Response to Reviewers

Anonymous Referee #3

The study characterizes the dust properties during the beginning of trans-Atlantic transport of dust particles. It presents new airborne measurements of dust size distribution, composition, shape, and optical properties within the Saharan Air Layer (SAL) and the Marine Boundary Layer (MBL) taken during the AERosol Properties – Dust (AER-D) fieldwork campaign in August, 2015. In their 6 flights, the authors used wing-mounted optical particle counters and shadow probes to measure dust sizes between 0.1 and 100 m diameter, a nephelometer and an absorption photometer to measure dust optical properties, and an in-cabin filter collection system to collect dust samples.

The focus of the study is to highlight the presence and contribution of coarse and giant mode dust particles to the dust size distribution, mass loading, shape, composition, refractive indices and optical properties. The authors found that within the SAL, dust particles with diameter (D) greater than 20m are detected in 100% of the cases, and those with D>40m are detected about 36% of the cases. Of the dust particles detected, 14% of the masses are for dust particles with size D<2.5m, 60% for size D>5m, and about 10% for D>20m. In addition, the authors also found the following: the shape of the measured particle size distribution does not vary significantly between dust layers; the modal aspect ratios are in between 1.2 to 1.4; the real part of dust refractive index in both SAL and MBL is within 1.47 to 1.49, but the imaginary part is between 0.0012 - 0.003i in the MBL and between 0.0004 - 0.0005i within the SAL. They also found that the single-scattering albedo (SSA) at 550nm decreases in the SAL when the measured coarse and giant dust particles are included in the calculation. However, they concluded that the variability of the SSA is not controlled by the dust size distribution, but by the variability in dust composition, contrary to previous studies.

Observational datasets for the coarse and giant dust particles, reported in this paper, are very important to better constrain dust properties in climate models. Current climate models over-estimate the fine-mode dust particles and under-estimate the coarse-mode particles, leading to uncertainties in the estimation of dust optical properties. This is largely due to inadequate observational constrains, and only few similar measurements of size-resolved dust properties are publicly available, with few obtained during the summer time period. Hence, high-quality measurements with a wider particle size range, like those reported in this study, are needed.

We thank the reviewer for their comments, and are pleased that they consider our observations high-quality and important for better constraining dust properties in climate models. In response to the three main comments, we have shortened sentences for clarity as much as possible throughout the whole manuscript, provided a detailed response to the back trajectories point, and expanded on the applicability of Mie theory in this work. Details are given below.

The paper is generally well written, and I believe it also meets the ACP standards. I recommend it for publication, if the authors can address the following comments:

1. Reading through the paper, some parts of it are rather confusing. This is primarily because some of the sentences are too long, making the reading of the paper a bit tiring. The long sentences also sometimes obscure the point the author may want to pass across. I encourage the author to look more closely into each sentence, separating the long ones to multiple short sentences, where necessary. While few of these sentences are highlighted below, I cannot point to all the instances and I hope the author will do the due diligence in addressing this comment throughout the paper.

Pg 14 Lines 6-8, 14-16. Pg 15 Line 1-4. Pg 17 Line 1-4, 10-12. Pg 18 Line 22-26. Pg 20 Line 2-5. Pg 25 lines 16-19

In all cases apart from one, these sentences have been shortened. We have also been through the whole paper and shortened long sentences where possible.

2. Pg 6: The authors should provide a more objective assessment of the dust source areas. While HYSPLIT back-trajectory understandably are associated with uncertainty at the trajectory endpoints, it is still a reasonable method to determine the age of the dust particles, especially when the alternative is subjective. This is particularly useful for the dust particles in the SAL, where such trajectory can easily be estimated along a constant potential temperature surface, therefore avoiding possible influence of the convective events within the boundary layer. Doing it this way, may give a more close and objective approximation of the dust age, to which the SEVIRI images can eventually confirm. Free-tropospheric dust aerosols generally preserve their temperature for a considerable distance from the source region. Isentropic trajectories are therefore suitable above the boundary layer (e.g. Merrill et al., 1986).

From the HYSPLIT website (https://ready.arl.noaa.gov/HYSPLIT_traj.php), the figure below shows an example of the isentropic back-trajectory for flight #b932 starting on 20/Aug/2015 at 12Z for an arbitrary height of 2800 m above sea level. This height corresponds approximately to the highest extinction in your Fig. 4. The figure is a 3-day back-trajectory and it appears to suggest that the starting point after 3 days is approximately in the same area as suggested by SEVIRI in you Figure 1. This calculation can be repeated for different height within the SAL, and can also be combined with the SEVIRI images to give a more objective estimate of the dust sources, the age and the starting location.

In addition, the figure below uses the NCEP reanalysis dataset. It may be useful, however, to use a better quality meteorological dataset, like ERA-Interim with relatively higher resolution, to drive the HYSPLIT back-trajectories. ECMWF assimilates meteorological data from radiosondes that launch from few but important stations over north Africa. This may reduce the uncertainty even further, giving some more credence to the methodology.

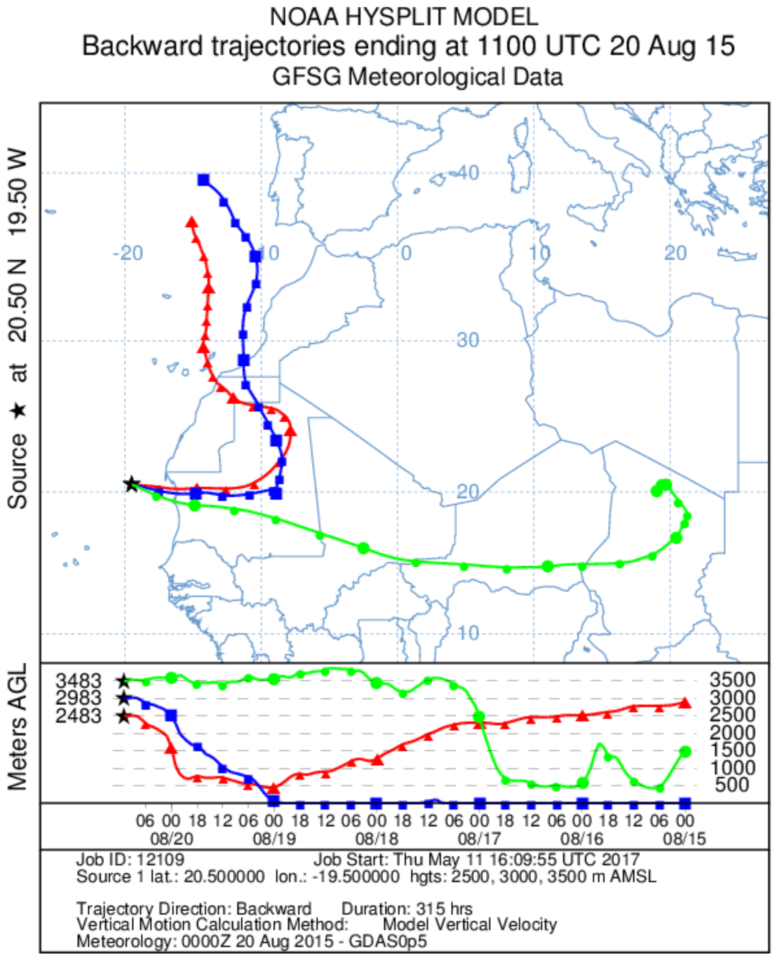
We appreciate the reveiwer's efforts to investigate one of our cases with HYSPLIT. We have to point out, however, that the trajectory endpoint location was incorrect as the b932 dust investigated was centred at around 20W, 20N (see red flight track in Figure 1) rather than at the Cape Verde Islands themselves. Below we show a HYSPLIT back trajectory that was used as part of the analysis that in part led to the discussion in Section 2.2, using the correct location and time for the in situ sampling of b932. Three starting heights were chosen to cover the altitudes of the dust layer sampled. We also show two SEVIRI images indicating the two dust uplift times for this case.

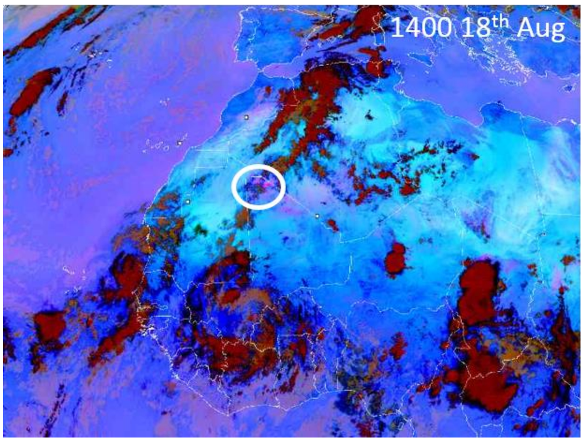
It can be seen that the back trajectories do not capture the actual uplift location, times or transport path of the dust over the Sahara at all. The back trajectories would lead us to infer dust uplift times/locations of 00UTC on 19 Aug in central Mauritania at ~20N (blue) and ~22N (red), and at ~12UTC on 17 Aug in northern Chad. While in fact the SEVIRI images show that uplift occurred firstly near the Mali/Algeria border between 17 Aug 1000 UTC to 0100 UTC 18 Aug, and then again over Northern Mali at 1200-1400 UTC on 18 Aug. Therefore we believe that the uplift locations suggested by the back trajectories are incorrect, and that we have a better representation for these events using the SEVIRI imagery. This should not be interpreted as a negative appreciation of back trajectories in general.

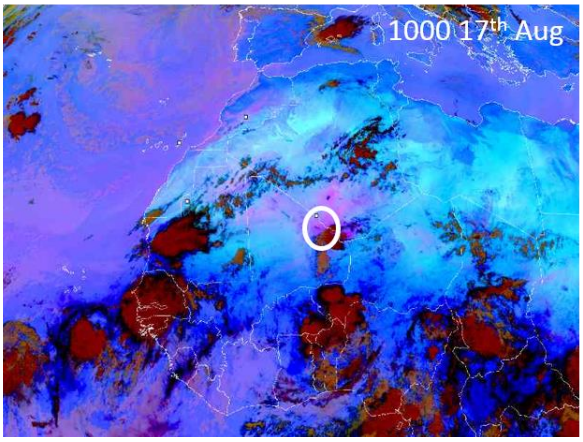
Secondly, according to HYSPLIT timings, the dust would be inferred to be aged >36h (lower layer, red/blue) and >96h (upper layer, green). The SEVIRI imagery dust ages are 45-47 h for the Northern Mali uplift, and 58-73 h for the Mali/Algerian border uplift.

The transport pathway of the dust is clearly visible on the satellite images. The dust is transported from the Mali/Algeria border region to the northwest, before moving southeastwards to the coastal area. This pathway is not captured at all by the back trajectories.

The image below shows back trajectories calculated using the GDAS 0.5 degree meteorology dataset. We also ran the same case with the NCEP reanalysis data, and the results were similar. To our knowledge, ERA-Interim data is not available with the web-based HYSPLIT trajectory model.







As stated in Section 2.2, we had already examined all the HYSPLIT back trajectories for our dust cases, and compared them to the SEVIRI imagery. ("HYSPLIT back trajectories were also run, but are not used to determine source location or age here, since in every case they indicated a transport path differing from that shown by the SEVIRI imagery.") Occasionally the dust source location was similar to that from SEVIRI, even though the indicated transport pathway was different. However, the back trajectories also always showed either too fast or too slow transport, which would lead to an incorrect assignment of dust age. Additionally, another limitation of back trajectories is that they only indicate when an air mass nears the surface, but do not reflect potential uplift conditions (e.g. surface wind strength, soil conditions…).

We have rewritten the last paragraph of Section 2.2 to explain this more clearly.

We agree with the reviewer that back trajectories, following a constant potential temperature, can be a very useful tool for situations like dust in the SAL. However, for the large part of the time between dust uplift and sampling during AER-D, the dust was over the Sahara and within the Saharan Boundary Layer, which can extend up to 5 km altitude. The SEVIRI images show that convection and clouds were frequently present along the transport pathway of the dust. Therefore over the Sahara our dust events cannot be assumed to follow isentropic trajectories, and the difference between the HYSPLIT results and the SEVIRI imagery confirms this.

Several Fennec studies examined model biases over the Sahara, including the effects of unresolved cold pools. Garcia-Carreras et al. (2013) found a "crucial role of convective cold pools in explaining model tropospheric temperature bias," and suggest that, "the misrepresentation of moist convective processes can affect continental-scale biases, altering the West African monsoon circulation," even when additional radiosonde data is assimilated. Engelstaedter et al. (2015) found that models have errors in moisture distribution which "is likely to have consequences for simulations of Saharan thermodynamics and dust emissions caused by convection-driven cold pools." Roberts et al. (2017) find that ERA Interim winds are systematically underestimated over the Sahara. Despite the assimilation of a few radiosondes over the Sahara, models still struggle to resolve Saharan meteorology (Garcia-Carreras et al., 2013), which has knock on effects on dust back trajectories which rely on model fields. We have added citations of these papers in Section 2.2.

Given the challenges models still face in simulating clouds, convection and dynamics over the Sahara, and the clear visibility of the dust transport pathways in the SEVIRI imagery, the uncertainty and subjectivity in the SEVIRI methodology was perhaps overstated in Section 2.2. The last paragraph of Section 2.2 has been rewritten to try to better reflect this, as follows:

"The SEVIRI imagery is not able to give altitude-resolved information, and can be subjective, particularly when dust loadings are light, at low altitude or in a moist environment, making dust appear less pink and more difficult to identify (Brindley et al., 2012). This is more evident in the dust tracked for flights b932 and b934 where dust loadings were lower. This introduces a small level of uncertainty into both the source locations and dust ages, which we account for by giving generous error bars to the dust uplift times and source locations. HYSPLIT back trajectories (Draxler and Hess, 1998; Stein et al., 2015) were also run for the AER-D dust events. In only one of the five dust events was the dust source location similar to that observed in the SEVIRI imagery. In every case the back trajectories indicated a transport path and transport time different to that shown by the SEVIRI imagery. Although the SEVIRI methodology has its limitations, the back trajectory method results were clearly not compatible with the information from SEVIRI. Therefore back trajectories are not used to determine source location or age here. Additionally, another limitation of back trajectories is that they only indicate when an air mass nears the surface, but do not reflect potential uplift conditions (e.g. surface wind strength or soil conditions). It has been shown that models and reanalyses are currently unable to adequately represent convective events and winds over the Sahara and Sahel, particularly due to the challenges of representing cold pools. For example, Garcia-Carreras et al. (2013) examine the role of convective cold pools and suggest that "the misrepresentation of moist convective processes can affect continental-scale biases, altering the West African monsoon circulation." Many other publications have examined the misrepresentation of Saharan convective events (Marsham et al., 2011; Heinold et al., 2009; Sodemann et al., 2015; Trzeciak et al., 2017; Allen et al., 2015; Roberts et al., 2017; Engelstaedter et al., 2015). Since convective events are the drivers of dust uplift in all the AER-D cases we do not consider HYSPLIT back trajectories (with relatively low model resolution of half a degree) to be informative here due to the challenges the models face in representing Saharan circulation. Finally, we note that back trajectories are recommended to be used with caution for dust events over the summertime Sahara (Trzeciak et al., 2017)."

3. The authors should either carefully justify the application of the Lorenz-Mie theory for dust particles larger than 20m or use a more appropriate methodology for this size range. The manufacturer-provided size bin diameters were calibrated against polystyrene latex spheres, which the authors corrected to diameter of dust using Lorenz-Mie method (on PCASP and CDP). But Lorenz-Mie theory is only valid when the particle size is comparable to the wavelength (Bohren and Huffman, 1983). For coarse and giant dust particles with diameter

larger than 20 m, the application of Lorenz-Mie theory is no longer valid, and instead the geometric optics method may be useful (see Bi et al., 2009).

Firstly, although we process the entire CDP PSD using Mie theory, covering diameters up to around 50 microns, we only use the CDP data up to diameters of 20 microns, as at this point the CIP15 or 2DS data is given precedence. Therefore this is not an issue for the CDP data.

Secondly, we would like to point out that Mie theory is an exact solution for spheres of any size, and has no upper (or lower) limit, but converges to geometric optics for larger sizes and to Rayleigh scattering approximations at smaller sizes. (e.g. Petty, 2006). However, we assume that the reviewer is referring to the applicability to Mie code for the use of non-spherical particles. In this work we assume that the particles are spherical for optical property calculations. Sensitivity of SSA to the assumption of spherical particles was tested by Otto et al. (2009) and Johnson and Osborne (2011), who found that SSA changed by under 1% and 2% respectively when non-spherical particles were assumed. This is less than our error in SSA described in Section 2.3.1, and therefore we consider this an acceptable assumption. We have added this information and citations to the text, as well as a new methodology section 2.6 ‘Calculation of Optical Properties’ to make this clear.

Petty, (2006) A first course in Atmospheric Radiation, Ch 12, Sundog Publishing, USA.

Specific Comments:

Pg 5, Line 7. Pg 7, Line 20. Pg 14, Line 4. Pg 16, line 25. Pg 18, line 2. Pg 21, line 15: The table numbers referenced here are wrong. Please check all other reference in the paper.

All table references have been corrected.

Pg 3, Line 9-10: Re-write for clarity.

Done

Pg 9, Line 8-9: I wonder if this difference between the “all-in” and the “center-in” is actually quantified. This text referenced here appear to be an assumption as suggested by the use of word “considered”. If the latter is the case, I suggest this sentence should be re-written to clarify this point.

The sample area is actually adjusted depending on the particle size and whether all-in or center-in is used, since they both impact the effective array width and therefore the sample area, and hence the number concentration calculated (McFarquhar et al., 2017). We have added the sentence, “The sample area is adjusted for the effective array width, which is different depending on whether ‘all-in’ or ‘centre-in’ is used (McFarquhar et al., 2017), and therefore the calculated number concentrations account for this.”

Pg 16, Line 24: There is no need for “6a”, there is just one figure. Please also correct this in other places of the manuscript.

These have been corrected.

Pg 18 line 14: Figure 8c is not provided.

Corrected.

There is no definition of some acronyms – an example is the “SLR” acronym in the text or in Fig. 4. I suggest the author look through the paper and make sure every acronym is defined before use.

We have added more detailed flight manoeuver information and explanations to section 2.1, and also added acronym explanations as an appendix.