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 <u>Advanced Very High Resolution Radiometer,</u> 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.

line 279: It is interesting to make a connection between the AR and AAR. Here is written SS AAR are similar to AR in distribution (I assume geographical distribution is meant here), what about the frequency? I assume the height of transport is also different in both?

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 $\sim2 \times 10^{-3}$ 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.