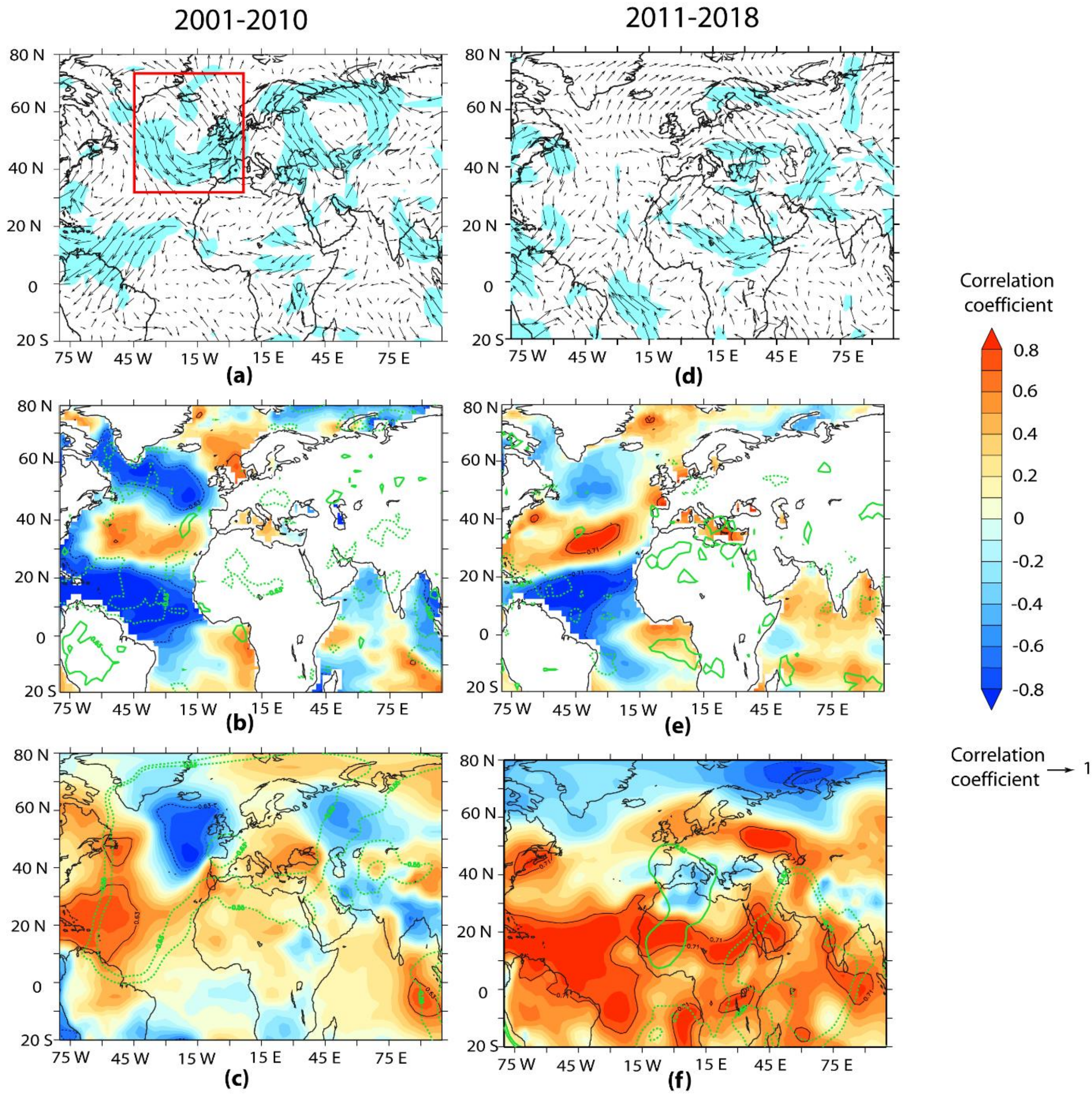

Figure 8: *Correlation between the April-June North Atlantic Difference Index (NADI) and different meteorological parameters from NCEP/NCAR Reanalysis averaged for May-September for (left panels) 2001-2010 and for (right panels) 2011-2018. (a) and (d) Arrows show correlation between NADI and wind vectors averaged between 850 and 700 hPa pressure levels. Light blue shade highlights the regions where one of the components of the wind vector is significantly (95% confidence level) correlated with NADI. (b) and (e) Shading shows correlation between NADI and SST and the green contours enclose the regions where significant correlation (at 95% level) exists between NADI and precipitation. Black contours indicate the regions where correlation between NADI and SST are significant at 95%. (c) and (f) Shading shows correlation between NADI and sea level pressure and the green contours enclose the regions where significant correlation exists between NADI and velocity potential at 850 hPa pressure level: inner and outer contours indicate 95% and 90% confidence levels respectively. Black contours indicate the regions where correlation between NADI and sea level pressure are significant at 95% level. For all the panels continuous and dashed contours are indicative of significant positive and negative correlations respectively.*

12. *Line 311-313, the North Atlantic tripole pattern is also significant in Figure 5b. The relationship between NADI and the North Atlantic tripole SST in the early period is very significant, and the relationship between NADI and the North Atlantic tripole SST in the late period is only significant in the two southern regions.*

Although NADI is correlated with the North Atlantic SST tripole during both the periods, there are differences in the locations, extent of the regions of significant correlations and the magnitude of SST anomalies between these two periods. For example, during 2001-2010, NADI has significant (at 90%) positive correlation with only a small region over the mid-latitude North Atlantic. However, during 2011-2018, NADI has significant (at 95%) positive correlation with a much larger region over the mid-latitude North Atlantic. Moreover, this mid-latitude North Atlantic region (that is, the northern box of NADI index) had negligible SST trend during 2001-2010 but has strong positive trend during 2011-2018. These differences induced circulation changes between 2001-2010 and 2011-2018, which are explained in detail in response to Reviewer's comment #13.

It cannot be seen that the influence from the Pacific Ocean in the early period is changed to the influence from the Atlantic Ocean in the late period.

Based on the comment by the reviewer, we have now included a new section in the revised manuscript, Section 3.2 titled "Reduced influence of the Pacific Ocean on South Asian dust". In this Section we have illustrated how meteorological conditions conducive to increased dust over South Asia is controlled by warming of the equatorial central Pacific SST during 2001-2010 and how the Pacific influence has weakened since 2011. Please see L352-381 of the revised manuscript.

3.2 Reduced influence of the Pacific Ocean on South Asian dust

Several studies have linked warming of the central equatorial Pacific Ocean, associated with the developing phase of an El Niño, to weak monsoon over South Asia and drought (e.g., Kumar at al., 2006; Ashok et al., 2007; Wang et al., 2015). This is due to the shifts in the Walker circulation leading to anomalous ascending motion over the warm SST region and compensating descending motion over South Asia. In Figs. 6 a-b we can see such signatures of weakening of monsoon induced by central equatorial Pacific (taken as 175-140ºW longitude, 5ºN-5ºS latitude) SST warming during September-October months of 2001-2010. This is characterized by anomalous lowering of the 200-hPa geopotential height over South Asia during May-September due to reduced diabatic heating. There is anomalous northerly wind over the northern IO and negative precipitation anomalies over large part of India and surroundings. The negative precipitation anomalies over northwest India, Pakistan and Afghanistan along with anomalous northwesterly at 850-700 hPa over the Indo-Gangetic Plain are most relevant to increased dust emission, transport and longer atmospheric residence time due to less wet depositions. In contrast, during 2011-2018, central Pacific SST does not have any significant impact on geopotential height and precipitation over the dust belt of South Asia (Figs. 6c-d). This points to a weakening relation between central Pacific SST and atmospheric circulation over South Asia. The northwesterly wind anomaly induced over some parts of the Indo-Gangetic Plain during this period overlaps partially with dust source regions. Overall, it appears that dryness due to suppression of precipitation over large area plays an important role compared to anomalous wind in the lower-to-mid troposphere. Partial correlation between annual averaged central equatorial Pacific SST and $DA_{\%}$ adjusted for annual NADI gives a correlation coefficient of 0.64 during 2001-2010, which is significant at 95%. However, for the period 2011-2018, the partial correlation only yields a value of -0.23.

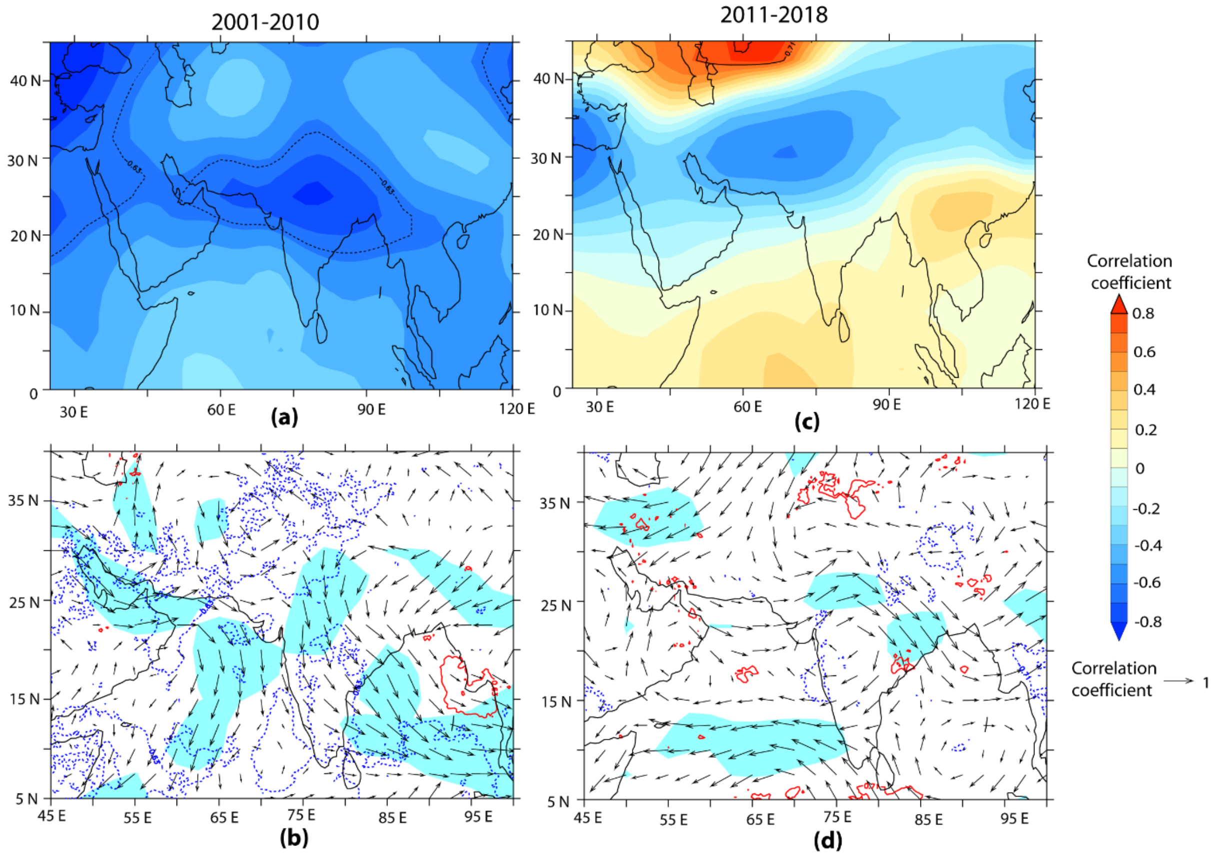

Figure 6: Correlation between September-October central equatorial Pacific SST and different meteorological parameters averaged for May-September for (left panels) 2001-2010 and for (right panels) 2011-2018. (a) and (c) Shading shows correlation between Pacific SST and geopotential height at 200 hPa pressure level and the contours enclose the regions where correlations are significant at 95%. (b) and (d) Continuous red (dashed blue) contours enclose regions having positive (negative) correlation between Pacific SST and precipitation significant at 95% confidence level. Arrows show correlation between Pacific SST and wind vectors averaged over 850-700 hPa pressure levels. Light blue shade highlights the regions where one of the components of the wind vector has significant (at 95%) correlation.

13. Line 316-318, in figure 5b, the south branch SST over the tropical Atlantic is also present the negative pattern, which is resembled as the 5f. It is consistent with the SST distribution in the late tropical Atlantic Ocean. Why the atmospheric pressure not perform the uniform anomalous high?

In Figures 8c (5c) and 8f (5f) of the revised (original) manuscript, correlation is shown between NADI and sea level pressure (SLP) for 2001-2010 and 2011-2018 respectively. To explain why atmospheric pressure responds differently between the 2 periods, we have separately correlated SST over the northern and the southern boxes of NADI with SLP for each of the two periods. This is shown in the following figure. We see that during 2001-2010, SST warming in the northern box has little impact on the SLP over tropical North Atlantic and adjacent regions. However, SST cooling in the southern box can give rise to high pressure over larger area over this region. During 2011-2018, on the other hand, the combined effect of SST warming over the northern box and SST cooling over the southern box leads to anomalous high SLP. The northern box coincides with the location of the Azores high, which forms the northern part of the descending branch of the tropical Hadley cell. Anomalous SST warming in this region, through overlying mass redistribution,

can induce anomalous descending motion and increase SLP in the tropics. The main difference between the two periods is that the SST over the northern box showed negligible trend during 2001-2010, contrasted by an increasing trend during 2011-2018, which is also shown in Figure 5a and b of the revised manuscript. We presume that this positive anomaly of SST during 2011-2018, strengthened the positive impact of SST on SLP over the tropical North Atlantic.

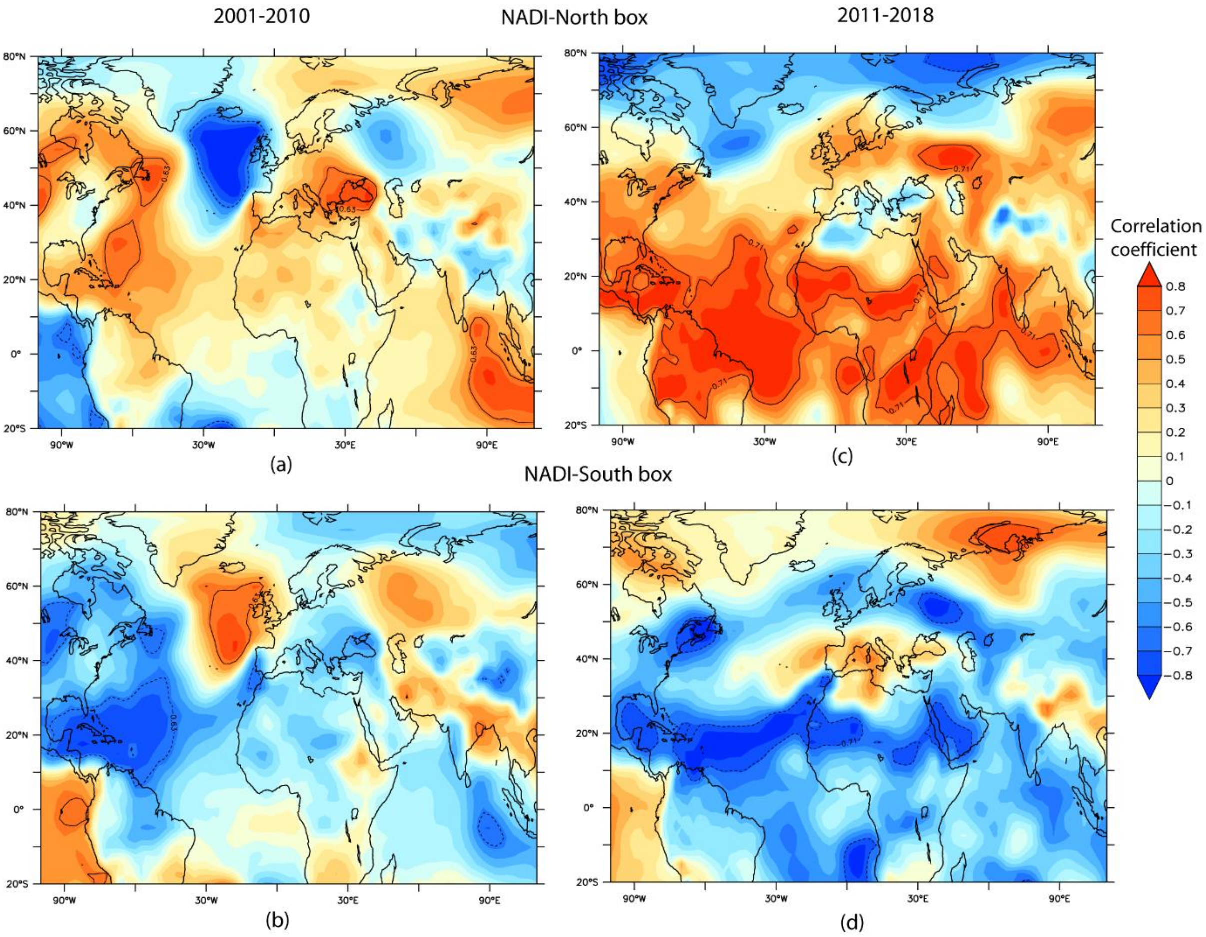

Figure: Correlation between (a) and (c) the northern box of April-June NADI and May-September SLP and (b) and (d) the southern box of April-June NADI and May-September SLP. The correlations for 2001-2010 are shown in the left panels and those for 2011-2018 are shown the right panels. Continuous (dashed) contours enclose the areas having significant positive (negative) correlations at 95% level.

We have included the above Figure as Supplementary Fig. S3. We have also added the following sentences (L419-426) in the revised manuscript to explain this mechanism clearly:

Correlating the north and south boxes of NADI separately with sea level pressure shows that the combined effect of SST warming over the northern box and SST cooling over the southern box leads to this anomalous high sea level pressure (Supplementary Fig. S3). The northern box coincides with the location of the Azores high, which forms the northern part of the descending branch of the Hadley cell. Anomalous SST warming in this region, through overlying mass redistribution, can induce anomalous descending motion and increase SLP in the tropics. Since SST over mid-latitude North Atlantic showed significant positive trend during 2011-2018, as opposed to the period 2001-2010, the impact of the SST over the north box of NADI on the sea level pressure is pronounced during 2011-2018.

14. Line 318-321, the relation with the North Atlantic SST leads to the convergence and precipitation, but how the North Atlantic SST result in? I am confused the process.

The warming of the SST over the mid-latitude North Atlantic during 2011-2018, which constitutes the northern box of NADI, extends to the European coast and the Mediterranean Sea. This warming leads to cyclonic motion and a region of convergence and precipitation. This is illustrated by the following diagram where the Mediterranean region is zoomed in.

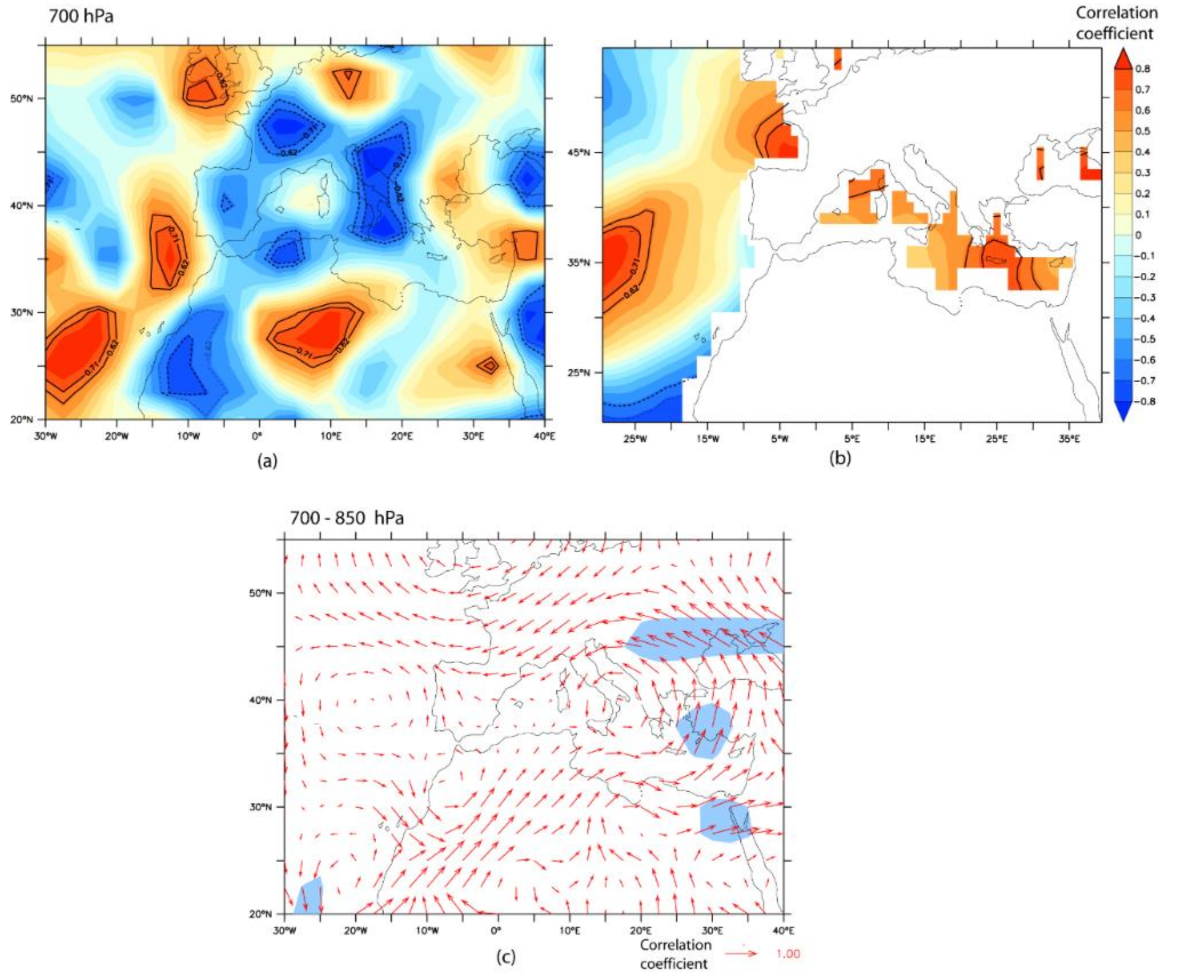

Figure: Correlation between April-June NADI and (a) wind divergence at 700 hPa, (b) SST and (c) wind vectors averaged for 700-850 hPa for May-September of 2011-2018. In (a) and (b) inner (outer) contours show 95% (90%) significant levels for correlation analysis. The light blue shade in (c) highlights the regions where one of the components of the wind vector is significantly (95% level) correlated with NADI. Negative values in (a) indicate convergence.

We have further made the following modifications to make the relation clearer. Please refer to L426-431 in the revised manuscript:

The eastward extension of anomalous warm mid-latitude SST have resulted in convergence, as indicated by 850 hPa velocity potential (green contours in Fig. 8f), and positive precipitation anomaly over the Mediterranean region including North Africa and northwestern part of the Arabian Peninsula (green contours in Fig. 8e).

Additionally, warming (cooling) in the tropical North Atlantic SST can induce a compensatory descending (ascending) motion over the Mediterranean region (Sun et al., 2009).

15. Line 321-324, why the convergence over the Mediterranean region can induce the next area divergent?

Warm SST over the Mediterranean gives rise to surface-level convergence and ascending motion. This can lead to anomalous circulations emanating from the region of ascending motion. As a result of mass continuity, readjustments in the atmosphere takes place, which results in subsidence in the surrounding regions. This results in divergent motion at the surface.

16. In figure 5, Why not directly correlate the dust index with each air and sea field and see how climate variables modulate the dust index?

We have correlated different SST indices (e.g., NADI) with meteorological fields, like wind and precipitation, that are well known to modulate dust over this region. By analysing how SSTs control these fields we can understand the behaviour of the factors that control dust and, by extension, interannual variability of dust.

In addition, both the correlation between Atlantic NADI index and the Atlantic tripole SST field in the early and late periods is significant.

Please see our response to the first part of Comment 12.

How can we see the physical process of dust index changing from influenced by the Pacific Ocean to the Atlantic Ocean? You don't give the Pacific SST's relation pattern in the early periods.

We have now added a new Section in the revised manuscript, Section 3.2, in which we have described how Pacific SST influenced dust during 2001-2010 and how that influence has reduced since 2011. Please see our response to Comment 12.

References

Gastineau, G. and Frankignoul, C.: Influence of the North Atlantic SST Variability on the Atmospheric Circulation during the Twentieth Century, J. Climate, 28, 1396–1416, https://doi.org/10.1175/JCLI-D-14-00424.1, 2015.

Pan, L.: Observed positive feedback between the NAO and the North Atlantic SSTA tripole, Geophys. Res. Lett., 32, L06707, doi:10.1029/2005GL022427, 2005.

Peng, S., Robinson, W. A., and Li, S.: North Atlantic SST forcing of the NAO and relationships with intrinsic hemispheric variability, Geophysical Research Letters, 29(8), 1276. https://doi.org/10.1029/2001GL014043, 2002.

Visbeck, M. H., Hurrell, J. W., Polvani, L., and Cullen, H. M.: The North Atlantic Oscillation: past, present and future, P. Natl. Acad. Sci. USA, 98, 12876–12877, 2001.