Answers to Reviewers

Manuscript: Aerosol Atmospheric Rivers: Climatology, Event Characteristics, and Detection Algorithm Sensitivities by Sudip Chakraborty et al.

We are thankful to the reviewers for their insightful comments and help improving the manuscript. Our responses are below, comments by reviewers are italicized.

Reviewer #1 (Comments to Author (shown to authors):

Thank you very much for your suggestions and the insightful comments. We have made changes to the manuscript following your suggestions. The major changes and response comments are highlighted in yellow.

> *This manuscript is an extension of an existing study on classifying strong and confined events of aerosol transport similar to the concept of atmospheric rivers for water transport. The analysis is based on aerosol (dust, sea-salt, carbon and sulfate) and meteorological re-analysis data for the years 1997-2014. It shows interesting features driving the main transport patterns from various high emission regions. It is often argued that AAR are important to understand air pollution episodes and climate impacts. However I think, that using the re-analysis dataset which gives already a 4 dimensional aerosol distribution is as well suited to study those two subjects. It is not clear what additional crucial information AAR give here, this could be more elaborated. There have been many studies published which describe the intercontinental transport of pollutants, describing transport heights and time scales, the relation to those studies is lacking in the paper. Otherwise it gives valuable information on these extreme transport events and I think it is suitable for publication after revisions.*

Thank you very much for this point. Now, we have added discussions regarding the previous studies on aerosol transport and air pollution in the introduction section. We have also discussed about the relation between AAR and the aerosol transport events as well as the importance of AARs on aerosol transport in connection with the previous studies. Please see the introduction section and lines 590-602 of the conclusion section.

General remarks:

> *In some analysis BC and OC are separated in some combined, I think in most analysis they could combined.*

We have combined OC and BC in Figures 1 and 2 that show the mean integrated aerosol transport (IAT) and emission of different species of aerosols to remove redundancy. Given that OC and BC have similar sources and transport mechanisms, they have very similar geographical distributions in terms of sources and IAT value around the globe. In other figures we have separated OC and BC particularly because of the significance of the impact of BC on the radiative forcing. For our AAR database, we will be providing BC and OC AARs separately so that future studies can separate out where appropriate (e.g. impact of BC AARs on the radiative

forcing). Also, OC rivers generally carry a higher mass of aerosols than BC rivers. We have clarified this rationale better in lines 312-314.

"Herein forth, we separately show the CA rivers as OC and BC rivers, especially because BC AARs can significantly impact the radiative forcing compared to OC AARs and because the mean mass of aerosols being transported by the OC is about five times that of BC AARs (Fig. 4)."

> *It would be interesting to see a calculation of the total mass transported by the AAR and not only the flux to get a better picture of their importance.*

The total amount of mass transported can be deduced from Figure 6 that shows the annual total IAT transport (in tons m^{-1} or kg m^{-1}) and the fraction of that contributed by AARs (shading).

Abstract:

> *line 35: in the paper often a range is given e.g. AAR contribute between 40-80% to the total transport. Looking at figure 6 the fraction is between 0 and 80%, there is a need to specify this in more detail, i.e. why 40% was chosen. If this is globally calculated (which would make sense), why is it such a large range? If it is given for the boxes, which are chosen differently for each aerosol type, it is quite an arbitrary choice. Could give one example for a region, but then also state the global (average/median) number.*

Given that the maps show 0-80% and there are lots of 0, 10, 20 % regions, we are pointing toward the maximum values for a given species. We agree with the reviewer it's not obvious what criteria we have been using while calling out a specific percentage. These 40-80% values represent that maximum fractional transport of aerosols that can be attributed by AARs over the major transport pathways. The range refers to the different maximum values among different aerosol species. For example, DU aerosols can contribute up to 80% of the annual transport over the Sahara Desert- Caribbean pathway, SS AARs can transport up to a maximum of 50-60% near the west coast of Europe, and other species of AARs can contribute up to 40% of the total annual transport. Thus, the range of the maximum values are 40-80%. We have mentioned that in lines 35, 473, 478, 487, 489, 492, and 495.

We have also mentioned this in the conclusion section : " The global total annual transport by All and AAR events are inhomogeneous in terms of their geographic distributions. F_{AAR} varies between 0-40% for SU, OC, and BC AARs, between 0-80% for DU AARs, and between 0-50% for SS AARs over various regions of the world. Our results show that on average, 30-40 SU, BC, and OC AAR days every year are responsible for a maximum of 30-40% of total annual aerosol transport for a given aerosol species over certain major transport pathways around the globe. Over the major transport pathways of the SS (DU) AARs, F_{AAR} can reach up to a maximum of 50 (80) % of the total annual aerosol transport of the respective species."

> *line 36: the abbreviation for the aerosol categories havn't been defined (e.g. DU, SS, CA) before use*

Thanks for pointing these out. We have defined the abbreviations in the abstract.

> *line 40: That the mass mixing ratio decreases monotonically with height is mainly true for sea salt, for other aerosol types it is not so clear.*

Thanks for pointing this out. We have deleted "and monotonically decreases with altitude"

> *line 43: if the average length is 4000km and the average width is 600km - why is the ratio between those 8 and not 7?*

This is due to the skewness of the distribution. We have mentioned that in lines 534.

Introduction:

> *line 49: What is meant by: aerosols have impact on the convective lifetime? Is it the lifetime of aerosol or the convective cells, which is meant here?*

"of convection". Thanks for the suggestion. We have clarified in lines 51.

> *line 62: The long range transport could not only be observed since satellite analyses were used, but also surface observations in remote areas were used to prove the transport events.*

We have modified and added detailed information about the aerosol transport detected by the satellites, in-situ, and models in the introduction as:

"In addition, in-situ measurements have been conducted to detect aerosol transport events over various regions of the world, even in the remote polar regions (Gohm et al., 2009a; Tomasi et al., 2007a; Wang et al., 2011a; Rajeev et al., 2000a; Bertschi et al., 2004a; Qin et al., 2016a; Ackermann et al., 1995; Fast et al., 2014a). Many studies have previously investigated the long-range aerosol transport events between various regions of the world (Prospero, 1999; Sciare et al., 2008; Abdalmogith and Harrison, 2005; Swap et al., 1996; Kindap et al., 2006a; Weinzierl et al., 2017) including inter-continental transport events. Many regions have been studied including the transport events from the Sahara Desert to the United States (Prospero, 1999), Europe to Istanbul (Kindap et al., 2006b), East Asia to California (Fan et al., 2014), and South Africa to the South Atlantic region (Swap et al., 1996). Many other studies have investigated aerosol aging and chemical processes during the transport events (Febo et al., 2010; Kim et al., 2009; Mori et al., 2003; Markowicz et al., 2016; Song and Carmichael, 1999) including the secondary organic aerosol formation and depicted the impact of the long-range aerosol transport on clouds (Wang et al., 2020a; Garrett and Hobbs, 1995), precipitation (Fan et al., 2014), radiation (Ramanathan et al., 2007), and air quality events including the PM2.5 level (Han et al., 2015; Chen et al., 2014; Prospero et al., 2001; Febo et al., 2010). Apart from the studies using satellite and in-situ measurements, climate models have often been used to understand aerosol transport (Takemura et al., 2002; Chen et al., 2014; Ackermann et al., 1995; Fast et al., 2014). As mentioned above, many of these studies used different approaches and methodologies and thus comparing one region to the another around the globe or depicting one species' character of extreme events to

another species with a common framework is difficult. Although these studies identify aerosol transport events across the globe, a clear picture about the identification of the extreme aerosol transport events (see methods) using long-term climatological observational data sets, their climatology and major transport pathways, and fractional contribution of those extreme transport events to the global annual transport were lacking.

Leveraging the concept of atmospheric rivers (ARs) (Ralph et al., 2020; Zhu and Newell, 1994) and a widely used global AR detection algorithm (Guan and Waliser, 2019, 2015; Guan et al., 2018), our previous study developed an aerosol atmospheric rivers (AARs) detection algorithm (Chakraborty et al., 2021a). As with ARs that were studied around the globe using different algorithms in different places, including global change studies, it was hard to get a consistent assessment based on one homogeneous method of identifying the transport events. A value of this study comes from the extension of a well-developed algorithm and applied uniformly around the globe and across species."

> *line 73: AAR are responsible for 40-80% of the total annual transport in 20-30 days - how is this span defined? For different region, if yes which?*

The span is simply the range between different aerosol species. We have further clarified in the text that this comes from the number of AAR days and their fractional transport over those major transport pathways in lines 108-111:

"Moreover, it was found that along major transport pathways, AARs are detected about 20-30 days per year and can be responsible for up to a maximum of 40-80%, depending on the species of aerosols, of the total annual aerosol transport (Fig. 3, Chakraborty et al., 2021a)."

Data
> *line 102: describe what DUFLUXU and DUFLUXV stands for*

We've clarified this now in lines 141.

> *The emissions used here are an important part, you could describe from which inventory they come from and annual totals. I assume there was a significant decrease in the sulfate and also black carbon emission since 1997? How does this impact the detections of AAR - does this change the frequency towards earlier years?km ,, '*

Summary of the emissions used in MERRA-2 can be found from the table 1 in Randles et. al. 2017. We have added "MERRA-2 accounts various sources for emissions (Randles et al., 2017). Dust emissions in MERRA-2 use a a map of potential dust source locations. Emissions of both DU and SS are wind driven for each size bin and parameterized. Sea salt emission is estimated using the sea surface temperature and the wind speed dependency with sea salt emission parameterization depends on the frictional velocity. For SS, lake emissions are also considered. SU aerosol emissions derive from both natural and anthropogenic sources. Inventories for sulfate includes volcanic Sulfur dioxide emissions as well as those from the aircraft, energy-sectors, and anthropogenic aerosol sources. Emissions of CA and SU aerosols in MERRA-2 come from various inventories over the time. From 2010, the Quick Fire Emissions Dataset version 2.4-r6 is

used. Locations of fires are obtained from MODIS level-2 fire and geolocation products. Please see table 1 of Randles et al., 2017 for details. Before that MERRA-2 utilizes the Global Fire Emission Dataset from MODIS. MERRA-2 also applies biome-dependent correction factors, fractional contributions of emissions from different forests with applying correction to the monthly mean emissions that cover 1980–96 and are based on Advanced Very High Resolution Radiometer, the Along Track Scanning Radiometer, and the Total Ozone Mapping Spectrometer Aerosol Index.

Please note that 1) Anthropogenic emissions (mostly from HTAP) are frozen after 2010. SO, MERRA-2 does not account for changes in anthropogenic emissions after 2010; natural emissions (dust and sea salt) are properly handled since they are dynamically computed.
2) It is important to notice that aerosol data assimilation effectively functions as a form of sources, compensating for missing emissions. However, the single channel AOD data cannot discern contributions from different species, thus the partition of the analysis increments among specifies is chiefly determined by the prescribed emissions.

We are working on the influence of the events like ENSO, MJO, emissions etc on the variations in AARs' occurrences and trends. That warrants a separate manuscript and will be provided once we extend the data up to 2020 for a better trend estimation. We are currently expending the datasets so that we have a longer period of time for the trend analysis.

Results:

> *line 227: why are there only low CA AAR in the midlatitudes? Fig 3d from Chakraborty et al., 2021 shows there is IAT in this region?*

CA rivers over the midlatitudes are more frequent (shading) but their mean IAT (Figures 3C and 3E, Chakraborty et al., 2021) is less than those originating from the global rainforests and south China (size of the arrows). We have modified the statement in lines 279-283 as

"Over most of the midlatitudes in the Northern Hemisphere, the emissions of CA aerosols (Fig. 2D) (also IAT values, Fig. 1D) is less than that over the global rainforests and China in all four seasons (Fig. 1). As a result, although CA (OC and BC) AARs are more frequent over the midlatitude region, the mean IAT by those rivers are less than those AARs that originate from the global rainforests and China (Chakraborty et al., 2021a).".

> *line 246: how many AAR have been identified for the volcanic eruption? You could give the number in the text.*

Our algorithm detects AARs at every six-hour interval. In April 2010, 80 such rivers (or ~20 AAR days, due to 4 steps / day) that originate and propagate in different directions have been detected over that region. We have added "In April 2010, out algorithm detected ~80 SU AARs (using six-hour analyses time steps i.e., ~20 SU AAR days) originating over that region and propagating to different directions." Please see lines 309-311.

ARs' frequency and SS AARs' frequency have been provided in Chakraborty et al. 2021. Figure 3A shows the frequency of occurrences of ARs and Fig. 3D shows the same for SS AARs. In the mid latitudes, there are ~35 (20) ARs (SS AARs) are observed. ARs are detected over the midlaitude region, whereas many SS AARs are also detected over the tropical region. We have added the following in lines 338-343:

" The SS AARs in the midlatitudes carry the signature of the storm tracks, and have distributions similar to ARs (Guan and Waliser, 2015). Every year, in the midlatitude region, 30-40 ARs are detected (Chakraborty et al, 2021a), whereas ~20 AAR days/year occur in the mid-latitudes with mean IAT of ~2 x 10^{-3} kg m^{-1} s^{-1}. The distributions between ARs and SS AARs are not quite the same; the SS AARs are biased equatorward toward the trade winds."

Figure 4 is the same as in Chakraborty et al., 2021, you could refer to this figure and omit here.

Figure 4 in Chakraborty et al, is based on a threshold computed using 5 climatological months of running IAT values as per the original AR algorithm. Based on the strong seasonality found in some regions, we have changed that to 3 climatological months in this study. This is mentioned in lines 215-220 as "Finally, Chakraborty et al. (2021a) computed the climatological 85th percentile threshold IAT values for each month based on the 5 climatological months centered on that month, as in the original AR algorithm (Guan and Waliser, 2015). However, it was found that a 3-month window better resolves the annual cycle of IAT and meanwhile still retains sufficient sampling over the period of 1997–2014. For example, the IAT 85th percentile for February is calculated using the IAT values using January-March data from 1997-2014. "

In addition, the Figure 4 shows the major transport pathways that we refer multiple times in this article. Thus, we keep this figure for ease of reading.

line 289 is a repetition of line 285

Deleted.

Figure 5:
The unit of the y-axis is missing, the legend is too small and also to inset with the regions is too small. In the x-axis the factor e.g. 10-11 is hardly readable. Unit of the first column is missing.

We have modified the figure according to your suggestions.

Why is a box at the west coast of the US used and not the east coast of the US, which is the origin of the major emission sources and also subject to transatlantic transport driven by strong westerly winds?

We have added the IAT profiles, aerosol mixing ratio, and the wind profiles for SU, OC, and BC AARs. We have also added related discussions in the text. Thanks for raising this question as we see the SU AARs over the eastern US have SU aerosols mass mixing ratio close to those from China.

For analyzing the AAR in these boxes, it would be interesting to know how many AAR are captured within the boxes (i.e. fraction to the global total).

The total number of AARs within the boxes can be deduced from Figure 4. For example- the orange box over the tropical Atlantic in Figure 1B will have ~25 AARs per year. We have analyzed between 1997-2014. So, there could be 400-500 AARs analyzed.

Please see an example cited as "For example, the orange box over the Sahara-Caribbean pathway experiences a presence of 25-30 AARs per year (Fig. 4A). Based on our analysis between 1997-2014, the profiles shown in Figs. 5A, 5B, and 5C shows the mean and standard deviation of ~400-500 AARs." in lines 367-370.

line 317: space before "(red)"

Thanks for pointing this out.

line 332: remove "-" after Sahara

Noted. And removed at other places too.

line 348: the inversion effect is not due to pollutants; it is rather an accumulation of pollutants due to an inversion effect.

Thank you very much. We have changed to "the impact of the boundary layer inversion effect on the accumulation of the pollutants" in lines 424-425.

line 378: accounted is misspelled

Thanks for pointing this out.

Figure 6; For the dust species, there are features with maximum fraction over Thailand - this looks like an artifact, as the frequency of AAR is very low over this region. Please check.

It appears that the dust transport over there is not frequent (smaller arrows in Fig. 6A). So, the AARs (shading, Fig. 4A) show very small object-mean IAT values (arrows in Fig. 4A). Still, a small number of DU AARs occasionally travel over there (~5/year) and cause dust transport. It

appears that other than these occasional dust events, there is no other way dust is transported over there (red color showing >80% of the transports). We have mentioned in lines 478-483 "Over some regions far from the dust source region, such as over the maritime continent, the annual IAT value is very less by All events (Fig. 6A). About 5 AARs (shading, Fig. 4A) with very small object-mean IAT values (arrows, Fig. 4A) are observed over there each year. It appears that although AARs are not frequent (~ 5 AARs/year) over there, they are responsible for 80-100% of the total annual transport."

line 380: These are quite high numbers, for easier readability convert from kg to tons.

We have added the values in tons. In order to be consistent with the other units used in the study, we also use kg. Please see the modified figure.

line 387: typo after Fig

Corrected. Thank you.

Figure 8: why is in panel D BC and OC so different? What is the unit of the frequency? The legend is quite small, maybe reduce to one panel an make it larger

The mean IAT of CA rivers (as well as SU rivers) are smaller than that of the SS and DU rivers. Please see Figure 1 for the seasonal IAT values, Figure 2 for the emissions, and Figure 4 for mean IAT values by AARs to compare between different species of AARs. The unit of frequency if the fraction of the AARs observed in every bin divided by the total number of AARs detected.

Figure 9: title too small, change units to reduce the number of zeros

Please see the modified Figure with improved front.

line 479: spaces in the number sequences are on the wrong position

corrected. Thank you.

Figure 10: very similar for all species, you could reduce to one panel showing the average for all

Please see the new figure with mean values and standard deviation. Text is also modified accordingly.

line 545: duplicate length in the end of the sentence

Deleted. Thank you.

Reviewer #2 (Comments to Author (shown to authors):

Thank you very much for your suggestions and the insightful comments. We have made changes to the manuscript following your suggestions. The changes are highlighted in yellow in the manuscript.

This paper is an extension of authors' previous work on the detection of aerosol atmospheric rivers (AARs) with the MERRA-2 aerosol reanalysis. The study focuses on the characteristics of AARs derived from 18-years (1997-2014) of data record. The paper is generally well written, but some clarifications and elaborations are needed.

General comments:

Numerous studies have used satellite remote sensing, ground-based networks, and global chemical transport models to characterize aerosol long-range transport across continents. How is this study related to previous studies? What new value will this study add? How can people use the generated datasets to advance sciences? These points need to be elaborated in the paper.

Thank you for this valuable suggestion. We have added

"In addition, in-situ measurements have been conducted to detect aerosol transport events over various regions of the world, even in the remote polar regions (Gohm et al., 2009a; Tomasi et al., 2007a; Wang et al., 2011a; Rajeev et al., 2000a; Bertschi et al., 2004a; Qin et al., 2016a; Ackermann et al., 1995; Fast et al., 2014a). Many studies have previously investigated the long-range aerosol transport events between various regions of the world (Prospero, 1999; Sciare et al., 2008; Abdalmogith and Harrison, 2005; Swap et al., 1996; Kindap et al., 2006a; Weinzierl et al., 2017) including inter-continental transport events. Many regions have been studied including the transport events from the Sahara Desert to the United States (Prospero, 1999), Europe to Istanbul (Kindap et al., 2006b), East Asia to California (Fan et al., 2014), and South Africa to the South Atlantic region (Swap et al., 1996). Many other studies have investigated aerosol aging and chemical processes during the transport events (Febo et al., 2010; Kim et al., 2009; Mori et al., 2003; Markowicz et al., 2016; Song and Carmichael, 1999) including the secondary organic aerosol formation and depicted the impact of the long-range aerosol transport on clouds (Wang et al., 2020a; Garrett and Hobbs, 1995), precipitation (Fan et al., 2014), radiation (Ramanathan et al., 2007), and air quality events including the PM2.5 level (Han et al., 2015; Chen et al., 2014; Prospero et al., 2001; Febo et al., 2010). Apart from the studies using satellite and in-situ measurements, climate models have often been used to understand aerosol transport (Takemura et al., 2002; Chen et al., 2014; Ackermann et al., 1995; Fast et al., 2014). As mentioned above, many of these studies used different approaches and methodologies and thus comparing one region to the another around the globe or depicting one species' character of extreme events to another species with a common framework is difficult. Although these studies identify aerosol transport events across the globe, a clear picture about the identification of the extreme aerosol transport events (see methods) using long-term climatological observational data sets, their climatology and major transport pathways, and fractional contribution of those extreme transport events to the global annual transport were lacking.

Leveraging the concept of atmospheric rivers (ARs) (Ralph et al., 2020; Zhu and Newell, 1994) and a widely used global AR detection algorithm (Guan and Waliser, 2019, 2015; Guan et al., 2018), our previous study developed an aerosol atmospheric rivers (AARs) detection algorithm (Chakraborty et al., 2021a). As with ARs that were studied around the globe using different algorithms in different places, including global change studies, it was hard to get a consistent assessment based on one homogeneous method of identifying the transport events. A value of this study comes from the extension of a well-developed algorithm and applied uniformly around the globe and across species."

Also, we have added the following in the conclusion section:

"To our knowledge, this study significantly advances the understanding of global aerosol transport events. This study is the first to provide a common detection and analytical basis for studying extreme transport events, heavily leveraging the heritage and methodologies by the (water vapor) atmospheric river community. Moreover, this study identifies the extreme transport events by selecting grid cells with IAT values greater than the 85th percentile of their climatological values and retaining the stronger 50% of those objects detected based on the object-mean IAT values. This study creates a database of the AAR events between 1997-2014 that will be expanded till 2020 and will provide a valuable platform for aerosol transport-related research including their impacts on the climate and air quality. Furthermore, the algorithm developed to detect AARs can be used to detect the real-time AAR events using the nature run of the GOES FP system that provides analyses and forecasts produced in real-time, using the most recent validated GEOS system (https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php).

> *Discussion of potential uncertainties associated with the analysis: MERRA-2 assimilates satellite observed aerosol optical depth (clear-sky radiance associated with it). This offers strong constraint to the AOD in MERRA-2. However, aerosol components (e.g., sulfate, dust, sea-salt, and carbonaceous aerosol) are not fully constrained. How will this lack of constraint in the aerosol components affect your detection and quantification of AARs? MERRA-2 aerosol vertical distribution is also not constrained by satellite-based lidar observations, which constitutes of another uncertainty. You could use CALIPSO lidar observations to evaluate the MERRA-2 aerosol extinction profiles in major AAR regions (e.g., those defined in Figure 5).*

We agree with the reviewer. There is an attempt to use CALIPSO and HSRL examine the vertical structure of aerosols in MERRA-2; see the Buchard et al. 2017 paper. Regarding speciation: single channel AOD data has no information about speciation. The model, informed by specified emissions, comes up with this speciation. We acknowledge this limitation, there is no good way to quantify it, except perhaps by using lidar typing as in the paper below. They found that "despite having the column AOT constrained by MODIS, comparison to the CALIOP VFM reveals a greater occurrence of dusty aerosol layers in our MERRAero-CALIOP VFM due to errors in MERRAero aerosol speciation. "

Nowottnick, E. P., P. R. Colarco, E. J. Welton, and A. da Silva, 2015: Use of the CALIOP vertical feature mask for evaluating global aerosol models. Atmospheric Measurement Techniques Discussions, 8, 1401–1455, https://doi.org/10.5194/amtd-8-1401-2015.

As a result, owing to the importance of the fact that MERRA-2 aerosol vertical distribution is also not constrained by satellite-based lidar observations, we are currently investigating the CALIPSO profiles as a part of a new analysis. We have added:

"It is important to keep in mind that the aerosol vertical structure in MERRA-2 is not directly constrained by measurements, and are chiefly determined by the injection height of the emissions as well as turbulent and convective transport processes parameterized in the model. Evaluation of the vertical structure of MERRA-2 aerosols appears in Buchard et al. (2017). Buchard et al. (2017) has attempted to use Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) to examine the vertical structure of aerosols in MERRA-2. In section 4.3

We acknowledge in the conclusion section that

"We acknowledge a source of uncertainty in the aerosol mass mixing ratio and IAT profiles shown in this study from the MERRA-2 data since MERRA-2 aerosol vertical distribution is also not constrained by satellite-based lidar observations. A recent study found that comparison to the CALIOPO VFM data detects a greater occurrence of DU aerosols in MERRA-2 due to errors in MERRAero aerosol speciation (Nowottnick et al., 2015). In a future study, an in-depth analysis will be performed using the observation from the ground-based and air borne measurements (wherever available) and CALIPSO. For example, ORACLES mission and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation can be used to to study the subsidence that depresses the plumes once they reach the Atlantic Ocean off the west African Coast (Das et al., 2017)."

We acknowledge the importance of the question and it will be addressed in a future study We show one example here from our current analysis here,
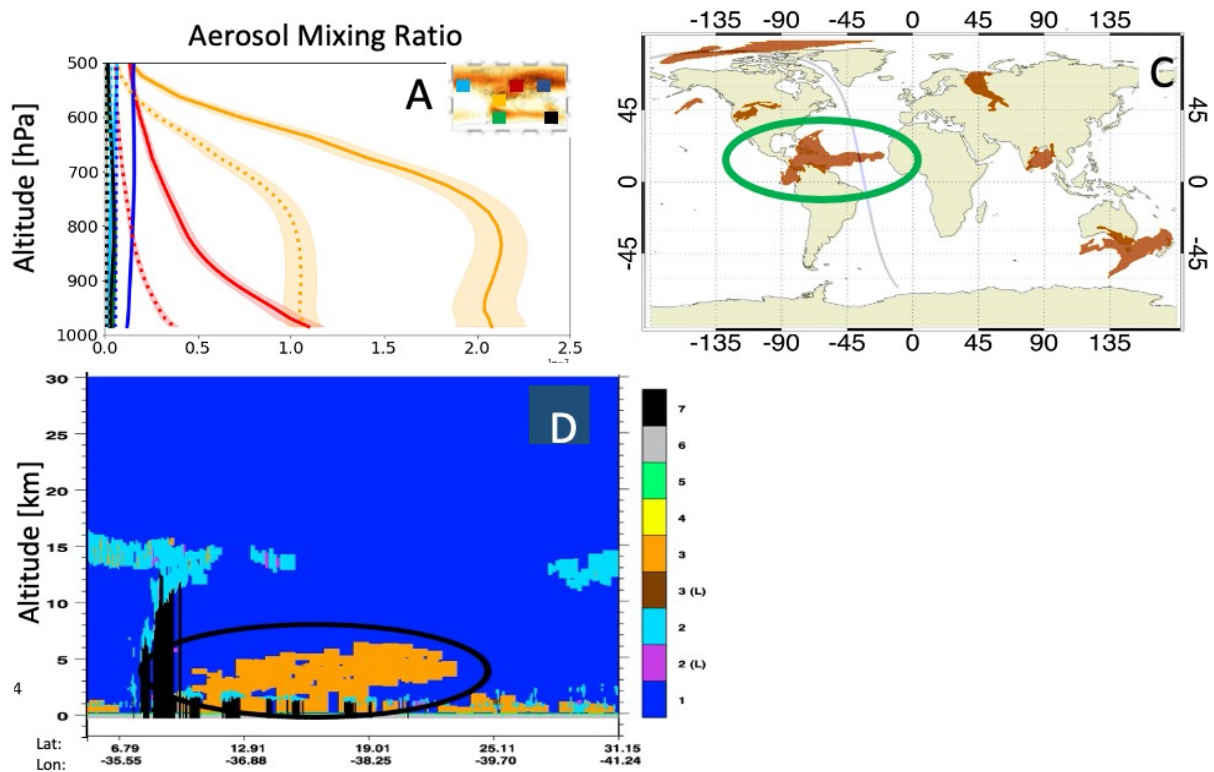
Figure. (A) Mean aerosol mass mixing ratio for all the dust AARs observed between 1997-2014 over the locations marked in the map shown in the inset. (B) DU AARs detected and CALIPSO overpass in the daytime on 25th June, 2008. (C) CALIPSO vertical feature mask over the region where a DU AAR (encircled in green) is detected to transport aerosols from the Sahara Desert to the Caribbean region. Color bar represents: **1: Clear air, 2: cloud, 3: tropospheric aerosols, 4: stratospheric aerosols, 5: surface, 6: subsurface, 7 attenuated, and L: low confidence**. The aerosol layer is encircled in black.

Figure A shows the elevated DU aerosol mixing ratio for DU over the Sahara to Caribbean pathway (orange). (B) shows the AARs detected on 25th June 2008 and the CALIPSO track on the same day overpassing a DU AAR. And (C) shows the CALIPSO vertical feature mask overpass on the same day observing the cross section of the DU AAR (Fig. B; circled) travelling from the Sahara Desert to the Caribbean region/Southern US/ North of the South America. From (C), it is clear that CALIPSO can see that the aerosol layers are elevated up to 6 km between 12–23° N (exactly over the AAR) and is consistent with the DU profile (orange color, The Sahara Desert to the Caribbean pathway) in (A) or Fig. 5B in the manuscript. It is to be noted that CALIPSO can also detect aerosols outside the AAR boundary since AAR detection is restrained by the IAT values, not the aerosol mass that is not being extremely transported (IAT values < 85th percentile). We acknowledged the importance of the question and we have added the importance of this in the conclusions section and it will be addressed in a future study.

An 18-years data record of AARs has been generated. But this study only analyzed climatology and seasonal variations of AARs. I strongly suggest that the authors analyze and present interannual variations of AARs in the paper.

We agree with the reviewer and thanks for the great suggestion. This manuscript is intended to provide more details regarding the algorithm development and sensitivities so that the database can be released and used by others, and subsequently we, and others, can undertake this sort of variability studies. We are working on the influence of the events like ENSO, MJO, emissions etc on the variations in AARs' occurrences, interannual variations, and also the trends. That warrants a separate manuscript and will be provided once we extend the data up to 2020. We are currently extending the datasets so that we have a longer period of time for the trend analysis.

Specific comments:

In the abstract: aerosol components DU, CA, SU, and SS are used but not defined.

Thanks for pointing this out.

Lines 56-58: not sure about what you mean here.

We have clarified in lines 56-62:

"Aerosols can influence a plant's health in two ways. Firstly, aerosols are known to increase the amount of diffuse radiation (Xi & Sokolik, 2012). The implications for plants are that along with decreasing the direct beam photosynthetically active radiation (PAR), the presence of aerosols would lead to greater diffused PAR, which means illumination of a greater portion of plant canopies, including shaded leaves, for which direct PAR was not accessible previously (Gu et al., 2003; Knohl & Baldocchi, 2008; Niyogi et al., 2004)."

Lines 61-64: there have been numerous studies of aerosol intercontinental transport, based on satellites, global models, and even ground-based networks. What is a relationship between your study and these previous studies?

Thank you for pointing this out, and we agree with your assessment. We have provided a more complete literature review in the introduction to connect our work with previous work. Please see the introduction section and lines 590-602 of the conclusion section.

Line 70: here you define CA (carbonaceous aerosol) as a sum of organic and black carbon. Later when discussing CA AARs, you present organic carbon (OC) and black carbon (BC) separately. To be consistent, it is better to combine OC and BC.

We have combined OC and BC in Figures 1 and 2 that show the mean IAT and emission of different species of aerosols to remove redundancy. They have almost similar geographical distributions in terms of sources and IAT value around the globe. In other figures we have separated OC and BC particularly because of the significance of the impact of BC on the

radiative forcing. We will provide BC AARs in the data base separately for future studies on the impact of BC AARs on the radiative forcing. Also, OC rivers generally carry a higher mass of aerosols than BC rivers. We have mentioned that in lines 312-314.

"Herein forth, we separately show the CA rivers as OC and BC rivers, especially because BC AARs can significantly impact the radiative forcing compared to OC AARs and the differences in the mean mass of aerosols being transported by the OC and BC AARs (Fig. 4). "

> *Lines 94-95: no need to define DU, SU, SS and CA again. They are already defined in lines 69-70.*

Thanks for pointing this out.

> *Lines 103-104: Given it assimilates satellite observations of aerosol optical depth, MERRA-2 should be able to "capture the global aerosol optical depth reasonably well". This is obvious.*

While aerosol data is only assimilated twice daily under clear sky conditions, the MERRA-2 aerosol reanalysis data capture the global aerosol optical depth reasonably well and are well-validated by many studies using observation.

> *Figure 2: what do you mean SU emission here? Do you mean emitted sulfate or precursor gases (e.g., SO2 and DMS)? Direct emissions of sulfate are very small. Then what is unit for the sulfur emission? What is unit for carbonaceous aerosol (CA) emission?*

Yes, we have used SO_2. We have modified the text accordingly from SU to SO_2. The units (kg m^{-2} s^{-1}) are provided in the figure title and the caption. Thanks for pointing this out.

> *Line 217: can "boreal forests" be referred to as "rainforests"?*

We have corrected as "Globally, boreal and rainforests are the most significant contributors to the CA aerosols (Fig. 2D). "Please see lines 268 and 625.

> *Lines 252-254: But if satellite observations (e.g., AOD) captured the ash plume, the ash signal would be evident in the MERRA-2 product to some extent.*

This is correct. However, since ash is not explicitly included as a species in MERRA-2, the correction implied by the ash signal in AOD would be erroneously ascribed to another species, and without having the correct vertical structure, subsequent transport would likely be wrong as well. Successfully, the algorithm detects many SU AAR over there.

> *Lines 259-260: "in terms of AOD" - do you really need these four words?*

Deleted.

Line 288: are you sure that MERRA-2 don't account for biogenic sources like Carbonyl Sulfide and Dimethyl Sulfate? I cannot believe that an aerosol model dealing with sulfur cycle doesn't account for DMS.

We have rectified the sentence. MERRA-2 includes sources and transports Dimethyl Sulfate (DMS), with mechanisms for creating sulfate aerosols from DMS. While OCS is included in the current development version of the GEOS model, it was not available in the earlier version of the model used in MERRA-2. Please see the modified sentence in line 349.

Lines 318-319 (and Figure 5A): There is a secondary peak at about 960 mb, which should be discussed. I assumed that the two peaks are associated with seasonal variations of trans-Atlantic dust transport.

Thank you very much for pointing this out. This warrants further study on the roles of different jet streams on the IAT profiles- their seasonal variabilities. We hope to address that in another study.

However, we have added in lines 385-395: "There is also a secondary peak at the 960 hPa (Fig. 5A). The aerosol mixing ratio (Fig. 5B) slightly decreases from the surface up to a height of 960 hPa and then increases above it. This might suggest the influence of the gravitational force and settlement on the aerosol mixing ratio as observed in many of the aerosol mixing ratio profiles of other species over other regions (for example, the red line showing the aerosol mixing ratio profile for the Sahara-European pathway). However, a smaller peak in the wind profile (Fig. 5C) around 950 hPa indicates the influences from the low-level jets and the seasonal variations of trans-Atlantic dust transport that have not been studied yet. A detailed seasonal analysis is required to understand the existence of the smaller peak at 960 hPa. However, the presence of the African easterly jet-north or AEJ-N above, centering 600-700 hPa, further lifts the aerosols and attain a peak around 750 hPa. "

Figure 5: why do you use aerosol mixing ratio? It is more suitable to show mass concentration?

To be consistent with the classic AR study where we use specific humidity as the moisture variable, we use mixing ratio here as well.

Line 379: "compoment" should be "component", right?

Corrected.

Lines 517-518: if CA AARs are associated with burning of boreal forests, can we still call them "rainforests"?

Thanks for pointing this mistake. We have added boreal and rain forests in lines 268 and 625.

Lines 519-520: How can the presence of SU AARs all year around in the northern hemisphere be explained by the biomass burning and biogenic activities?

We have removed that speculation from the sentence.