

Dear Editor and Reviewers,

Thank you for handling and reviewing our manuscript. We greatly appreciate the substantial amount of time and effort that you dedicated to this review process.

We have revised the manuscript according to your comments point-to-point and the response is presented below.

It should be introduced that the serial numbers of the figures are changed in the revised manuscripts.

1. The reply on RC-1 is provided from Page 2 to Page 23;
2. The reply on RC-2 is provided from Page 24 to Page 33;
3. The mark-up manuscript is presented from Page 34 to Page 73.

Many thanks and best regards.

Guangyao Dai and Songhua Wu

On behalf of the co-authors

The combination of two space-based lidars (CALIPSO and Aeolus) is new and deserves attention. The Saharan dust transport across the Atlantic Ocean is a well-known large-scale phenomenon and suited to demonstrate the novel approach. Personally, I welcome the resubmission of the now improved version of the manuscript. However, there are still some major reviews necessary till the final publication.

Major comments:

1. The comparison of the 3 cross sections on 19 June 2020 is misleading (Section 4.2). With the 3 cross sections just some hours (<4 h) apart, you get a snapshot of an existing dust plume whose maximum is currently over the central Atlantic. Lower values of the backscatter coefficient above the Sahara and the Caribbean (cross section 1 and 3) can not be directly linked to emission and deposition (named by you “emission phase” and “deposition phase”). Usually, there are several days between emission and deposition and not just some hours. So, there is no benefit in reporting the backscatter values for the 3 cross sections. I would consider removing these values from the abstract and the conclusion.

Your next Section 4.3 is better suited to follow the dust from emission to deposition.

AR: Thanks for the suggestion. Yes, we agree with you. We think **the dust layers captured by Aeolus and CALIPSO during several hours on 19 June 2020 (cross-section 1, 2 and 3 in Fig 6 (b), (c)) are relatively static compared with the whole dust plume transport process. Namely, we took a snapshot of the dust plumes on this day.** As discussed in Section 4.1 and Section 4.3 of the manuscript, the emission-transport-deposition process of the dust plume needs almost two weeks, not just some hours.

Sorry for the misleading. **“During emission phase”, “during development phase” and “during deposition phase” in the manuscript have been modified as “over the emission region (Western Sahara)”, “over the transport region (Middle Atlantic)” and “over the deposition region (Western Atlantic)”** in the description of the dust

advection values on 19 June 2020. Besides, we rewrote the part of Section 4.2, which is renamed as “Observation snapshot of the dust plume and dust advection calculation on 19 June 2020”, to illustrate the overall geographical distribution of dust layers as a snapshot on the morning of this day. And the mean backscatter values of the 3 cross sections have been removed from the abstract and the conclusion. The revised descriptions of this portion are shown as below:

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase. Finally, the advection value for different dust parts and heights on 19 June and on the entire transport routine during transportation are computed. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region.” (from the abstract section)

#### **“4.2 Observation snapshot of the dust plume and dust advection calculation on 19 June 2020**

In this section, the dust event observation snapshot captured by ALADIN and CALIOP on 19 June 2020 is introduced in detail. The quasi-synchronized observations from ALADIN and CALIOP on 19 June 2020 are presented in Fig. 6, where the purple

lines indicate the scanning tracks of ALADIN and the green lines indicate the scanning tracks of CALIOP. It is found that the overpasses of each satellite are only around 3 hours apart. Hence, we captured the dust layers on the morning of 19 June 2020 quasi-simultaneously over the Western Sahara, the Middle Atlantic and the Western Atlantic, i.e., took a snapshot of the dust plumes. From the profiling of dust optical properties, discriminated by the CALIOP measurements, the dust geographical distribution over Atlantic Ocean on this day could be determined. The extinction coefficients and backscatter coefficients at the wavelengths of 355 nm, 532 nm and 1064 nm within the dust mass are also determined. From the profiling, it was found that the mean backscatter coefficients at 532 nm were about  $3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 1”,  $7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 2” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 3”. On 19 June 2020, the dust layers existed over the Western Sahara, the Middle Atlantic and the Western Atlantic quasi-simultaneously, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive.

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In Fig. 8, the dust advection at different heights of the three cross-sections are presented. From the profiling, the mean dust advection value is about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 1” (over the emission region),  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 2” (over the transport region) and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 3” (over the deposition region), respectively.

In conclusion, on 19 June 2020, the dust layers over the Western Sahara, the Middle Atlantic and the Western Atlantic are observed by ALADIN and CALIOP nearly in the meanwhile. And the dust advectons of the three cross-sections indicate the quasi-

simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on the same day.” (from Section 4.2)

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase.

Finally, the advection at different dust parts and heights on 19 June and on the entire transport routine during transportation are computed, respectively. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region, from which we can infer the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on this day...” (from Section 5)

2. The calculation of the mean mass concentration is not well defined. How do you define your dust layer? Or do you take an average over the whole cross section? You mention some upper and lower threshold values for the mass concentration based on previous observations. However, if you observe such an intense dust event (“Godzilla”), the mass concentration may exceed the upper threshold. To calculate a mean mass concentration, you should define your dust layer, probably with a

lower backscatter or extinction coefficient threshold and then take the average over the entire dust layer.

AR: **Actually, the dust aerosol was identified and verified by two steps.** Firstly, before the particle mass concentration estimation, **the Vertical Feature Mask (VFM) product from CALIOP was used to identify the dust aerosol.** Only the data bins (from the common data pixel grid of Aeolus and CALIPSO) identified as “dust” are applied in the estimation of the dust mass concentration. Secondly, the **relative humidity data provided by ECMWF is used to filtrate dust aerosol which has absorbed moisture.** When the relative humidity is larger than 90%, the dust aerosol will be influenced by the hygroscopicity effect and its properties could change. Then the mass concentration calculation method does not make sense any more. After two steps of dust aerosol identification and verification, the “real” dust aerosol was selected and its optical properties (backscatter coefficients at 532 nm and 1064 nm, extinction coefficients at 355 nm, 532 nm and 1064 nm) are used in the estimation of the dust mass concentration. **In conclusion, we did not take an average over the whole cross section, but the filtered cross section instead.**

Thanks for the suggestion. **We recalculated the mean mass concentration of each dust layer with a lower mass concentration threshold and without an upper mass concentration threshold.**

It is positive, that you compare two different methods. In order to judge the differences, you should add uncertainties to both derived mean mass concentrations (Table 1+2).

AR: Thanks for the suggestion. We have added the uncertainties to both mean mass concentrations in the Table 1 and Table 2 of the revised manuscript, which are shown as below:

**“Table 1. Mean dust mass concentration of each cross-sections on 19 June 2020 calculated by two methods**

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Cross-section	1	2	3
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Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (the retrieval method)	$0.28\pm 0.23$	$0.26\pm 0.24$	$0.22\pm 0.19$
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Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (the factor method)	$0.37\pm 0.24$	$0.40\pm 0.25$	$0.39\pm 0.27$
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**Table 2. Mean dust mass concentration of each cross-sections at different times during the dust transport calculated by two methods**

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Date	15 June	16 June	19 June	24 June	27 June
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (retrieval method)	$0.30\pm 0.23$	$0.27\pm 0.24$	$0.26\pm 0.24$	$0.27\pm 0.24$	$0.22\pm 0.19$
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (factor method)	$0.26\pm 0.17$	$0.39\pm 0.24$	$0.40\pm 0.25$	$0.42\pm 0.21$	$0.34\pm 0.20$

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For the factor method, do you use the extinction coefficient provided by CALIPSO or the extinction coefficient calculated with the adapted lidar ratio (58 sr)? The later would be preferable to be consistent with your advection calculation procedure.

AR: Thanks. We used the extinction coefficient calculated with the adapted lidar ratio (58 sr) in the factor method.

3. In Section 4.3, you should make sure that the same dust was observed in all the cross sections. The description stays a bit vague. A so-called Lagrangian case study was presented in Weinzierl et al., BAMS 2017, there an aircraft observed the same dust sample at the coast of Africa and some days later over the Caribbean. You have

all the trajectory calculations ready, just use them in a more quantitative way to show that you track the same dust event. For example, you could add dots to the trajectories marking intervals of 24 h in Fig. 9. The dots alone won't be sufficient.

AR: Thanks for the suggestion. Please be aware that, since we omitted the Figure 7 and 10 in the revised manuscript, the original Figure 9 becomes Figure 8. We modified Fig. 8(a) and (d) in the revised manuscript. **The square symbols on the HYSPLIT trajectory lines have been added in the revised Fig. 8(a) and (d) to indicate the trajectories' locations of 15 June, 16 June, 19 June, 24 June and 27 June, which are matched with the 5 cross-sections by ALADIN and CALIOP.**

According to the HYSPLIT modeling trajectories and the satellites' cross-sections, we can find that at **different cross-sections of Aeolus and CALIPSO, the dust transport paths modelled with HYSPLIT match well spatially with the enhanced backscatter and extinction coefficient values (indicating the presence of dust).** However, **the cross-sections captured by ALADIN and CALIOP do not match perfectly with the HYSPLIT trajectories in time dimension.** The backward trajectories match well with the cross-sections on 15, 16 and 19 June while the forward trajectories from position A match well with the cross-sections on 24 and 27 June. But the forward trajectories from position B and C are slightly mismatched with the cross-sections on 24 and 27 June. It is considered that there are two aspects of reasons of the mismatch in time dimension. It is considered that there are two aspects of reasons for the slight mismatch in time dimension. On the one hand, **the modelled trajectories present complex transport routes of the dust plumes and meanwhile indicate various transport speed of different dust plumes drove by separate air mass over the Atlantic.** On the other hand, **restricted by the strict track matching method implemented in this study, several observation cross-sections above the transport regions (e.g., Gulf of Mexica, North America) which also capture dust plumes are eliminated.**



**The durations of the same dust event are reported as 14-28 June 2020 (Pu and Jin, 2021) and 13-17 June 2020 (Yu et al., 2021), individually.** Furthermore, combined with the “Dust Score Index” data and the HYSPLIT trajectories (analysed in Section 4.1), **it can still be concluded that the enhanced backscatter and extinction coefficient regions of the 5 cross-sections 1) track the same dust event,** 2) represent the dust layers of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase, respectively.

References:

*Pu, B., and Jin, Q.: A Record-Breaking Trans-Atlantic African Dust Plume Associated with Atmospheric Circulation Extremes in June 2020, Bulletin of the American Meteorological Society, 102(7), E1340-E1356, <https://doi.org/10.1175/BAMS-D-21-0014.1>, 2021.*

*Yu, H., Tan, Q., Zhou, L., Zhou, Y., Bian, H., Chin, M., Ryder, C. L., Levy, R. C., Pradhan, Y., Shi, Y., Song, Q., Zhang, Z., Colarco, P. R., Kim, D., Remer, L. A., Yuan, T., Mayol-Bracero, O., and Holben, B. N.: Observation and modeling of the historic “Godzilla” African dust intrusion into the Caribbean Basin and the southern US in June 2020, Atmos. Chem. Phys., 21, 12359–12383, <https://doi.org/10.5194/acp-21-12359-2021>, 2021.*

The revised Fig. 8 and the corresponding description is shown as below:

**“4.3 Dust advection during the lifetime of dust event during 14 June and 27 June 2020**

During this dust event, the quasi-synchronized observations with ALADIN and CALIOP were selected to follow the transport and dispersion of dust. The detailed information about the ALADIN and the CALIOP observations on 15, 16, 19, 24, 27 June 2020 along the transport route and the HYSPLIT modelling (which are also presented and analysed in Section 4.1) are shown in Fig. 8. In Fig. 8(a), the scanning

tracks of ALADIN and CALIOP on those days are indicated by dark purple lines and green lines, respectively. The HYSPLIT trajectories modelled from the altitudes of 3 km, 4 km, 5 km at position A, B and C (the aerosol profiles of which are presented and analysed in Section 4.1) are shown respectively in Fig. 8(a) and (d). The squares in Fig. 8(a) and (d) indicate the HYSPLIT trajectories positions corresponding to the 5 cross-sections in time. In Fig. 8(b) and (c), 5 cross-sections of extinction coefficient at 355 nm measured at different times with Aeolus and 5 cross-sections of backscatter coefficient at 532 nm measured at different times with CALIOP are plotted, respectively. Additionally, the forward trajectories and backward trajectories and presented in dark red lines and light purple lines in Fig. 8(b) and (c). From these figures, we can find that at different cross-sections of Aeolus and CALIPSO, the dust transport modelled with HYSPLIT match well spatially with the enhanced backscatter and extinction coefficient values indicating the presence of dust. In Fig. 8(d), a side view of the HYSPLIT trajectories is shown. Consistent with the observations from ALADIN and CALIOP in Fig. 8(b) and (c), there is an apparent descent along the transport route of the dust event. However, the cross-sections captured by ALADIN and CALIOP do not match perfectly with the HYSPLIT trajectories in time dimension. The backward trajectories match well with the cross-sections on 15, 16 and 19 June while the forward trajectories from position A match well with the cross-sections on 24 and 27 June. But the forward trajectories from position B and C are slightly mismatched with the cross-sections on 24 and 27 June. It is considered that there are two aspects of reasons of the mismatch in time dimension. On the one hand, the modelled trajectories present complex transport routes of the dust plumes and meanwhile indicate various transport speed of the dust plumes drove by separate air mass over the Atlantic. On the other hand, restricted by the strict track matching method implemented in this study, several observation cross-sections above the transport regions (e.g., Gulf of Mexico, North America) which also capture dust plumes are rejected. Nevertheless, combined with the “Dust Score Index” data and the HYSPLIT trajectories (analysed in Section 4.1), it can still be concluded that the enhanced backscatter and extinction coefficient regions of the 5 cross-sections 1) track the same dust event, 2) represent the dust layers of this

dust event's emission phase, development phase, transport phase, descent phase and deposition phase, respectively.

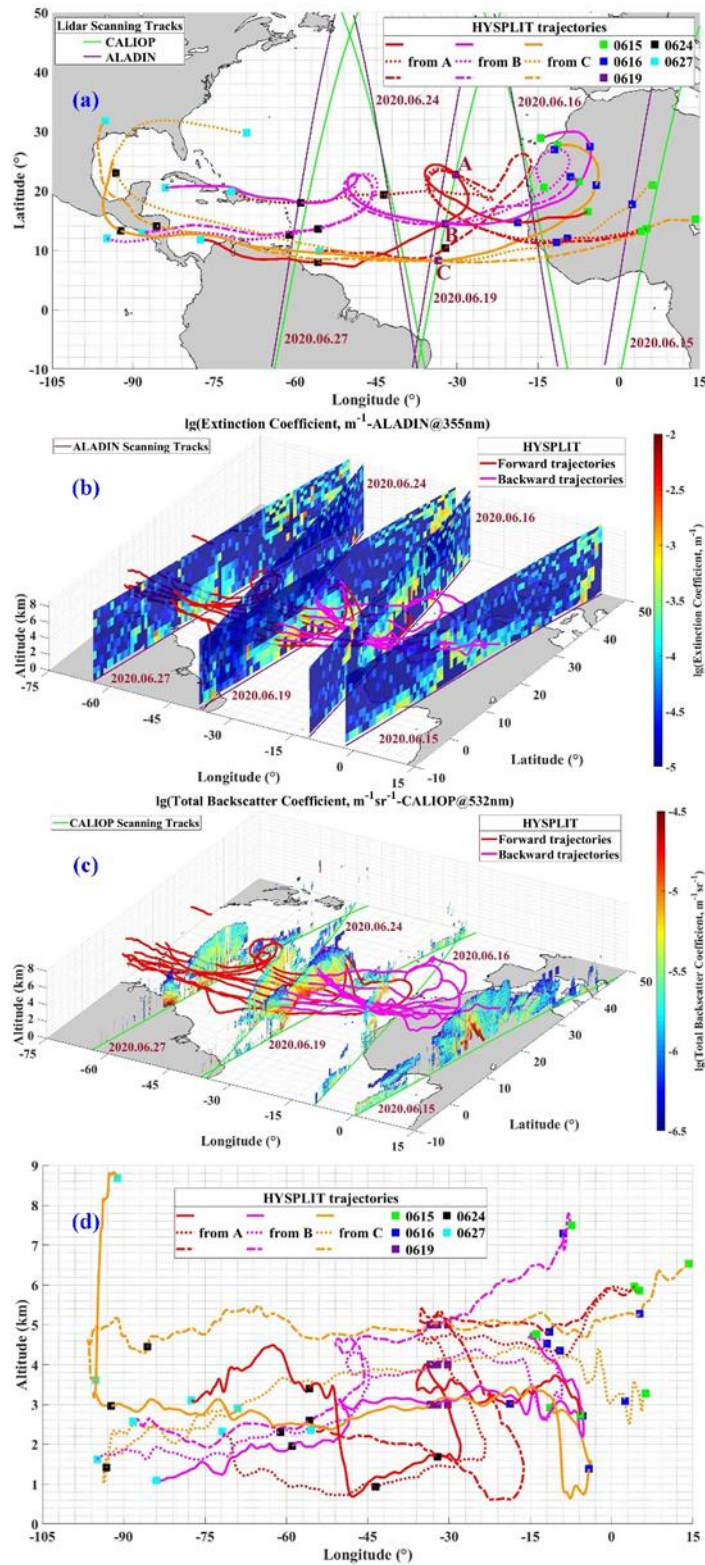


Figure 8. Observation of dust event during 15 and 27 June 2020 with ALADIN and CALIOP and the corresponding HYSPLIT trajectories. (a) Vertical view of ALADIN and CALIOP scanning tracks and HYSPLIT trajectories; (b) Extinction coefficient cross-sections measured with ALADIN and HYSPLIT trajectories; (c) Total backscatter coefficient cross-sections measured with CALIOP and HYSPLIT trajectories; (d) Side view of HYSPLIT trajectories. In (a) and (d), the solid lines, the dot lines and the dot dash lines of the HYSPLIT trajectories represent the trajectories modelled from the altitudes of 3 km, 4 km and 5 km.”

4. The CALIPSO examples introduced in Fig. 4 and 5 are later on not used anymore. It would be better to show in Fig. 4 some dates used in Section 4.3. In Fig. 5 you should definitely show the case of 19 June 2020 because it is later on used in the case study of Section 4.2.

AR: Thanks for the suggestions. We have replaced the VFM data and the corresponding CALIOP scanning tracks on 18 June 2020 and 23 June 2020 with those on 16 June 2020 and 27 June 2020 in the revised Fig. 4. The profiles and the trajectories in the revised Fig. 5 have been replaced as the case of 19 June 2020. The revised Fig. 4 and Fig. 5 are shown as below:

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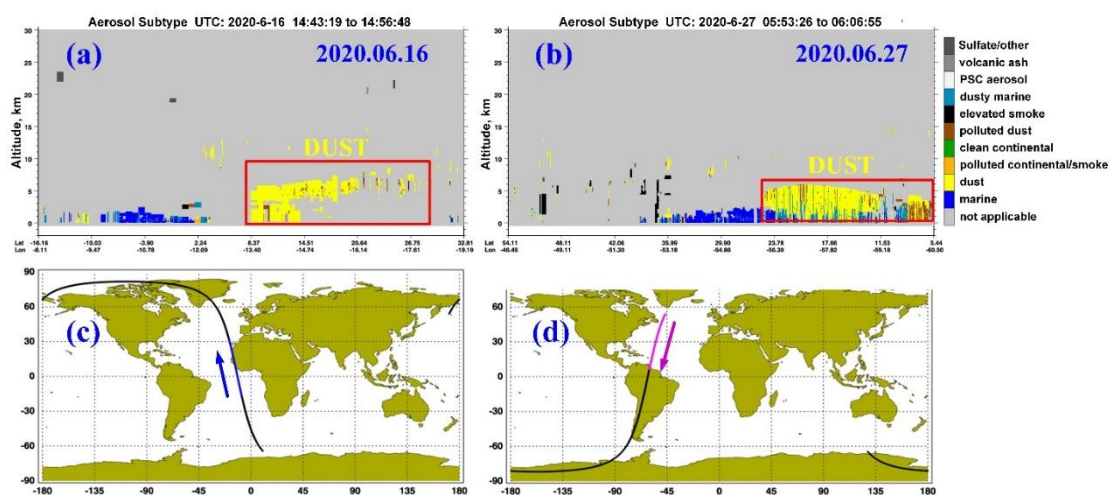
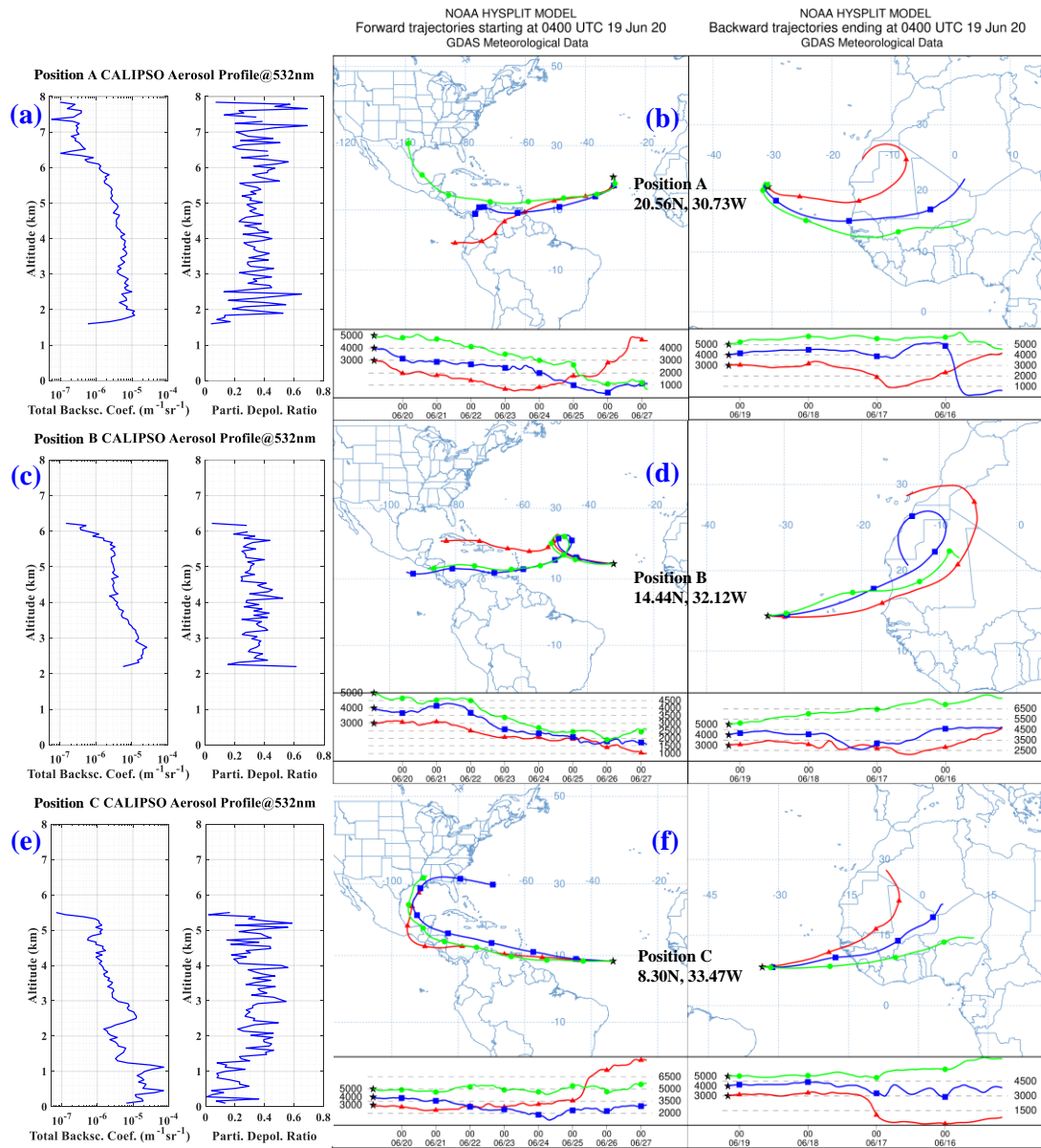


Figure 4. Vertical feature mask from CALIPSO L2 product (a) on 16 June 2020 over the west coast of Africa and the eastern Atlantic and (b) on 27 June 2020 over the western Atlantic (around the east coast of America). (c) and (d) show the corresponding CALIOP scanning tracks of (a) and (b) respectively, the arrows in which indicate the motion direction of CALIPSO ([https://www-calipso.larc.nasa.gov/products/lidar/browse\\_images/production/](https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/), last access: 24 March 2022).”

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**Figure 5. (a)(c)(e) CALIPSO total backscatter coefficient profiles and particle depolarization ratio profiles capturing dust layers at around 0400UTC 19 June 2020. (b)(d)(f) HYSPLIT backward trajectories and forward trajectories at different sites of corresponding CALIPSO profiles and different heights on 0400UTC 19 June 2020. The backward and forward trajectories’ durations are 120 hours and 192 hours respectively (<https://www.ready.noaa.gov/hypub-bin/trajtype.pl?runtype=archive>, last access: 23 March 2022).”**

5. It is a great step forward to use the lidar ratios for (Western) Saharan dust instead of global averages. The lidar ratio of 60 sr at 1064 nm seems a good estimate as recently confirmed by Haarig et al., ACP 2022 (57 – 69 sr). Although, a higher ratio of LR1064/LR532 was reported. Nevertheless, the values used seem to be reasonable.

AR: Thanks.

6. Aeolus aerosol products are usually reported on a very coarse horizontal resolution. How do you make sure that your profiles are not influenced by clouds? You are talking about the cloud screening in the case of CALIPSO, but not for Aeolus. Please add some comments on the cloud and aerosol separation in the case of Aeolus.

AR: Firstly, we **set strict match criterions of the ALADIN and the CALIOP scanning tracks**: (1) The distances between two satellites scanning tracks are less than 200 km; (2) The tracks of Aeolus are downwind of the tracks of CALIPSO. Secondly, **we utilized wind field data and relative humidity data from ECMWF as auxiliary data to illustrate the homogeneity between the matched two spaceborne lidars' scanning tracks**. Because of the relatively short distances and the stable wind fields (both of the standard deviation percentages of wind speed and direction between the tracks along each latitude line are less than 10%) between the matched tracks, it is considered that **the atmospheric conditions and the aerosol types are approximately the same on both two spaceborne lidars' scanning tracks**. Therefore, in the common data pixel grid of the Aeolus data and the CALIPSO data, **the cloud screening and the dust aerosol selection of CALIPSO are also approximately suitable to the Aeolus data**. Besides, if relative humidity is larger than 94%, then the probability that cloud presents is quite high (Flament et al., 2021). **Before the estimation of dust mass concentration, the Aeolus data is filtered when the relative humidity is larger than 90%**, which can also support to screen possible cloud conditions in the case of Aeolus data.

*Reference: Flamant, P., Dabas, A., Martinet, P., Lever, V., Flament, T., Trajon, D., Olivier, M., Cuesta, J., and Huber, D.: Aeolus L2A Algorithm Theoretical Baseline Document, Particle optical properties product, version 5.7, available at: <https://earth.esa.int/eogateway/catalog/aeolus-l2a-aerosol-cloud-optical-product> (last access: 15 March 2022), 2021*

7. Please add uncertainties to all your calculated values, especially to the mean dust advection values. Otherwise, you can't draw conclusions on changing values.

AR: The uncertainties of each cross-sections' mean mass concentration are added, and presented in Table 1 and 2 in the revised manuscript:

**“Table 1. Mean dust mass concentration of each cross-sections on 19 June 2020 calculated by two methods**

Cross-section	1	2	3
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (the retrieval method)	$0.28\pm 0.23$	$0.26\pm 0.24$	$0.22\pm 0.19$
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (the factor method)	$0.37\pm 0.24$	$0.40\pm 0.25$	$0.39\pm 0.27$

**Table 2. Mean dust mass concentration of each cross-sections at different times during the dust transport calculated by two methods**

Date	15 June	16 June	19 June	24 June	27 June
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (retrieval method)	$0.30\pm 0.23$	$0.27\pm 0.24$	$0.26\pm 0.24$	$0.27\pm 0.24$	$0.22\pm 0.19$
Mean mass concentration, $\text{mg}\cdot\text{m}^{-3}$ (factor method)	$0.26\pm 0.17$	$0.39\pm 0.24$	$0.40\pm 0.25$	$0.42\pm 0.21$	$0.34\pm 0.20$

”

The uncertainties of the mean dust advection values are also added in the revised manuscript, which are shown as below:

“On 19 June, the mean dust advection values are about  $1.91\pm 1.21 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  over the emission region,  $1.38\pm 1.28 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  over the transport region and  $0.75\pm 0.68 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  over the deposition region. In the whole life-time of the dust event,

the mean dust advection values are about  $1.51 \pm 1.03 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 15 June 2020,  $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 16 June 2020,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 19 June 2020,  $1.60 \pm 1.08 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 24 June 2020 and  $1.03 \pm 0.60 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 27 June 2020.”  
 (from Section 5 of the revised manuscript)

Minor comments

8. Text insides some figures (especially Fig. 3 + 4) is quite small and hard to read.

AR: Thanks. Figure 3 and 4 have been modified in the revised manuscript as below:

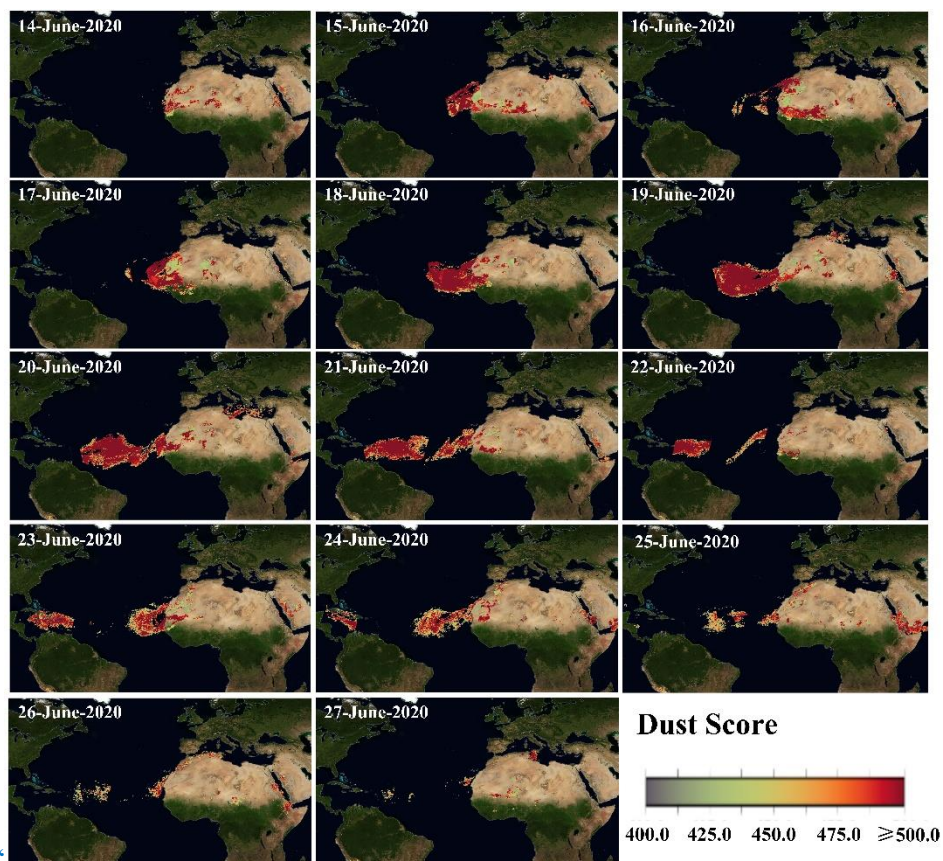
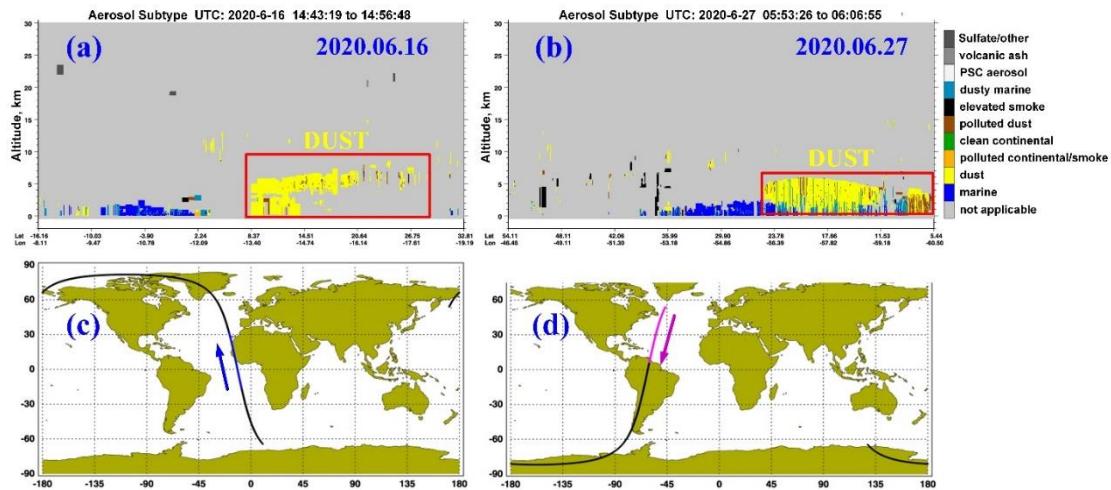


Figure 3. The Dust Score Index provided by AIRS/Aqua at different stages, including emission, transportation, dispersion and deposition (<https://airs.jpl.nasa.gov/map/>, last access: 10 January 2022).





**Figure 4.** Vertical feature mask from CALIPSO L2 product (a) on 16 June 2020 over the west coast of Africa and the eastern Atlantic and (b) on 27 June 2020 over the western Atlantic (around the east coast of America). (c) and (d) show the corresponding CALIOP scanning tracks of (a) and (b) respectively, the arrows in which indicate the motion direction of CALIPSO ([https://www-calipso.larc.nasa.gov/products/lidar/browse\\_images/production/](https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/), last access: 24 March 2022).”

9. Figure 7 and 10 are quite complex and hard to follow. The text is understandable even without these figures. In case of the wind speed and direction, you have the nice Fig. 12, and the other information from Fig. 7 and 10 are not necessary to understand the paper. I would consider removing these figures to make the paper easier to read.

AR: Thanks for your comments. We removed the original Fig. 7 and Fig. 10 in the revised manuscript. The corresponding explanations regarding the smooth distribution of wind fields and RH are also stated in the revised manuscript. Hence, please be aware that the figure numbers are changed accordingly.

10. L55: A reference about SHADOW is missing. What about Veselovskii et al., ACP 2016?

AR: Sorry for the careless. The reference Veselovskii et al. (2016) has been added in the revised manuscript:

Veselovskii, I., Goloub, P., Podvin, T., Bovchaliuk, V., Derimian, Y., Augustin, P., Fourmentin, M., Tanre, D., Korenskiy, M., Whiteman, D. N., Diallo, A., Ndiaye, T.,

Kolgotin, A., and Dubovik, O.: Retrieval of optical and physical properties of African dust from multiwavelength Raman lidar measurements during the SHADOW campaign in Senegal, *Atmos. Chem. Phys.*, 16, 7013–7028, <https://doi.org/10.5194/acp-16-7013-2016>, 2016.

11. The technical details about Aeolus could be moved from the introduction to Section 2.1. Just keep the most important facts about Aeolus as you have done it for CALIPSO.

AR: Thanks for the suggestion. We have moved the technical details about Aeolus from introduction to Section 2.1.

The revised description about Aeolus in the introduction are shown as below:

“...Thanks to the efforts of the European Space Agency (ESA), a first ever spaceborne direct detection wind lidar, Aeolus, which is capable of providing vertical wind fields globally with high temporal and spatial resolution has been developed under the framework of the Atmospheric Dynamics Mission (ADM) (Stoffelen et al., 2005; ESA, 1999; Reitebuch et al., 2012; Kanitz et al., 2019). The Atmospheric Laser Doppler Instrument (ALADIN) is a direct detection high spectral resolution wind lidar carried by Aeolus and provides the vertical profiles of the Horizontal-Line-of-Sight (HLOS) wind speeds. Further, the wind vector data assimilated with the HLOS wind speed data and the particle optical property data (e.g., extinction coefficient, backscatter coefficient) at 355 nm are also provided in the products of Aeolus.”

The technical details about Aeolus in the revised Section 2.1 of the manuscript are shown as below:

**“2.1 ALADIN/Aeolus**

On 22 August 2018, Aeolus was successfully launched into its sun-synchronous orbit at a height of 320 km (Witschas et al., 2020; Lux et al., 2020). A quasi-global coverage is achieved daily (~ 15 orbits per day) and the orbit repeat cycle is 7 days (111 orbits). The orbit is sun-synchronous with a local equatorial crossing-time of ~ 6 am/pm. ALADIN, which is the unique payload of Aeolus, is a direct detection high spectral resolution wind lidar. It is a pulsed ultraviolet lidar working at the wavelength of 354.8 nm with a laser pulse energy around 65 mJ and with a repetition of 50.5 Hz. As the receiver, a 1.5 m diameter telescope collects the backscattered light. In order to retrieve the LOS wind speeds, the Doppler shifts of light caused by the motion of molecules and aerosol particles need to be identified. Aiming at this, a Fizeau interferometer is applied in the Mie channel to extract the frequency shift of the narrow-band particulate return signal by means of the fringe imaging technique (Mckay, 2002). In the Rayleigh channel, two coupled Fabry-Perot interferometers are used to analyze the frequency shift of the broad-band molecular return signal by the double edge technique (Chanin et al., 1989; Flesia and Korb, 1999). ...”

12. 4 VFM – please write vertical feature mask

AR: Thanks, revised.

13. 4 “west coast of Africa”

AR: Thanks, revised.

14. 5 The term “source” might be misleading, because you show a “position” along the CALIPSO track and the corresponding profiles at this position. And then you use this position as source for your trajectories. Reading “source” reminded me on dust sources.

AR: Sorry for the misleading and thanks for the suggestion. We replaced “source” with “position” in Fig. 5 and the relevant description in Section 4.1 of the revised manuscript.

15. 6a – it is not a “vertical” view and HYSPLIT trajectories are not shown.

AR: Thanks. The caption of Fig. 6 (a) has been revised as “(a) Aeolus and CALIPSO scanning tracks”.

16. L286 Explain u and v component of wind vector to readers not familiar with these conventions.

AR: Thanks. The sentence has been revised as “The zonal wind velocity (u component of the wind vector, from west point to east), meridional wind velocity (v component of the wind vector, from south point to north) and supplementary geophysical parameters are contained in L2C data product.” in the revised manuscript.

17. L310 “Godzilla” – a nice piece of information which could already be placed in the introduction.

AR: Thanks. The relevant information about “Godzilla” has been added in the front of the last paragraph of Section 1 in the revised manuscript, which is also shown as below:

“A long-term, large-scale Sahara dust transport event which occurred between 14 June and 27 June 2020 is captured, tracked and analyzed. Because of this record-breaking trans-Atlantic African dust plume, the magnitude and duration of spaceborne-sensors retrieved aerosol optical depth over the tropical North Atlantic Ocean were the greatest ever observed during summer over the past 18 years (Pu and Jin, 2021). This dust plume caused a historic, massive African dust intrusion into the Caribbean Basin and southern US, which is nicknamed the “Godzilla” dust plume (Yu et al., 2021).”

References:

*Pu, B., and Jin, Q.: A Record-Breaking Trans-Atlantic African Dust Plume Associated with Atmospheric Circulation Extremes in June 2020, Bulletin of the American Meteorological Society, 102(7), E1340-E1356, <https://doi.org/10.1175/BAMS-D-21-0014.1>, 2021.*

[Yu, H., Tan, Q., Zhou, L., Zhou, Y., Bian, H., Chin, M., Ryder, C. L., Levy, R. C., Pradhan, Y., Shi, Y., Song, Q., Zhang, Z., Colarco, P. R., Kim, D., Remer, L. A., Yuan, T., Mayol-Bracero, O., and Holben, B. N.: Observation and modeling of the historic “Godzilla” African dust intrusion into the Caribbean Basin and the southern US in June 2020, Atmos. Chem. Phys., 21, 12359–12383, <https://doi.org/10.5194/acp-21-12359-2021>, 2021.](#)

18. 8 The color plots are shown on the CALIPSO or Aeolus tracks?

AR: In Fig. 7 (corresponding to the Figure 8 in the original manuscript), the color plots are shown exactly on the middle of the CALIPSO tracks and the Aeolus tracks, to represent the dust advection over the region between two satellites’ tracks. The modified Fig. 7 are shown as below:

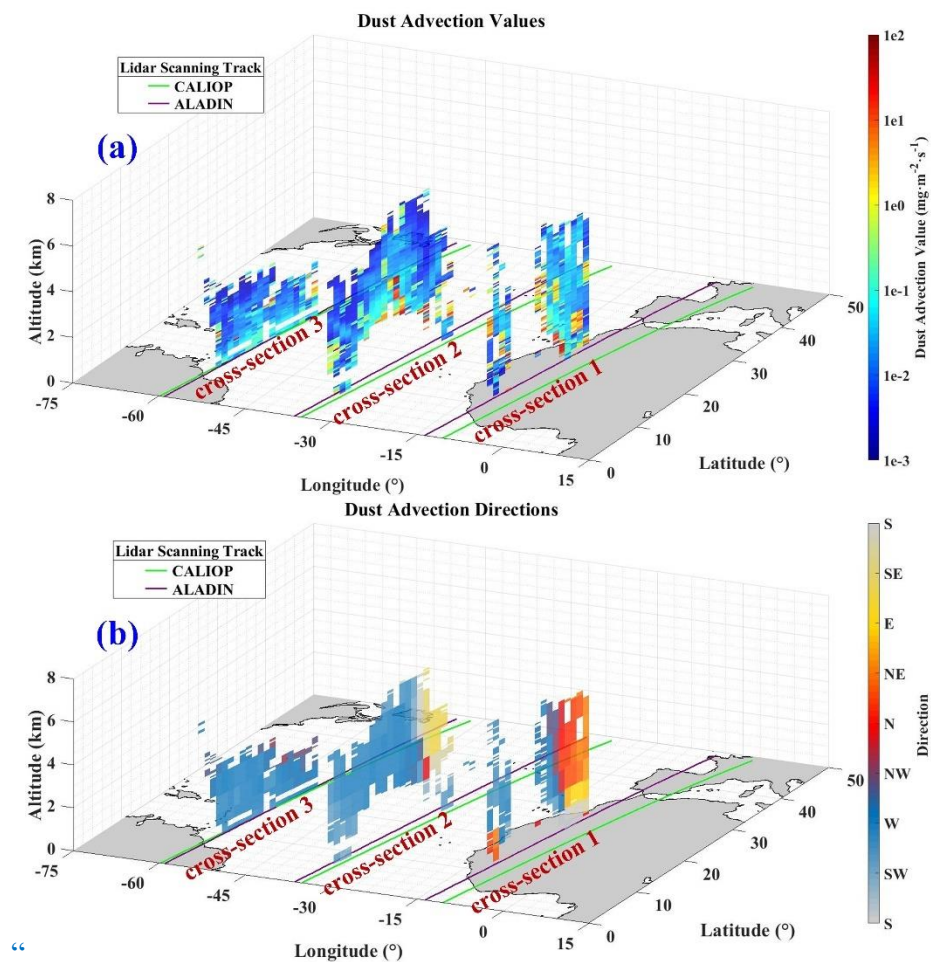


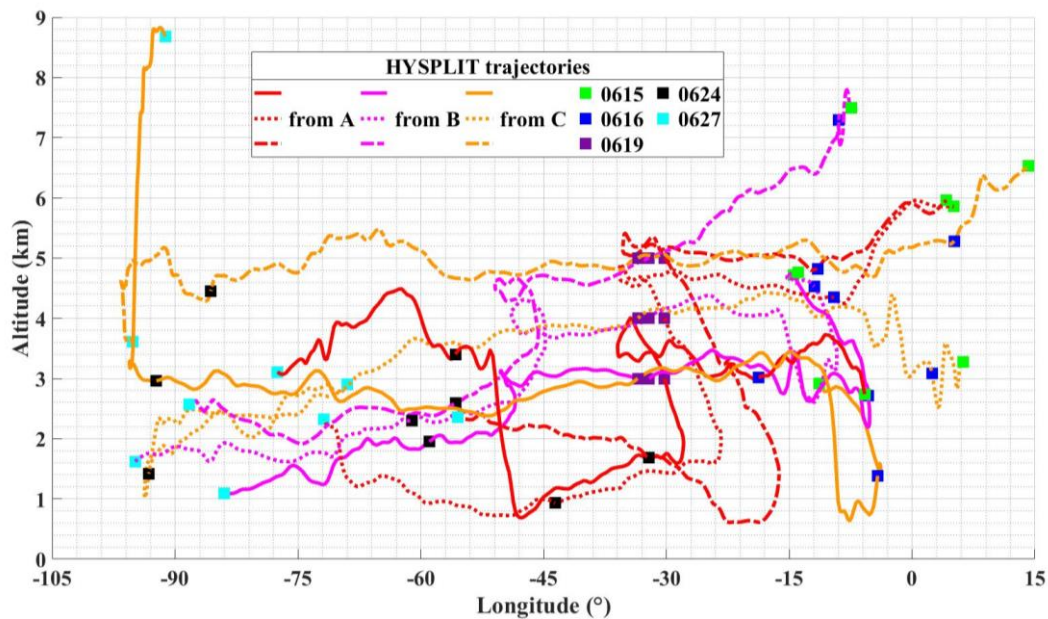
Figure 7. The dust advection calculated with data from ALADIN, CALIOP and ECMWF (a) the dust advection values at different cross-sections of dust plumes and (b) the dust advection directions at different cross-sections of dust plumes on 19 June 2020.”

19. L341 “dust mass” – you’re not showing the dust mass, but “enhanced backscatter and extinction values indicating the presence of dust”

AR: Thanks. This sentence has been revised as “From these figures, we can find that at different cross-sections of Aeolus and CALIPSO, the dust transport modelled with HYSPLIT match well with the enhanced backscatter and extinction coefficient values indicating the presence of dust.” in the revised manuscript.

20. 9d It is almost impossible to capture the latitudinal component in the plot – I would consider to show it on altitude – longitude plane (this is the interesting information!) and indicate the different positions in latitude by different lines, e.g., position A in dashed lines, position B in dotted lines, ...

AR: Thanks. We modified Fig. 8(d) (corresponding to Figure 9 of the original manuscript) according to your suggestions. The modified Fig. 8(d) are shown as below:



We show it on altitude-longitude panel. The different colors of the lines indicate the HYSPLIT trajectories modelled from different positions (the red lines are from position A, the magenta lines are from position B, the orange lines are from position C). the different styles of the lines indicate the HYSPLIT trajectories modelled from different altitude (the solid lines are from 3 km, the dot lines are from 4 km, the dot dash lines are from 5 km). The squares on the HYSPLIT trajectory lines have been added to indicate the trajectories position of 15 June, 16 June, 19 June, 24 June and 27 June, which are matched with the 5 cross-sections by ALADIN and CALIOP.

21. The “Saharan dust westward transport tunnel” (L.383) is somehow linked to the “Saharan Air Layer”.

AR: Thanks for the reminder. We revised the conclusion of the wind field cross-sections of this dust transport event observed by Aeolus as “Therefore, it can be considered that Aeolus provided the observations of the dynamics of this dust transport event in the Saharan air Layer (SAL), which is a hot, dry, elevated layer originating from the Sahara Desert and covering large parts of the tropical Atlantic (Carlson and Prospero, 1972; Prospero and Carlson, 1972).” And the references are added as:

*Carlson, T. N., and Prospero, J. M.: The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic, Journal of Applied Meteorology and Climatology, 11(2), 283-297. [https://doi.org/10.1175/1520-0450\(1972\)011<0283:TLSMOS>2.0.CO;2](https://doi.org/10.1175/1520-0450(1972)011<0283:TLSMOS>2.0.CO;2), 1972.*

*Prospero, J. M., and Carlson, T. N.: Vertical and areal distribution of Saharan dust over western equatorial north Atlantic Ocean, J. Geophys. Res., 77, 5255–5265, [doi:10.1029/JC077i027p05255](https://doi.org/10.1029/JC077i027p05255), 1972.*

This paper describes the combination of satellite borne lidar data from two instruments in combination with model wind field data and back and forward trajectory analyses to investigate the advection of a major dust storm across the Atlantic Ocean. The paper focus on a case study of a major dust storm to assess how the combined CALIPSO and Aeolus satellite products can be combined with ECMWF driven trajectories to describe dust transport and loss. The paper was previously submitted to ACPD and this version has been considerably improved.

I do, however, have a major reservation about section 4.2 and the accompanying statements in the abstract and summary sections. Section 4.2 presents lidar curtains at three locations across the sub-tropical north Atlantic on a day in the middle of the dust storm. The three curtains are close to the source region, over the mid-Atlantic and towards the west, in the far-field of the plume. However, the satellite overpasses presented are taken only 3 hours apart. The advection times between the most easterly lidar curtain and the most westerly are of the order of a week or more. The data in section 4.2 show the overall geographical distribution of dust across the Atlantic as a snapshot on the morning of 19/6/2020. What they do not do is say anything at all about the dynamics of the dust plume as it advects across the Atlantic region. The source region may have changed or emissions of dust varied and the transport pathways may be affected by changing atmospheric conditions over the course of the event. However, section 4.2 assumes the dust plume is time invariant and describes the scene as representing different ages of the plume. This is misleading and in any case is described much better in section 4.3. Either section 4.2 should be rewritten to illustrate geographical variability at a single point in time or removed. Furthermore, the way the results from this section are presented in the abstract and summary should be reframed or removed as they are written as though the data were taken in a pseudo lagrangian way and they were not.

AR: Thanks for the suggestion. Actually, we also think [the dust layers captured by Aeolus and CALIPSO during several hours on 19 June 2020 \(cross-section 1, 2](#)



and 3 in Fig 6 (b), (c)) are relatively static compared with the whole dust plume transport process. Sorry for the misleading. According to your suggestion, we rewrote the part of Section 4.2 and reframed the relevant conclusion in the abstract and the summary. Section 4.2 of the revised manuscript has been renamed as “Observation snapshot of the dust plume and dust advection calculation on 19 June 2020”. The description was reframed to illustrate the overall geographical distribution of dust layers as a snapshot on the morning of this day.

The revised part of Section 4.2 is shown as below:

#### **“4.2 Observation snapshot of the dust plume and dust advection calculation on 19 June 2020**

In this section, the dust event observation snapshot captured by ALADIN and CALIOP on 19 June 2020 is introduced in detail. The quasi-synchronized observations from ALADIN and CALIOP on 19 June 2020 are presented in Fig. 6, where the purple lines indicate the scanning tracks of ALADIN and the green lines indicate the scanning tracks of CALIOP. It is found that the overpasses of each satellite are only around 3 hours apart. Hence, we captured the dust layers on the morning of 19 June 2020 quasi-simultaneously over the Western Sahara, the Middle Atlantic and the Western Atlantic, i.e., took a snapshot of the dust plumes. From the profiling of dust optical properties, discriminated by the CALIOP measurements, the dust geographical distribution over Atlantic Ocean on this day could be determined. The extinction coefficients and backscatter coefficients at the wavelengths of 355 nm, 532 nm and 1064 nm within the dust mass are also determined. From the profiling, it was found that the mean backscatter coefficients at 532 nm were about  $3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 1”,  $7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 2” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 3”. On 19 June 2020, the dust layers existed over the Western Sahara, the Middle Atlantic and the Western Atlantic quasi-simultaneously, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and

extensive.

.....

In Fig. 7, the dust advection at different heights of the three cross-sections are presented. From the profiling, the mean dust advection value is about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 1” (over the emission region),  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 2” (over the transport region) and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 3” (over the deposition region), respectively.

In conclusion, on 19 June 2020, the dust layers over the Western Sahara, the Middle Atlantic and the Western Atlantic are observed by ALADIN and CALIOP nearly in the meanwhile. And the dust advectons of the three cross-sections indicate the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on the same day.”

The revised parts of the abstract and the summary are shown as below:

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase. Finally, the advection value for different dust parts and heights on 19 June and on the entire transport routine during transportation are

computed. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region.” (from the abstract)

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase.

Finally, the advection at different dust parts and heights on 19 June and on the entire transport routine during transportation are computed, respectively. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region, from which we can infer the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on this day...” (from the summary)

Specific recommendations

Lines 62-63: “Additionally, the CALIOP product Vertical Feature Mask product (VFM)” better to write

“Additionally, the CALIOP Vertical Feature Mask product (VFM)”

AR: Thanks, it is revised.

Line 74 “(e)motion”

AR: Thanks, it is revised.

Line 170-174 “Based on the dataset consists of the backscatter coefficients and extinction coefficients at the wavelengths of 1064 nm and 532 nm from CALIOP and the extinction coefficients at the wavelength of 355 nm from ALADIN, the aerosol volume concentration distribution can be calculated based on the regularization method which was performed by generalized cross-validation (GCV) from Müller et al. (1999).”

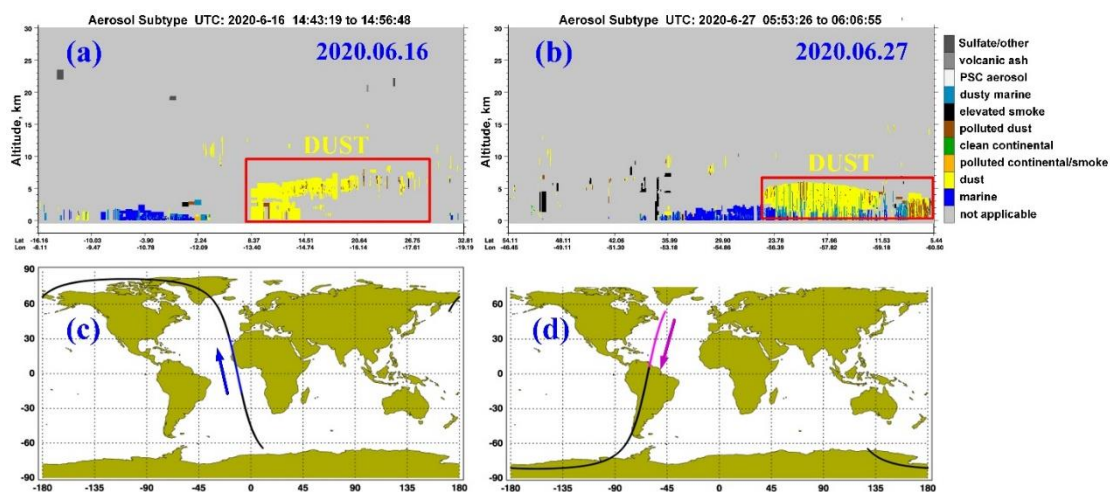
A confusing sentence that needs to be rewritten

AR: This sentence has been rewritten as “Based on the dataset consisting of the backscatter coefficients and extinction coefficients at the wavelengths of 1064 nm and 532 nm from CALIOP and the extinction coefficients at the wavelength of 355 nm from ALADIN, the aerosol volume concentration distribution can be estimated based on the regularization method which was performed by generalized cross-validation (GCV) from Müller et al. (1999).”

lines 240-241: Figure 4a shows the majority of the dust has been lifted to a maximum of around 7km or less south of 20N on 18/6/2020, there is only a small proportion of the dust at the far north end of the overpass that has a maximum close to 10 km. This probably needs rephrasing.

AR: Thanks for the suggestion. We updated Fig. 4 with the VFM products on 16 June 2020 and 27 June 2020, to make them matched with part of the satellite cross-sections presented in Section 4.3. The modified Fig. 4 and the relevant description are shown as below:

“Figure 4 presents the vertical distribution of the dust plume during the development phase (16 June 2020) over the eastern Atlantic and during the deposition phase (27 June 2020) over the western Atlantic. From Fig. 4 (a), it can be seen that the dust plume has been lifted up to around 7 km. Figure 4 (b) presents the descending dust plume, the bottom of which may mix with marine aerosol and become dusty marine aerosol. Therefore, the VFM data of CALIPSO captures the dust plume vertically over the eastern and the western Atlantic and verifies the dust transportation process.



**Figure 4. Vertical feature mask from CALIPSO L2 product (a) on 16 June 2020 over the west coast of Africa and the eastern Atlantic and (b) on 27 June 2020 over the western Atlantic (around the east coast of America). (c) and (d) show the corresponding CALIOP scanning tracks of (a) and (b) respectively, the arrows in which indicate the motion direction of CALIPSO ([https://www-calipso.larc.nasa.gov/products/lidar/browse\\_images/production/](https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/), last access: 24 March 2022).”**

Lines 276-282: The narrative in the section assumes a pseudo-lagrangian language but the lidar passes are on the same day so these are different slices of a dust event that has lasted several days (fig 3) and has a transit time of multiple days between the overpasses shown in fig 5. The wording here needs to better reflect that these are cross sections at different geophysical locations in the plume and do not directly represent plume evolution. This discussion is extended to report values of backscatter and advection for different phases of the dust plume. However, these don't reflect actual advection of the same air. The underlying assumption is the dust plume does not change with time. Clearly, this is not the case, so the determinations from the 3 different overpasses cant really be compared in the way that is done in the analysis in 4.2. At best this gives a snapshot of the plume at a single point in time across much of the Atlantic. This section needs to be rewritten in my view to make this clear and to convey why this is appropriate, otherwise it is best removed. This same approach is also followed up in the summary (402-406). The analysis is not pseudo-lagrangian and should not be inferred as such, the different phases of the storm were emitted many days apart and may have had very different conditions at source and during advection. This needs to be made explicit. The abstract also has the same errors between lines 22-25. This needs to be removed or corrected.

AR: Thanks for the suggestion. **We reframed and rewrote part of Section 4.2 and the relevant conclusion in the abstract and the summary to illustrate the overall geographical distribution of dust layers as a snapshot on the morning of this day.**

The revised part of Section 4.2 is shown as below:

#### **“4.2 Observation snapshot of the dust plume and dust advection calculation on 19 June 2020**

In this section, the dust event observation snapshot captured by ALADIN and CALIOP on 19 June 2020 is introduced in detail. The quasi-synchronized observations from ALADIN and CALIOP on 19 June 2020 are presented in Fig. 6, where the purple

lines indicate the scanning tracks of ALADIN and the green lines indicate the scanning tracks of CALIOP. It is found that the overpasses of each satellite are only around 3 hours apart. Hence, we captured the dust layers on the morning of 19 June 2020 quasi-simultaneously over the Western Sahara, the Middle Atlantic and the Western Atlantic, i.e., took a snapshot of the dust plumes. From the profiling of dust optical properties, discriminated by the CALIOP measurements, the dust geographical distribution over Atlantic Ocean on this day could be determined. The extinction coefficients and backscatter coefficients at the wavelengths of 355 nm, 532 nm and 1064 nm within the dust mass are also determined. From the profiling, it was found that the mean backscatter coefficients at 532 nm were about  $3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 1”,  $7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 2” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{sr}^{-1}$  in “cross-section 3”. On 19 June 2020, the dust layers existed over the Western Sahara, the Middle Atlantic and the Western Atlantic quasi-simultaneously, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive.

.....

In Fig. 7, the dust advection at different heights of the three cross-sections are presented. From the profiling, the mean dust advection value is about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 1” (over the emission region),  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 2” (over the transport region) and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in “cross-section 3” (over the deposition region), respectively.

In conclusion, on 19 June 2020, the dust layers over the Western Sahara, the Middle Atlantic and the Western Atlantic are observed by ALADIN and CALIOP nearly in the meanwhile. And the dust advectons of the three cross-sections indicate the quasi-

simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on the same day.”

The revised parts of the abstract and the summary are shown as below:

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase. Finally, the advection value for different dust parts and heights on 19 June and on the entire transport routine during transportation are computed. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region.” (from the abstract)

“...From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of



the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event's emission phase, development phase, transport phase, descent phase and deposition phase.

Finally, the advection at different dust parts and heights on 19 June and on the entire transport routine during transportation are computed, respectively. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the emission region,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the transport region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  over the deposition region, from which we can infer the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on this day..." (from the summary)

Line 293: "to calculate(d)"

AR: Thanks, it is revised.

Line 384: Affected not effected

AR: Thanks, it is revised.

# Dust transport and advection measurement with spaceborne lidars ALADIN, CALIOP and model reanalysis data

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**Abstract.** In this paper, a long-term large-scale Saharan dust transport event which occurred between 14 June and 27 June 2020 is tracked with the spaceborne lidars ALADIN and CALIOP together with ECMWF and HYSPLIT analysis. We evaluate the performance of ALADIN and CALIOP on the observations of dust optical properties and wind fields and explore the possibility of tracking the dust events and calculating the dust mass advection with the combination of satellite and model data.

15 The dust plumes are identified with AIRS/Aqua “Dust Score Index” and with the “Vertical Feature Mask” products from CALIOP. The emission, dispersion, transport and deposition of the dust event are monitored using the data from AIRS/Aqua, CALIOP and HYSPLIT. With the quasi-synchronized observations by ALADIN and CALIOP, combined with the wind field and relative humidity, the dust advection values are calculated. From this study, it is found that the dust event generated on 14 and 15 June 2020 from Sahara Desert in North Africa dispersed and moved westward over the Atlantic Ocean, finally being

20 deposited in the [western](#) Atlantic Ocean, the Americas and the Caribbean Sea. During the transport and deposition processes, the dust plumes are trapped in the Northeasterly Trade-wind zone between the latitudes of 5 °N and 30 °N, and altitudes of 0 km and 6 km (~~in this paper we name this space area as the “Saharan dust westward transport tunnel”~~). [Aeolus provided the observations of the dynamics of this dust transport event in the Saharan ~~air~~ Layer \(SAL\)](#). From the measurement results on 19 June 2020, [the dust plumes are captured quasi-simultaneously over the emission region \(Western Sahara\), the transport](#)

25 [region \(Middle Atlantic\) and the deposition region \(Western Atlantic\) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2](#)

30 [weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase. ~~influenced by the hygroscopic effect and mixing with other types of aerosols, the backscatter coefficients of dust plumes were increasing along the transport routes, with~~](#)

~~$3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in the “dust portion during emission phase”,  $7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in the “dust portion during development phase” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in the “dust portion during deposition phase”.~~ Finally, the advection value for different dust parts and heights on 19 June and on the entire transport routine during transportation are computed. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.06 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in the dust portion during over the emission phaseregion,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   $1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in the dust portion during over the development-transport phase-region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   $0.95 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  in the dust portion during over the deposition phaseregion.~~ In the whole life-time of the dust event, the mean dust advection values were about  $1.51 \pm 1.03 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.50 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 15 June 2020,  $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.41 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 16 June 2020,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 19 June 2020,  $1.60 \pm 1.08 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.01 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 24 June 2020 and  $1.03 \pm 0.60 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.15 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 27 June 2020. During the dust development stage, the mean advection values gradually increased and reaching their maximum on 16 June with the enhancement of the dust event. Then, the mean advection values decreased during the transport and the deposition of the dust over the Atlantic Ocean, the Americas and the Caribbean Sea.

## 1 Introduction

The global aerosol distribution and wind profiles have significant impacts on the atmospheric circulation, marine-atmosphere circulation and aerosol activities. As the most abundant aerosol types in the global atmosphere, the mineral dust influences the radiation budget, air quality, climate and weather via direct and various indirect radiative effects. Mineral dust is also considered as a major source of nutrients for ocean and terrestrial ecosystems. By the prevailing wind systems, mineral dust deposited over the ocean and land surface can significantly affect the carbon cycle and perturb the ocean and land geochemistry (Velasco-Merino et al., 2018; Banerjee et al., 2019). The atmospheric mineral dust can be transported over tens of thousands of kilometers away from its source regions (Uno et al., 2009, Haarig et al., 2017, Hofer et al., 2017). For instance, the biggest dust source, Africa, produced over half the global total dust (Huneeus et al., 2011), and African dust is transported westward over the Atlantic Ocean to reach South America (Yu et al., 2015; Prospero et al., 2020), the Caribbean Sea (Prospero and Lamb, 2003) and southern United States (Bozlaker et al., 2013). Hence, continuous observations of the dust long-range transport are crucial. As one of the best techniques for remotely studying the characteristics and properties of aerosols, lidar contributes much to ~~measuring-measure~~ the dust distribution. As introduced in previous papers, several comprehensive field campaigns including Aerosol Characterization Experiment ACE-Asia (Huebert et al., 2003; Shimizu et al., 2004), the Puerto Rico Dust Experiment PRIDE (Colarco et al., 2003; Reid et al., 2003), the Saharan Dust Experiment SHADE (Tanré et al., 2003), the Saharan Mineral Dust Experiments SAMUM-1 (Heintzenberg, 2009) and SAMUM-2 (Ansmann et al., 2011), the

Dust and Biomass-burning Experiment DABEX (Haywood et al., 2008), the Dust Outflow and Deposition to the Ocean project DODO (McConnell et al., 2008), the Pacific Dust Experiment PACDEX (Huang et al., 2008), the China-US joint dust field experiment (Huang et al., 2010), the Saharan Aerosol Long-Range Transport and Aerosol-Cloud-Interaction Experiment SALTRACE (Weinzierl et al., 2017), the study of Saharan Dust Over West Africa SHADOW (Veselovskii et al., 2016), and the Central Asian Dust Experiment CADEX (Hofer et al., 2017, 2020a, 2020b) were conducted.

However, the measurement data from these campaigns are still not able to meet the requirements for the investigation of global dust impact on climate, ocean/land geochemistry and ecosystems. Therefore, spaceborne lidars that are capable of observing aerosol have become effective instruments and are widely used in terms of dust plume measurements. The satellite-based lidar CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) carried by the platform of CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) provides us the backscatter coefficient and extinction coefficient at the wavelengths of 532 nm and 1064 nm (Winker et al., 2009). Additionally, the CALIOP ~~product~~ Vertical Feature Mask ~~product~~ (VFM) ~~product~~ (VFM) presents the aerosol sub-types classification so that the global dust events could be marked. Moreover, large efforts are still needed to monitor the dust emission, transport, dispersion and deposition, and to explore the dust's impact on the Earth's radiation, climate and ecosystems. Hence, the vertical profiling of the global wind field is necessary to calculate the dust advection. Thanks to the efforts of the European Space Agency (ESA), a first ever spaceborne direct detection wind lidar, Aeolus, which is capable of providing vertical wind fields globally with high temporal and spatial resolution has been developed under the framework of the Atmospheric Dynamics Mission (ADM) (Stoffelen et al., 2005; ESA, 1999; Reitebuch et al., 2012; Kanitz et al., 2019). ~~On 22 August 2018, Aeolus was successfully launched into its sun synchronous orbit at a height of 320 km (Witschas et al., 2020; Lux et al., 2020). A quasi-global coverage is achieved daily (~15 orbits per day) and the orbit repeat cycle is 7 days (111 orbits). The orbit is sun synchronous with a local equatorial crossing time of ~6 am/pm.~~ The Atmospheric Laser Doppler Instrument (ALADIN) is a direct detection high spectral resolution wind lidar carried by Aeolus and provides the vertical profiles of the Horizontal-Line-of-Sight (HLOS) wind speeds. Further, the wind vector data assimilated with the HLOS wind speed data and the particle optical property data (e.g., extinction coefficient, backscatter coefficient) at 355 nm are also provided in the products of Aeolus. ~~In order to retrieve the LOS wind speeds, the Doppler shifts of light caused by the motion of molecules and aerosol particles need to be identified. Aiming at this, a Fizeau interferometer is applied in the Mie channel to extract the frequency shift of the narrow band particulate return signal by means of the fringe imaging technique (Mekay, 2002). In the Rayleigh channel, two coupled Fabry Perot interferometers are used to analyze the frequency shift of the broad band molecular return signal by the double edge technique (Chanin et al., 1989; Flesia and Korb, 1999).~~

A long-term, large-scale Saharan dust transport event which occurred between 14 June and 27 June 2020 is captured, tracked and analyzed. Because of this record-breaking trans-Atlantic African dust plume, the magnitude and duration of spaceborne-sensors retrieved aerosol optical depth over the tropical North Atlantic Ocean were the greatest ever observed during summer over the past 18 years (Pu and Jin, 2021). This dust plume caused a historic, massive African dust intrusion into the Caribbean Basin and southern US, which is nicknamed the “Godzilla” dust plume (Yu et al., 2021). In the simultaneous observations of

the dust plume, the aerosol optical properties can be obtained by means of ALADIN and CALIOP. By further using the wind vector data from ALADIN, the wind field and relative humidity (RH) data from ECMWF and the trajectories from the HYSPLIT model, the dust transport route can be observed, and the dust advection can be calculated.

The paper is organized as follows: in Section 2 the satellite-based instruments, ECMWF and HYSPLIT models are introduced. Section 3 presents the details to the joint dust measurement strategy and methodology. In section 4 we provide the process of the dust event identification and verification as well as the observation results and the dust advection calculations of the dust transport measurements on 19 June 2020 and during the whole lifetime of the dust event.

## 2. Spaceborne instruments and meteorological models

### 2.1 ALADIN/Aeolus

On 22 August 2018, Aeolus was successfully launched into its sun-synchronous orbit at a height of 320 km (Witschas et al., 2020; Lux et al., 2020). A quasi-global coverage is achieved daily (~ 15 orbits per day) and the orbit repeat cycle is 7 days (111 orbits). The orbit is sun-synchronous with a local equatorial crossing-time of ~ 6 am/pm. ALADIN, which is the unique payload of Aeolus, is a direct detection high spectral resolution wind lidar. It is a pulsed ultraviolet lidar working at the wavelength of 354.8 nm with a laser pulse energy around 65 mJ and with a repetition of 50.5 Hz. As the receiver, a 1.5 m diameter telescope collects the backscattered light. In order to retrieve the LOS wind speeds, the Doppler shifts of light caused by the motion of molecules and aerosol particles need to be identified. Aiming at this, a Fizeau interferometer is applied in the Mie channel to extract the frequency shift of the narrow-band particulate return signal by means of the fringe imaging technique (Mckay, 2002). In the Rayleigh channel, two coupled Fabry-Perot interferometers are used to analyze the frequency shift of the broad-band molecular return signal by the double edge technique (Chanin et al., 1989; Flesia and Korb, 1999). -The two-channel high spectral resolution design of ALADIN allows for the simultaneous detection of the molecular (Rayleigh) and particle (Mie) backscattered signals ~~in two separate channels~~, each sampling the wind in 24 vertical height bins with a vertical range resolution between 0.25 km and 2.0 km. This makes it possible to deliver winds both in clear and (partly) cloudy conditions down to optically thick clouds at the same time. The horizontal resolution of the wind observations is about 90 km for the Rayleigh channel and about 10 km for the Mie channel. The detailed descriptions of the instrument design and a demonstration of the measurement concept are introduced in e.g. Reitebuch et al. (2009, 2012), Straume et al. (2018), ESA (2008), Marksteiner et al. (2013), Kanitz et al. (2019), Witschas et al. (2020) and Lux et al. (2020).

The data products of Aeolus are processed at different levels, namely Level 0 (instrument housekeeping data), Level 1B (engineering-corrected HLOS winds), Level 2A (aerosol and cloud layer optical properties), Level 2B (meteorologically-representative HLOS winds) and Level 2C (Aeolus-assisted wind vectors) (Flament et al., 2008; Tan et al., 2008, 2017). Within the Level 2B processor, the Rayleigh-clear and Mie-cloudy winds are classified, and the temperature and pressure corrections are applied for the Rayleigh wind retrieval (Witschas et al., 2020). In this study, the Level 2A (baseline 10 referring to the L2A processor v3.10) aerosol optical properties and Level 2C (baseline 10 referring to the L2A processor v3.10) wind vectors are

used. For the calculation of particle volume concentration distribution and mass concentration, the extinction coefficients at the wavelength of 355 nm are used.

## 130 **2.2 CALIOP/CALIPSO**

Launched in 2006, CALIPSO provides aerosol and cloud optical properties information, e.g., particle depolarization ratio, extinction coefficient, backscatter coefficient and Vertical Feature Mask (VFM) (Winker et al., 2009). The VFM product describes the vertical and horizontal distribution of cloud and aerosol types along the observation tracks of CALIPSO. In this study, the backscatter coefficients at the wavelengths of 532 nm and 1064 nm from the CALIPSO L2 product are used for the  
135 calculation of the dust volume concentration distribution and mass concentration. The VFMs from CALIPSO are also applied to identify the subtypes of aerosol layers. The extinctions from the CALIPSO L2 product are not used in this study, because global average lidar ratio taken for the CALIPSO retrieval is lower than the lidar ratio for Western Saharan dust. The extinctions at 532 nm and 1064 nm used in this study are calculated by the CALIPSO retrieved backscatters and the corrected lidar ratios: 58 sr at 532 nm (Amiridis et al., 2013), 60 sr at 1064 nm (Tesche et al., 2009).

## 140 **2.3 ECMWF climate reanalysis**

Supported by the Copernicus Climate Change Service (C3S), ECMWF provides the atmospheric reanalysis ERA5 which presents a detailed record of the global atmosphere, land surface and ocean waves from 1950 onwards (Hersbach et al., 2020). The 4D-Var assimilated ERA5 produces the hourly vertical profiles (at 37 pressure levels) of global wind fields with a grid resolution of 31 km. After the successful launch of the Aeolus, the ECMWF started to simulate the wind products of Aeolus  
145 from January of 2020. In this study, the wind field data from ECMWF is applied in filling in the missing data within the region between the tracks of Aeolus and CALIPSO and to illustrate the homogeneity of the wind field in this region.

## **2.4 HYSPLIT**

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) is a modelling system for determining the trajectories, transport and dispersion of air masses developed by the National Oceanic and Atmospheric Administration  
150 (NOAA) Air Resources Laboratory (ARL) (Draxler and Hess 1998; Draxler and Rolph 2012). Backward and forward trajectories are the mostly commonly-used model applications to determine the origin of air masses (Stein et al., 2015). In this study, HYSPLIT is used to describe and check the routes of transport, dispersion, and deposition of dust plumes.

## **3. Methodology**

In the study of dust transport and advection, as shown in Fig. 1, the dust identification, Aeolus and CALIPSO tracks match,  
155 data analysis and HYSPLIT model analysis are described in the schematic flowchart.

### 3.1 Method used to match CALIPSO and Aeolus data

To identify the dust events and to choose the quasi-synchronized observations with ALADIN and CALIOP, the “Dust score index” data provided by AIRS/Aqua are used to determine the dust plume coverage and transport route. With this information, the VFM products from the simultaneous observations with CALIOP are applied to cross-check the identification of dust events. Hence the vertical distributions of dust plumes are obtained. To find the original sources and to predict the transport routes of dust plumes, the backward trajectory and forward trajectory are used respectively. When the dust events are determined, the simultaneous observations with ALADIN and CALIOP have to be selected. Starting from the CALIOP observations, the nearest Aeolus footprints were found. Since the orbits of Aeolus and CALIPSO are different, they cannot meet each other at the exactly same time and same location. From our study, the closest CALIPSO scanning tracks to those of Aeolus, are about 4 hours ahead of Aeolus. Based on the transport directions of dust events modelled with HYSPLIT, the tracks of Aeolus should always be downwind of the tracks of CALIPSO. When the tracks of Aeolus and CALIPSO are selected, the distances between the tracks can be calculated. Assuming the wind speed between CALIPSO scanning tracks and Aeolus is in the range of  $5 \text{ m} \cdot \text{s}^{-1}$  to  $15 \text{ m} \cdot \text{s}^{-1}$ , the transport distances of the dust plumes are in the range of 72 km to 216 km. During this short ~~time~~ time period, dust optical properties remain almost unchanged (Haarig et al., 2017). Consequently, if the distances between two satellites scanning tracks are less than 200 km and the tracks of Aeolus are downwind of the tracks of CALIPSO, it is reasonable to state that the dust plumes captured by CALIPSO are transported towards the Aeolus scanning regions in around 4 hours, hence the following procedures could be continued. To conclude, a successful match at least meets two criteria including 1) the tracks of Aeolus are downwind of the tracks of CALIPSO and 2) the distances between two satellites scanning tracks are less than 200 km.

### 3.2 Datasets and quality control

This study uses the extinction coefficient at 355 nm from ALADIN and the backscatter coefficients at 532 nm and 1064 nm from CALIOP. The extinction coefficient at 355 nm corresponds to the “Aeolus Level 2A Product” retrieved by SCA (standard correction algorithm). In this study, we choose SCA instead of ICA (iterative correction algorithm) because the extinction coefficients from ICA are noisy and the assumption of “one single particle layer filling the entire range bin” in SCA is met in the situation of the heavy dust events. Additionally, we use the mid bin product (sca\_optical\_properties\_mid\_bins) of SCA instead of the normal product of SCA, because the mid-bin algorithm provides more robust results (Baars et al., 2021; Flament et al., 2021a). The extinction coefficient, which is more sensitive to noise and is the significant input of the dust advection calculation, is better retrieved through this “mid bin” averaged version of the algorithm. In terms of quality control, negative extinction coefficient values of L2A are excluded while the “bin\_1\_clear” flag and the “processing\_qc\_flag” of L2A are used to eliminate invalid data. The backscatter coefficients at 532 nm and 1064 nm are the “Total\_Backscatter\_Coefficient\_532” and “Backscatter\_Coefficient\_1064” from CALIPSO. Since the footprints of Aeolus and CALIPSO are not exactly matched, the missing wind data between their tracks have to be filled in using the ERA5 wind field data. There are two reasons for using

the ERA5 wind field data between Aeolus and CALIPSO tracks. One is that the ERA5 wind speed and direction data provide the evidence of dust transport from CALIPSO tracks towards Aeolus tracks. Secondly, the ERA5 wind field data between the tracks of Aeolus and CALIPSO at all height surfaces are smoothly distributed and the values are stable. However, the Aeolus L2C data can also be used at the location of the CALIPSO track.

### 3.3 Dust advection calculation

In Fig. 2, the flowchart of dust mass advection calculation procedure is provided. Based on the dataset ~~consists~~-consisting of the backscatter coefficients and extinction coefficients at the wavelengths of 1064 nm and 532 nm from CALIOP and the extinction coefficients at the wavelength of 355 nm from ALADIN, the aerosol volume concentration distribution can be ~~calculated~~-estimated based on the regularization method which was performed by generalized cross-validation (GCV) from Müller et al. (1999). The lidar ratio for Western Saharan dust is higher than the global average taken for the CALIPSO retrieval, thus the extinctions from the CALIPSO L2 product are not used in the calculation of the aerosol volume concentration. The extinctions at 532 nm and 1064 nm utilized for the regularization method are calculated from the CALIPSO backscatter and the corrected lidar ratios: 58 sr at 532 nm (Amiridis et al., 2013), 60 sr at 1064 nm (Tesche et al., 2009).

The advantage of this method is that it does not require prior knowledge of the shape of the particle size distribution and the estimated uncertainty of aerosol volume concentration is on the order of 50% if the estimated errors of the inputs are on the order of 20%. For the backscatter coefficient at 532 nm, during the daytime, the average difference between collocated CALIPSO and HSRL measurements is  $1.0\% \pm 3.5\%$  in V4 (Getzewich et al., 2018); for the backscatter coefficient at 1064 nm, the CALIOP V4 1064 nm calibration coefficients are accurate to within 3 % (Vaughan et al., 2019). Consequently, we consider that the uncertainties of CALIPSO-retrieved extinction and backscatter coefficients to be of order 20%. According to Flament et al. (2021a), because of the lack of cross-polarized light, backscatter coefficients at 355nm of Aeolus are underestimated, especially for dust aerosol. Nevertheless, the extinction is not affected. In this work, Aeolus retrieved backscatter coefficients at 355nm are not applied for the calculations of the dust volume concentration distribution and mass concentration. For the accuracy of the Aeolus-retrieved extinction coefficient, the simulation extinction coefficients fit the inputs well mostly, especially when the altitude is larger than 2 km (Flament et al, 2021a). Hence, we consider that after rigorous quality control, the Aeolus L2A extinction coefficient could be the input parameters of the regularization method. In conclusion, the estimated errors of the five input parameters we used to calculate the aerosol volume concentration are on the order of 20%. The estimate errors of dust advection are the combination of mass concentration estimate errors (~50%) and Aeolus L2C wind vector estimate errors.

It should be emphasized that due to the different vertical and horizontal resolution between Aeolus and CALIPSO data, a common pixel grid should be established before calculation. For vertical resolution, 23 data bins of Aeolus L2A mid bin optical property products are interpolated to 399 data bins of CALIPSO according to the altitude information of two products. For horizontal resolution, both Aeolus and CALIPSO products are averaged along every integer latitude to acquire a common



220 horizontal pixel grid. After integrating and multiplying an assuming typical dust particle density which is set as  $2.65 \text{ g} \cdot \text{cm}^{-3}$  referring to previous studies (e.g., Schepanski et al., 2009; Hofer et al., 2017; Mamouri and Ansmann, 2017), the particle mass concentration is estimated following the method of Engelmann et al. (2008). ECMWF wind field data and RH data between Aeolus and CALIPSO scanning tracks are averaged along longitude and averaged along every integer latitude, while, vertically, they are interpolated to CALIPSO data bins to match the common pixel grid. Since the observations with ALADIN and

225 CALIOP are not exactly simultaneous, the ECMWF wind field data between the two spaceborne lidars' scanning tracks is utilized to illustrate the homogeneity of the wind field between two tracks, so that the Aeolus L2C wind vector data along the Aeolus tracks can represent the wind field of the whole area and can be employed in the calculation of the dust mass advection. In the transport regions of the dust plume (between  $5^\circ \text{N}$  and  $30^\circ \text{N}$ ), if both of the standard deviation percentages of wind speed and direction along each latitude line are less than 10%, it is considered that the wind fields between the two spaceborne

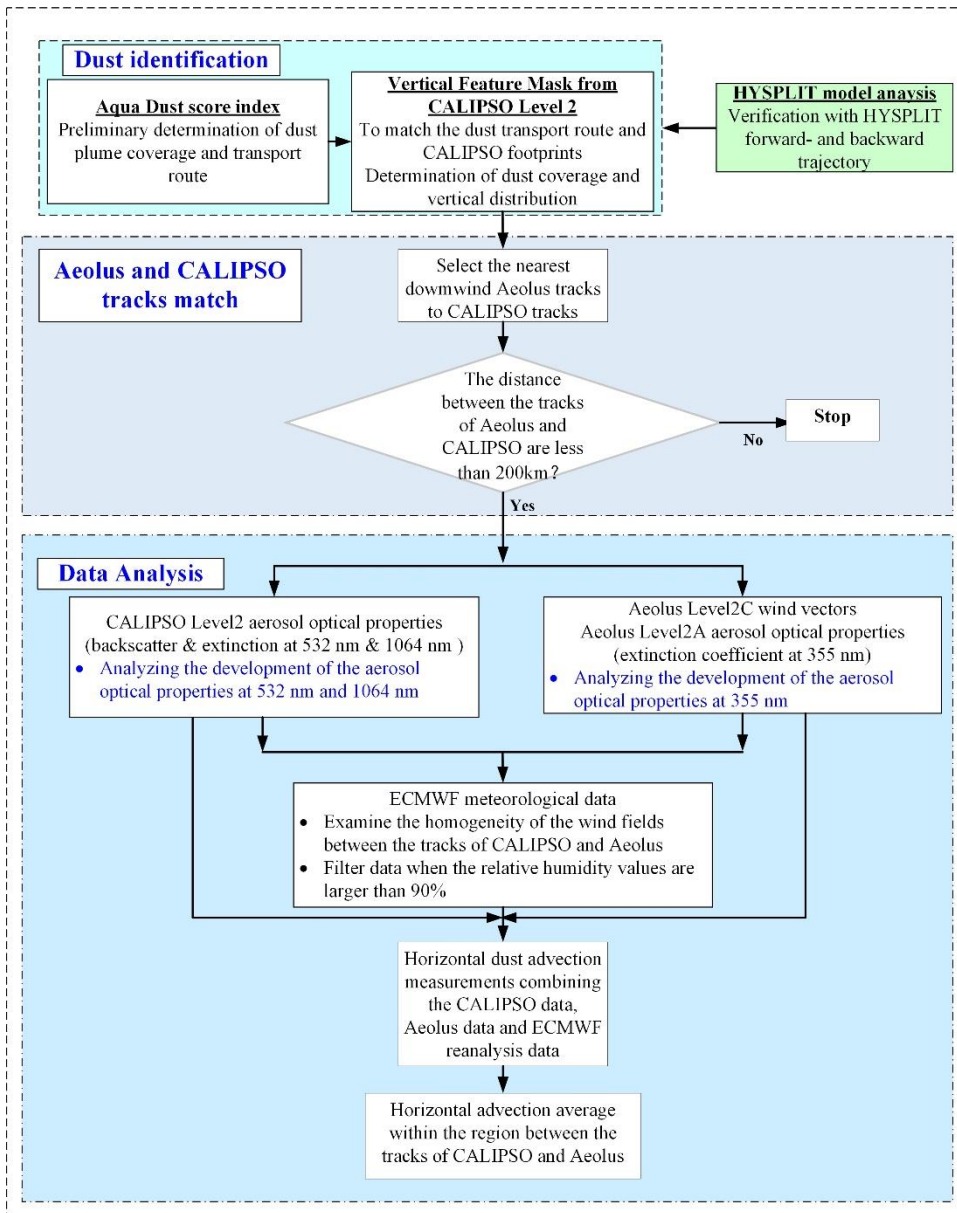
230 lidars' scanning tracks are homogeneous and stable. Besides, when the RH is larger than 90%, the dust aerosol will be influenced by the hygroscopicity effect and its properties could change. Then the mass concentration calculation method does not make sense any more (Engelmann et al., 2008). Meanwhile, if the RH is larger than 94%, then the probability that cloud presents is quite high (Flament et al., 2021bATBD of L2A, 待添加). ~~For the cloud screening, aside the RH data, we use Level 2-5 km aerosol profile of CALIPSO, which only provide aerosol optical properties so the cloud can be screened.~~ Therefore,

235 relative humidity data provided by ECMWF is used to filter unavailable data of which the RH is larger than 90%. For the cloud screening and dust aerosol separation of the common data pixel grid, aside the RH data, we use Level 2-5 km aerosol profile products of from CALIPSO, which only provide aerosol optical properties so the cloud can be screened, while the VFM products from CALIPSO are used to identify dust aerosol. Only the data bins of the common pixel grid are identified as "dust" are employed in the estimation of the dust mass concentration.

240 Ultimately, combining the particle mass concentration and the horizontal wind vector provided by Aeolus L2C product, the dust mass advection is defined as Eq. (1), to represent the transportation of dust aerosol quantitatively.

$$\overrightarrow{Advection}_{\text{aerosol-mass}} = m \cdot \vec{v}, \quad (1)$$

where  $m$  is the aerosol mass concentration and  $\vec{v}$  is the horizontal wind vector.



245 **Figure 1. Dust identification, Aeolus and CALIPSO tracks match and data procedures.**

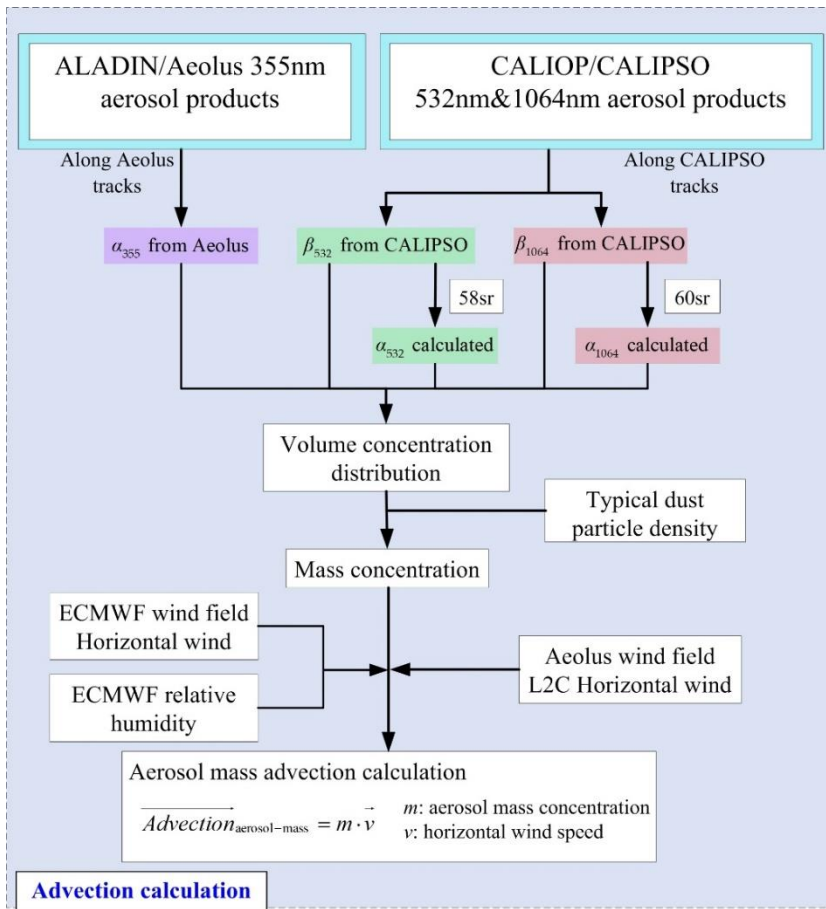


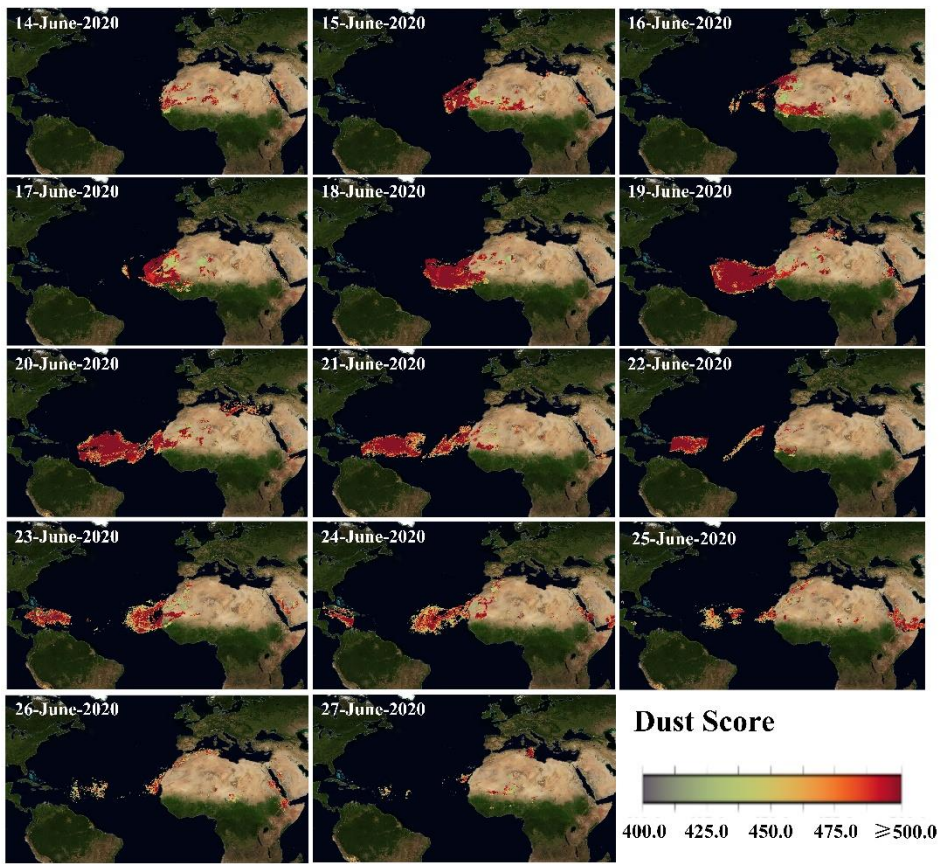
Figure 2. The flowchart of the dust mass advection calculation procedure.

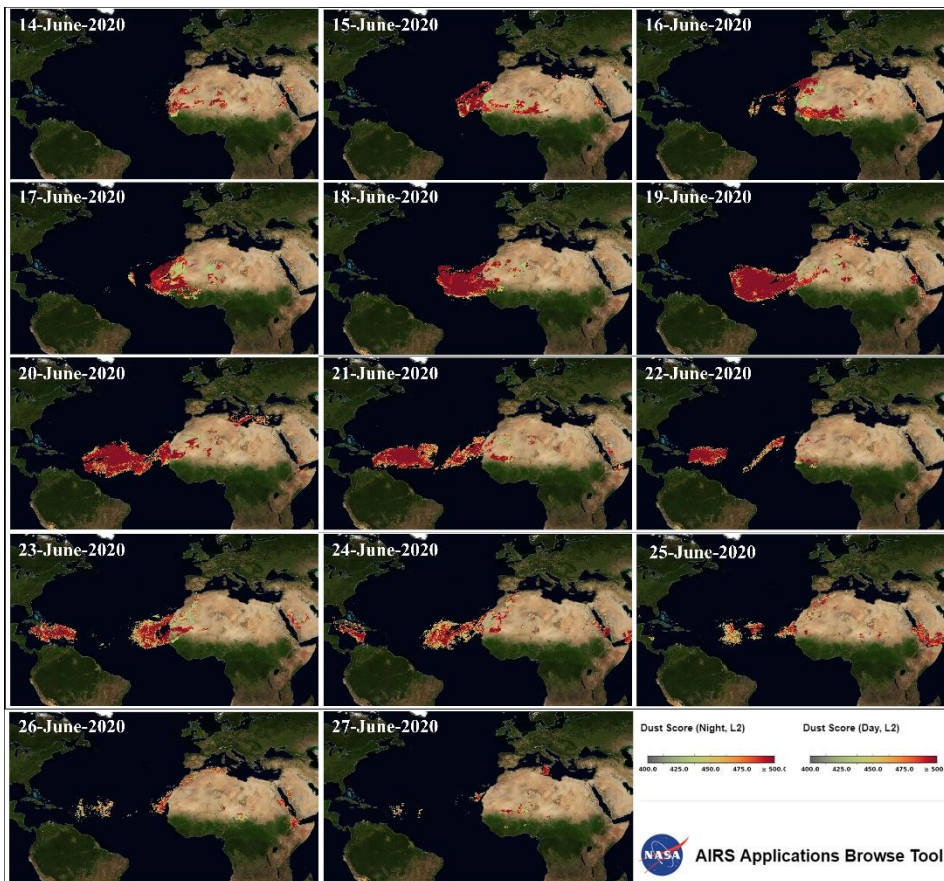
## 4. Results and discussion

### 4.1 Dust identification and verification by AIRS/Aqua, CALIOP and HYSPLIT

250 During 14 and 27 June 2020, a complete dust event process, including dust emission, transportation, dispersion and deposition, took place in the regions of Africa, Atlantic Ocean and the Americas. In Fig. 3, the “Dust Score Index” provided by AIRS/Aqua at different stages are presented. From this figure, the long-term dust event generated on 14 and 15 June 2020 from the Sahara Desert in North Africa dispersed and moved westward over the Atlantic Ocean, -finally being deposited in the western part of the Atlantic Ocean, the Americas and the Caribbean Sea. It should be emphasized that since the dust scores are provided per

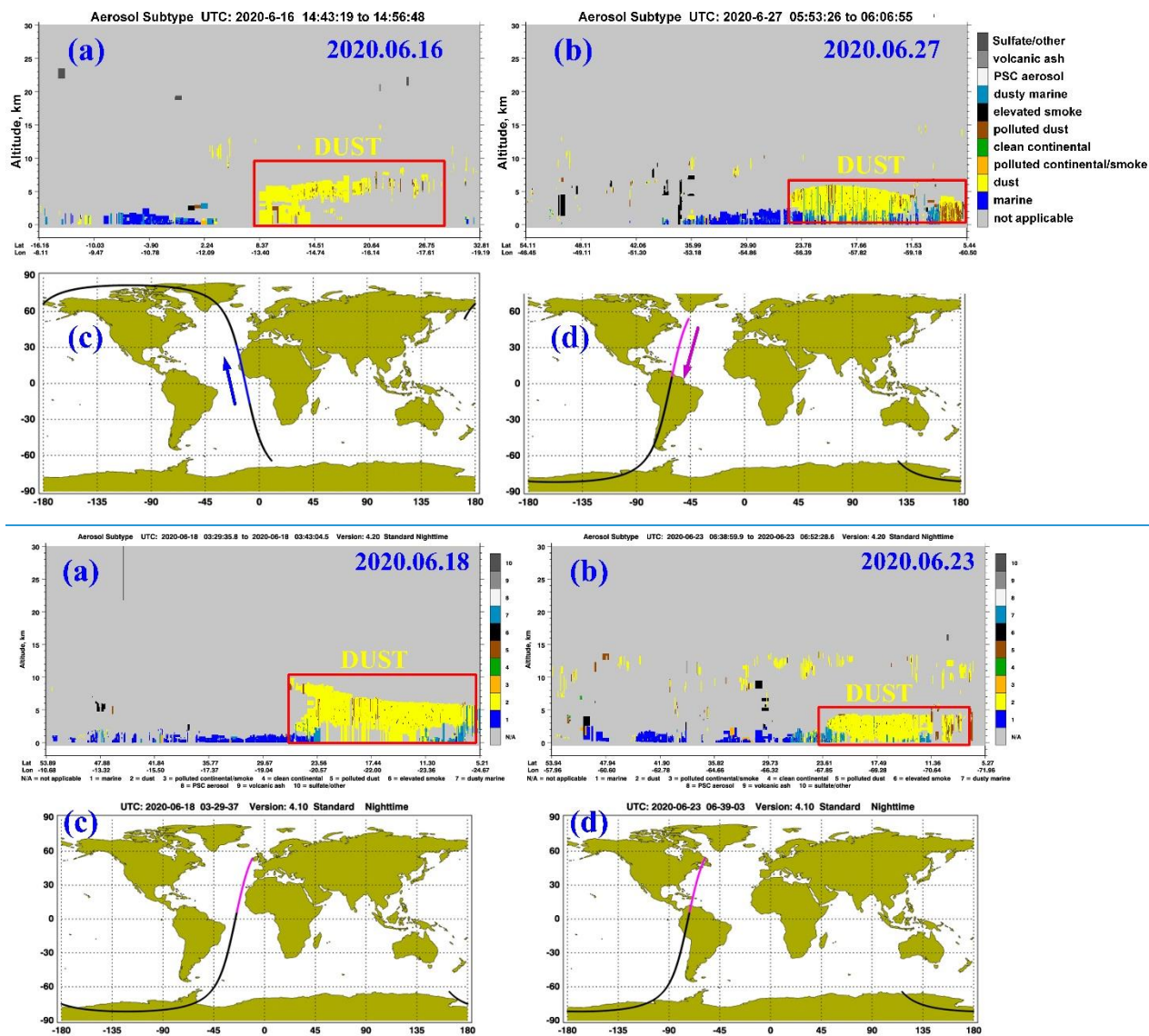
255 day, the dust events are just preliminarily classified. From the spaceborne CALIOP observations, it is found that sometimes dust events are actually present but are misjudged by AIRS/Aqua, which may result from the interference ~~from-of the~~ high-altitude cloud layers. The daily dust score data over the Sahara-Atlantic-Americas region generally reveals the transportation of the dust plume horizontally.





260

**Figure 3. The Dust Score Index provided by AIRS/Aqua at different stages, including emission, transportation, dispersion and deposition (<https://airs.jpl.nasa.gov/map/>, last access: 10 January 2022).**



265 **Figure 4. Vertical feature mask (VFM) from CALIPSO L2 product (a) on 18-16 June 2020 over the eastern Atlantic (around the west coast of Sahara Africa and the eastern Atlantic) and (b) on 23-27 June 2020 over the western Atlantic (around the east coast of America). (c) and (d) show the corresponding CALIOP scanning tracks of (a) and (b) respectively, the arrows in which indicate the motion direction of CALIPSO ([https://www-calipso.larc.nasa.gov/products/lidar/browse\\_images/production/](https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/), last access: 10-24 January-March 2022).**

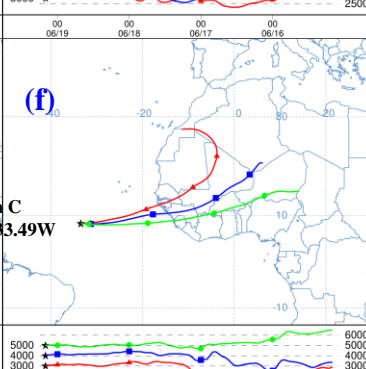
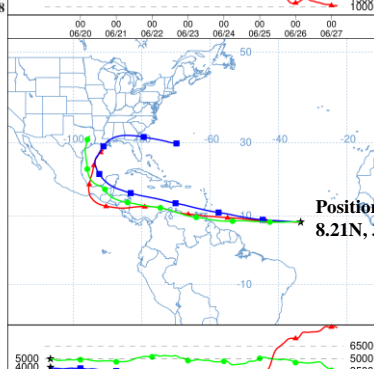
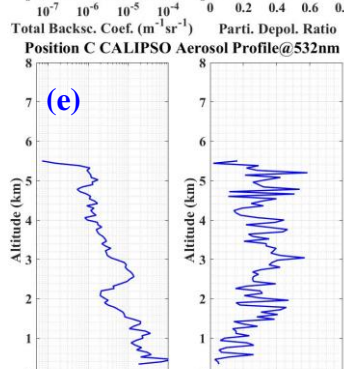
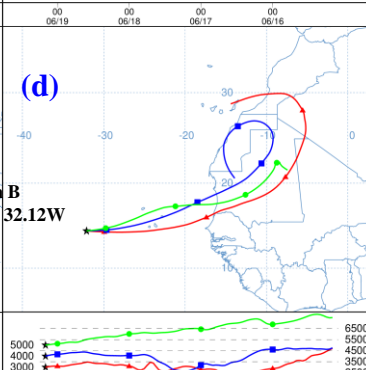
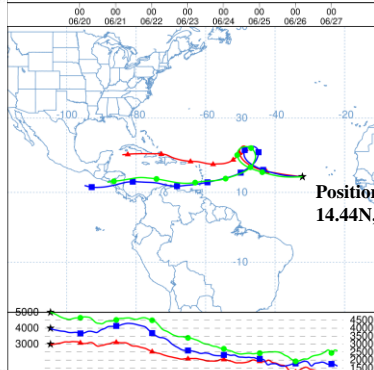
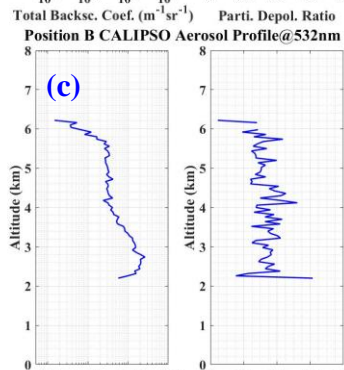
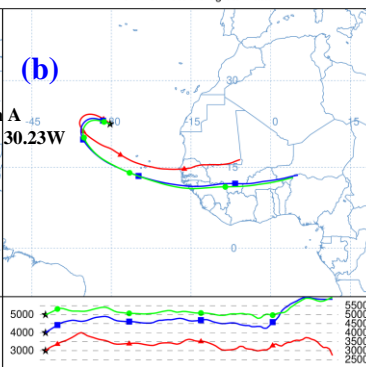
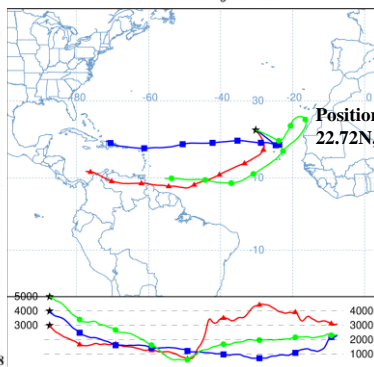
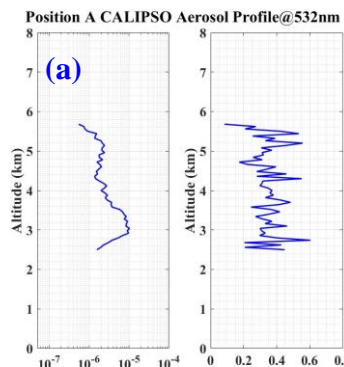
270 Figure 4 presents the vertical distribution of the dust plume during the development phase (18-16 June 2020) over the eastern Atlantic and during the deposition phase (23-27 June 2020) over the western Atlantic. From Fig. 4-(a), it can be seen that the dust plume has been lifted up to around 10-7 km. Figure 4-(b) presents the descending dust plume, the bottom of which may mix with marine aerosol and become dusty marine aerosol. Therefore, the VFM data of CALIPSO captures the dust plume vertically over the eastern and the western Atlantic and verifies the dust transportation process.

275 To cross-check the transport route of the dust events, three adjacent typical CALIPSO aerosol profiles capturing dust aerosol layers from one CALIPSO orbit, and the corresponding backward and forward trajectories starting at 0400UTC 19 June 2020 of these three positions conducted with the NOAA HYSPLIT model capturing a dust aerosol layer are shown in Fig. 5. Meanwhile, ~~the backward and forward trajectories of these three sources starting at 0500UTC 20 June 2020 with the NOAA HYSPLIT model were conducted.~~ CALIPSO total backscatter coefficient profiles and particle depolarization ratio profiles of ~~source position A ( 22.72°N, 30.23°W ), source position B ( 14.44°N, 32.12°W ) and source position C ( 8.21°N, 33.49°W )~~ are shown in Fig. 5-(a), (c) and (e). It can be ~~seen found~~ that there are dust aerosol layers at these three positions in the altitude range of ~~dust plume layers at source A and source B are approximately 3 km to 6 km, while the dust layer at source C is lower, is around 2-3 km to 4km5 km.~~ Hence, the starting altitude of the HYSPLIT trajectories of these three positions were setting as 3 km, 4 km and 5 km. Besides, the backward and forward trajectories' durations are 96 hours and 192 hours, respectively.

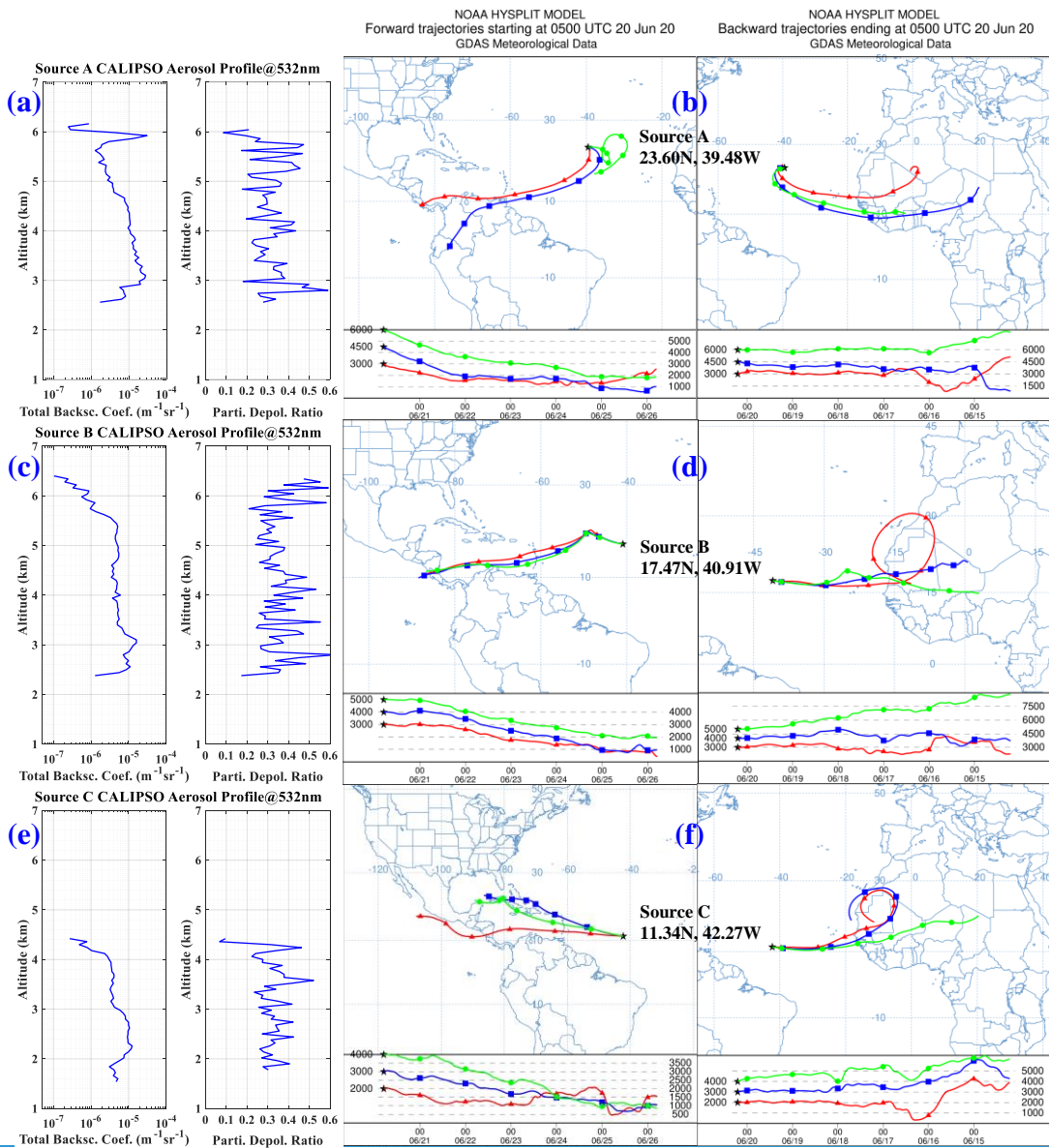
280 From Fig. 5 (b), (d) and (f), i.e. the HYSPLIT trajectories, it is seen that the dust ~~plumes aerosol at of positions source A, A, and source B~~ the dust aerosol at the altitude of 4 km and 5 km of position C are mainly generated from the ~~centre middle~~ of the Sahara Desert, ~~while~~ the dust plumes aerosol at source C at of about 3 km and 2 km position B, and the dust aerosol at 3 km of position C are originated from the ~~west side western of the Sahara Desert~~. The forward trajectories clearly indicate ~~that the descents of most the dust plumes and the possible continued transport of part of the dust plumes were separated into two directions.~~ The dust plumes transportation directions of source A, B and C are toward Central/South America respectively and the Caribbean Sea. At the end of ~~these three the~~ forward trajectories at 4 km and 5 km of position A and at the end of the forward trajectories of position B, the altitudes of the ~~trajectories dust aerosol~~ reduce to around 1 km to 2 km, which indicates ~~the a descents of the~~ dust plumes. However, the forward trajectories at 3 km of position A and position C show obviously ascents when approaching the end, indicating the possible continued transport of the dust plumes. Moreover, the trajectories of position C shows a relatively smooth transport of the dust aerosol from the Sahara to the Gulf of Mexico and North America. The trajectories of position A and position B circle above the Atlantic, which presents the slower transports of dust plumes than position C. It can be concluded that, ~~After from 15 June 2020 to 27 June 2020~~ 26 June, transported over the whole Atlantic Ocean, ~~most of the dust plumes from the Sahara were transported to Central/South America, Caribbean Sea, the Gulf of Mexico and even North America.~~ Most dust plumes descended and might deposit to ocean or land while part of the dust plumes were possibly transported continuously. It can also be inferred that, because of the different atmosphere conditions along the transport routes of separate positions, the transport speed of the dust plumes turned out different.

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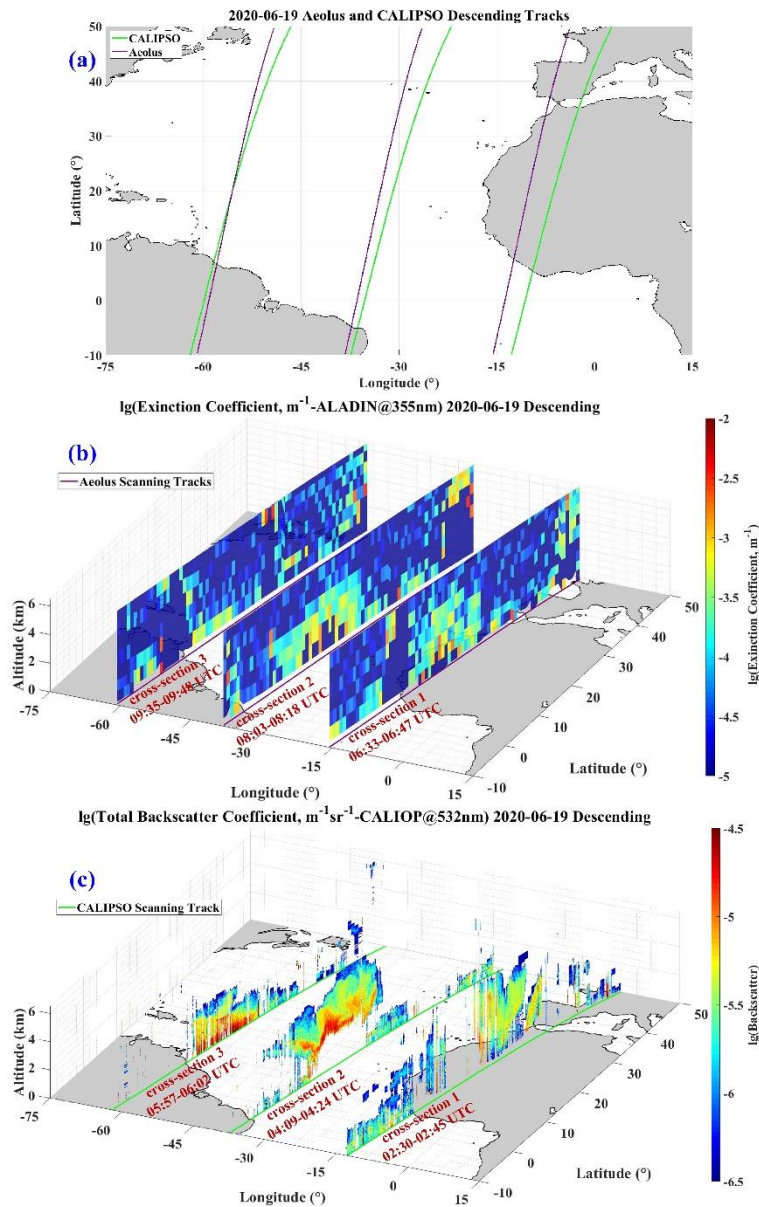






305 **Figure 5. (a)(c)(e) CALIPSO total backscatter coefficient profiles and particle depolarization ratio profiles capturing**  
**dust layers at around 0500UTC-0400UTC 20-19 June 2020. (b)(d)(f) HYSPLIT backward trajectories and forward**  
**trajectories at different sites-positions of corresponding CALIPSO profiles and different heights-altitudes on 0500UTC-**  
**0400UTC 20-19 June 2020. The backward and forward trajectories' durations are both 14496 hours and 192 hours**  
**respectively** (<https://www.ready.noaa.gov/hypub-bin/trajtype.pl?runtype=archive>, last access: 10-23 January-March  
 310 2022).

## 4.2 ~~Measurement case~~ Observation snapshot of the dust plume and dust advection calculation on 19 June 2020



**Figure 6.** Observation ~~tracks~~ cross-sections of Aeolus and CALIPSO on 19 June 2020. The purple lines indicate the tracks of Aeolus and the green lines indicate the tracks of CALIPSO. (a) ~~Vertical view of Aeolus and CALIOP~~ CALIPSO scanning tracks and HYSPLIT trajectories; (b) Extinction coefficient cross-sections measured with Aeolus ALADIN and (c) Total backscatter coefficient cross-sections measured with CALIOP.

In this section, the dust event ~~measurement case that occurred~~ observation snapshot captured by ALADIN and CALIOP on 19 June 2020 is introduced in detail. The quasi-synchronized observations from ALADIN and CALIOP on 19 June 2020 are presented in Fig. 6, where the purple lines indicate the scanning tracks of Aeolus-ALADIN and the green lines indicate the

320 scanning tracks of CALIPSO/CALIOP. It is found that the overpasses of each satellite are only around 3 hours apart. Hence, we captured the dust layers on the morning of 19 June 2020 quasi-simultaneously over the Western Sahara, the Middle Atlantic and the Western Atlantic, i.e., took a snapshot of the dust plumes. From the profiling of dust optical properties, discriminated by the CALIOP measurements, the dust geographical distribution dispersion over Atlantic Ocean on this day could be determined. The extinction coefficients and backscatter coefficients at the wavelengths of 355 nm, 532 nm and 1064 nm within  
325 the dust mass are also determined. From the profiling, it was found that the mean backscatter coefficients at 532 nm were about  $3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “cross-section 1”,  $7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “cross-section 2” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “cross-section 3”. On 19 June 2020, the main part of the dust plume layers was existed over the Western Sahara, the Middle Atlantic and the Western Atlantic quasi-simultaneously, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive.  
330 transported in the free troposphere over the eastern Atlantic, which can be verified in Fig. 3. “Cross section 2” is in the middle of the dust plume, while “cross-section 1” captured the dust layer over the western Sahara, which is the emission region of this dust event. However, the emission intensity of the dust from the emission region became weak on 19 June 2020. Thus, the backscatter coefficients in “cross-section 2” are larger than those of “cross-section 1”. Besides, the backscatter coefficients of the dust layer in “cross-section 3” slightly increased which may result from the fact of its mixture with other aerosol types  
335 (e.g., marine aerosol) near the ocean surface.

Based on the extinction coefficient at 355nm, the backscatter coefficients and extinction coefficients at 532nm and 1064nm, combined with the wind vector data from ALADIN, the dust advection can be calculated. The L2C wind product provided by Aeolus results from the background assimilation of the Aeolus HLOS winds in the ECMWF operational prediction model. The zonal wind velocity (u component of the wind vector, from west point to east), meridional wind velocity (v component of  
340 the wind vector, from south point to north) u and v components of the wind vector and supplementary geophysical parameters are contained in L2C data product. From literature reports (e.g., Lux et al., 2020), the Aeolus L2B Rayleigh LOS winds and the ECMWF model LOS winds show good agreement with a correlation coefficient of 0.92 and mean bias of  $1.62 \text{ m} \cdot \text{s}^{-1}$ . As introduced in Section 3.3, the ECMWF wind field data between the two spaceborne lidars scanning tracks is-are utilized to illustrate the homogeneity of the wind field between two tracks. Hence, in this study, if the wind fields between tracks is stable,  
345 the “analysis\_zonal\_wind\_velocity” and “analysis\_meridional\_wind\_velocity” from the Aeolus L2C wind vector product could be applied for the calculation of the dust advection.

To calculate the dust advection during this event, the wind field and relative humidity information are necessary. Since the observations with ALADIN and CALIOP are not exactly simultaneous, the stability of the wind field between the scanning tracks of them has to be estimated. Hence, the wind speed, wind direction and relative humidity between the tracks are analysed with the data from ECMWF, as presented in Fig. 7. From this figure, the wind speed, wind direction and relative humidity at the height surfaces of 1 km, 2 km, 3 km, 4 km, 5 km and 6 km are shown as examples. From these data, the wind fields and the relative humidity values between the tracks of Aeolus and CALIPSO at the height surfaces of 1 km, 2 km, 3 km, 4 km, 5

~~km and 6 km at all height surfaces~~ are smoothly distributed and the values are stable. Thus, the wind vector data from Aeolus L2C could be applied in the calculation of dust advection. It should be emphasized that, during the calculations of the dust advection, the results with relative humidity higher than 90% have to be removed.

In order to verify the retrieval results of the regularization method, we compare the mass concentration retrieved by the regularization method (the retrieval method) with the results calculated directly using the mass-specific extinction coefficient (the factor method) (Ansmann et al., 2012). According to Ansmann et al. (2012), the aerosol mass concentration can also be calculated by the method that the extinction coefficient at 532 nm divides the mass-specific extinction coefficient. Hence, the reference mass concentration of every cross-sections is calculated with the CALIPSO extinction coefficient at 532 nm along tracks and the Saharan dust mass-specific extinction coefficient ( $0.52 \text{ m}^2 \cdot \text{g}^{-1}$ ). Table 1 shows the mean mass concentration of every cross-section on 19 June 2020 calculated by the two methods. Referring to Ansmann et al. (2012), Ansmann et al. (2017) and Haarig et al. (2019), the mass concentrations of typical dust layers from Sahara vary from  $0.05 \text{ mg} \cdot \text{m}^{-3}$  to  $0.5 \text{ mg} \cdot \text{m}^{-3}$ . Moreover, this dust event is a historic and massive Saharan dust intrusion into the Caribbean Basin and southern US, which is nicknamed the “Godzilla” by Yu et al. (2021). Thus, it should be introduced that in the process of average calculation, the mass concentration values smaller than  $0.05 \text{ mg} \cdot \text{m}^{-3}$  ~~or larger than  $0.5 \text{ mg} \cdot \text{m}^{-3}$~~ , which are unreasonable, are excluded. From the comparison, it can be found that the results from the factor method are larger than the results from the retrieval method. However, considering the errors of these two methods, we consider that the mass concentration estimated by the regularization method is reasonable and acceptable.

**Table 1. Mean dust mass concentration of each cross-sections on 19 June 2020 calculated by two methods**

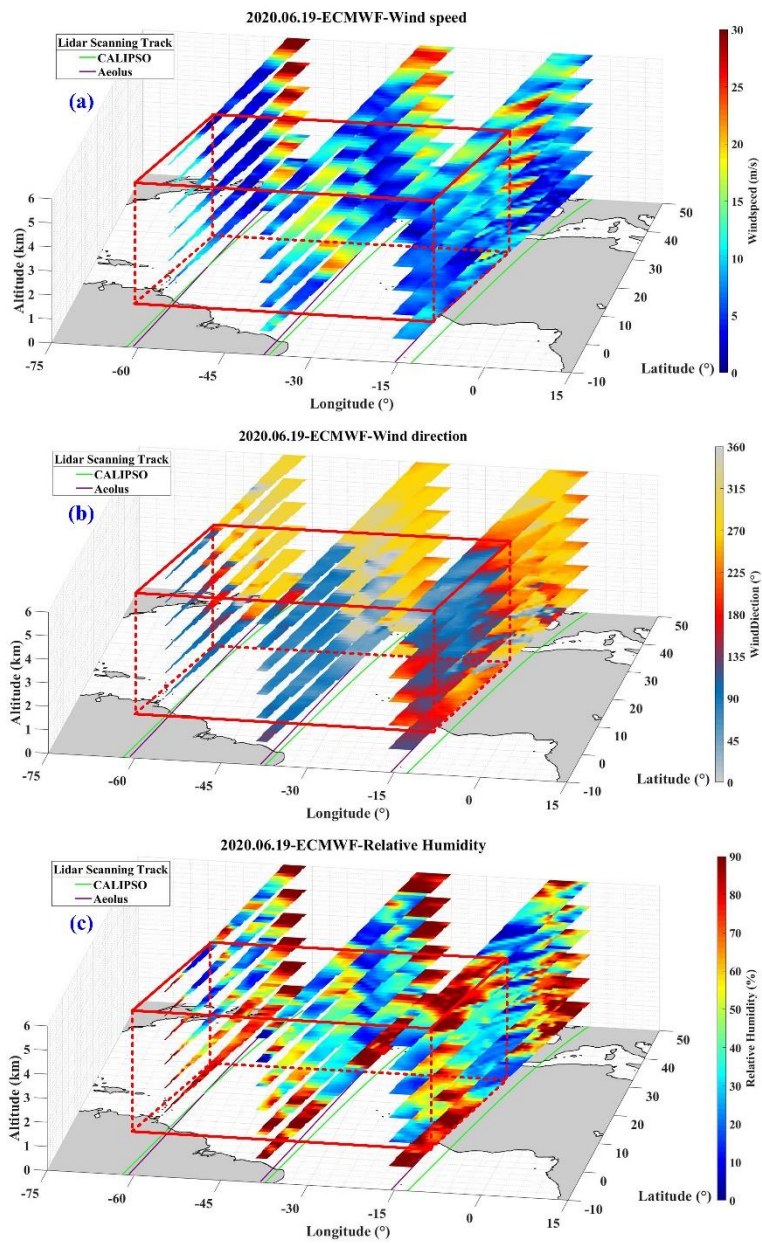
Cross-section	1	2	3
Mean mass concentration, $\text{mg} \cdot \text{m}^{-3}$ (the retrieval method)	<del>0.19</del> <u><math>0.28 \pm 0.23</math></u>	<u><math>0.26 \pm 0.24</math></u> <del>0.17</del>	<u><math>0.22 \pm 0.19</math></u> <del>0.15</del>
Mean mass concentration, $\text{mg} \cdot \text{m}^{-3}$ (the factor method)	<u><math>0.37 \pm 0.24</math></u> <del>0.24</del>	<u><math>0.40 \pm 0.25</math></u> <del>0.26</del>	<u><math>0.39 \pm 0.27</math></u> <del>0.20</del>

In Fig. 87, the dust advection values at different heights of the three snapshot cross-sections are presented. ~~It can be seen that, dominated by the Northeasterly Trade wind between the latitudes of  $5^\circ\text{N}$  and  $30^\circ\text{N}$ , the dust plumes are mainly transported to the west part of the Atlantic Ocean.~~ From the profiling, the mean dust advection value is about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.06 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  in “cross-section 1” (~~dust portion during over the emission phase region~~),  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  in “cross-section 2” (~~dust portion during over the development-transport~~

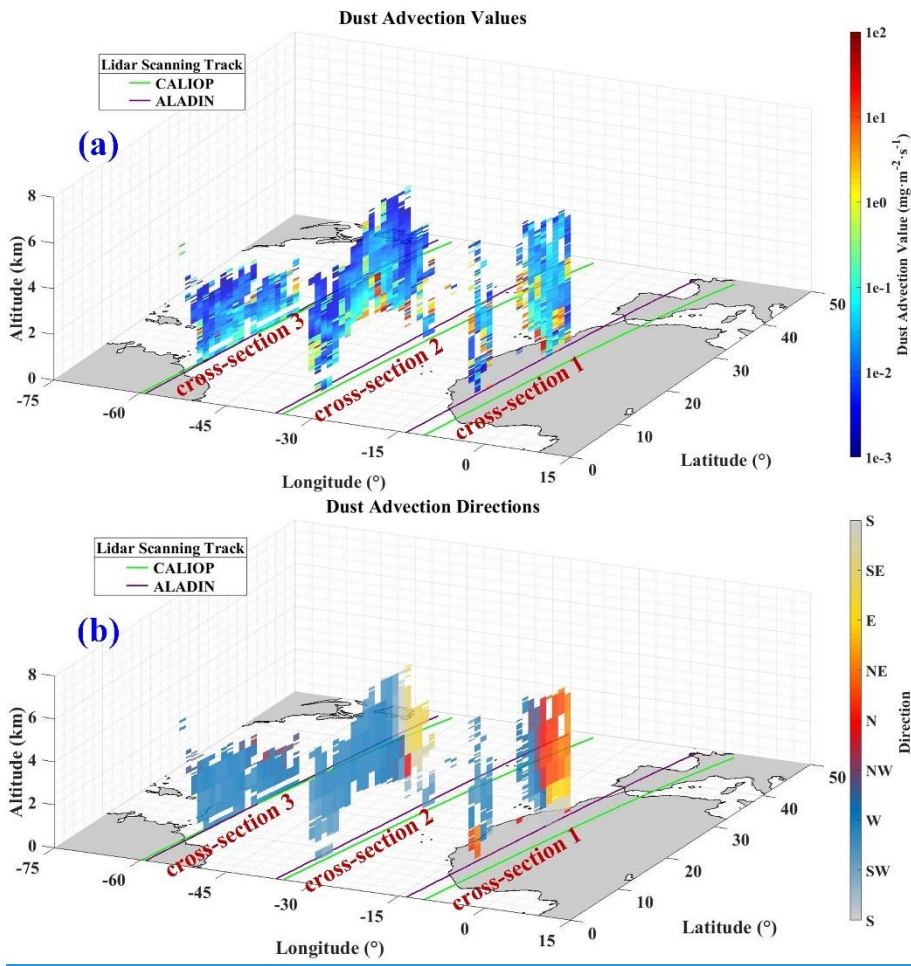
phaseregion) and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$0.95 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  in “cross-section 3” (~~dust portion during over the~~ deposition phaseregion), respectively.

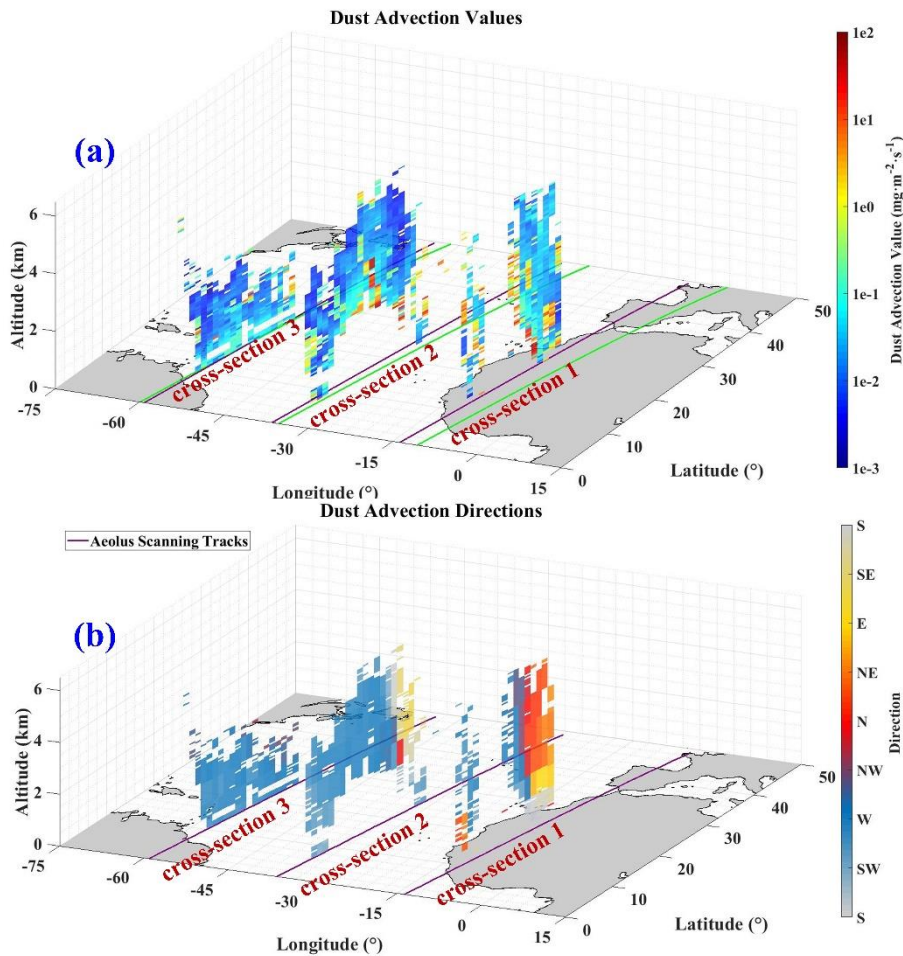
In conclusion, on 19 June 2020, the dust layers over the Western Sahara, the Middle Atlantic and the Western Atlantic are observed by ALADIN and CALIOP nearly in the meanwhile. And the dust advections of the three cross-sections indicate the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on the same day. The lowest value of the mean dust advection appears in “cross-section 3”, perhaps because cross-section 3 is farthest from the source region. During the dispersion and deposition processes of dust aerosol transportation, it is reasonable that the lowest value appears in cross-section 3.

380



385 **Figure 7. The wind speed, wind directions and relative humidity between the quasi-synchronization observation tracks of Aeolus and CALIPSO provided by ECMWF on 19 June 2020. The red frames indicate the transport region of the dust plume.**





390 **Figure 87.** The dust advection calculated with data from ALADIN, CALIOP and ECMWF (a) the dust advection values at different cross-sections of dust plumes and (b) the dust advection directions at different cross-sections of dust plumes on 19 June 2020.

#### 4.3 Dust advection during the lifetime of dust event during 14 June and 27 June 2020

During this dust event, the quasi-synchronized observations with ALADIN and CALIOP were selected to follow the transport and dispersion of dust. The detailed information about the ALADIN and the CALIOP observations on 15, 16, 19, 24, 27 June 2020 along the transport route and the HYSPLIT modelling (which are also presented and analysed in Section 4.1) are shown in Fig. 98. In Fig. 98(a), the scanning tracks of ALADIN and CALIOP on those days are indicated by dark purple lines and green lines, respectively. The HYSPLIT trajectories modelled from the altitudes of 3 km, 4 km, 5 km at position A, B and C (the aerosol profiles of which are presented and analysed in Section 4.1) are shown respectively in Fig. 98a and d. The square symbols in Fig. 98a and d indicate the HYSPLIT trajectories positions corresponding to the 5 cross-sections in time dimension. Additionally, the forward trajectories starting from 19 June and backward trajectories ending at 19 June are modelled and presented in dark red lines and light purple lines, respectively. In Fig. 98(b) and (c), 5 cross-sections of extinction coefficient

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at 355 nm measured at different times with Aeolus and 5 cross-sections of backscatter coefficient at 532 nm measured at different times with CALIOP are plotted, respectively. Additionally, the forward trajectories and backward trajectories and presented in dark red lines and light purple lines in Fig. 98b and c. From these figures, we can find that at different cross-sections of Aeolus and CALIPSO, the dust transport modelled with HYSPLIT match well spatially with the enhanced backscatter and extinction coefficient values indicating the presence of dust ~~dust masses at different cross sections of Aeolus and CALIPSO.~~ In Fig. 98(d), a side view of the HYSPLIT trajectories is shown. Consistent with the observations from ALADIN and CALIOP in Fig. 98(b) and (c), there is an apparent descent along the transport route of the dust event. However, the cross-sections captured by ALADIN and CALIOP do not match completely perfectly with the HYSPLIT trajectories in time dimension. The backward trajectories match well better with the cross-sections on 15, 16 and 19 ~~16~~ June while only the forward trajectories from position A match well with the cross-sections on 24 and 27 June. But the forward trajectories from position B and C are slightly mismatched with the cross-sections on 24 and 27 June. It is considered that there are two aspects of reasons of the mismatch in time dimension. On the one hand, the modelled trajectories present complex transport routes of the dust plumes and meanwhile indicate various transport speed of the dust plumes drove by separate air mass over the Atlantic. On the other hand, restricted by the strict track matching method implemented in this study, several observation cross-sections above the transport regions (e.g., Gulf of Mexico, North America) which also capture dust plumes are rejected. Nevertheless, combined with the “Dust Score Index” data and the HYSPLIT trajectories (analysed in Section 4.1), it can still be concluded that the enhanced backscatter and extinction coefficient regions of the 5 cross-sections 1) track the same dust event, 2) represent the dust layers of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase, respectively.

In Fig. 10, ~~Similarly,~~ the wind speeds, and directions and relative humidity values at certain height surfaces between the tracks of CALIPSO and Aeolus on different days are ~~shown~~ obtained from the ECMWF model. The values ~~and~~ are smoothly distributed and ~~the values are~~ stable. Consequently, Aeolus L2C wind vector product can be employed in the calculation of the dust advection. The relative humidity is presented as well.

Table 2 presents the two sets of mean mass concentration of each cross-sections at different times during the dust transport calculated by the retrieval method and the factor method. Compared with the factor method calculation results, it is considered that the dust mass concentration from the retrieval method is reasonable and acceptable.

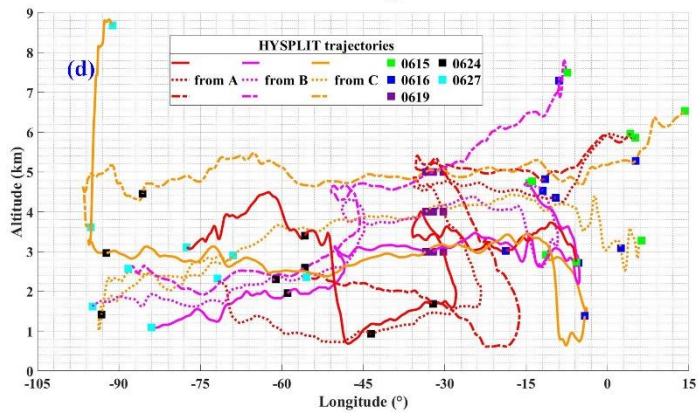
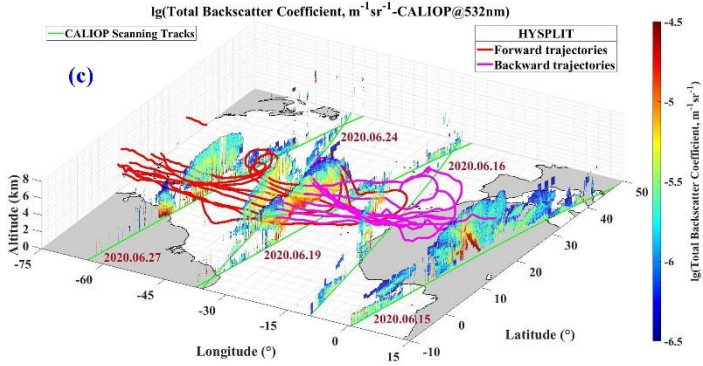
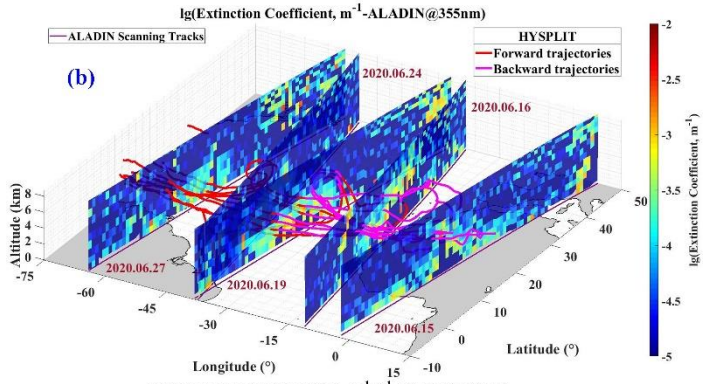
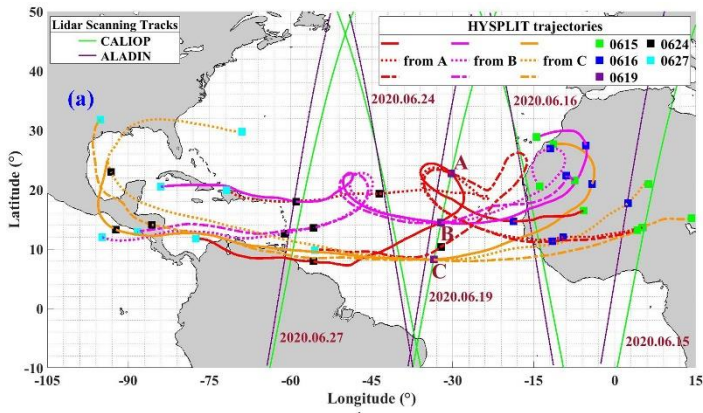
**Table 2. Mean dust mass concentration of each cross-sections at different times during the dust transport calculated by two methods**

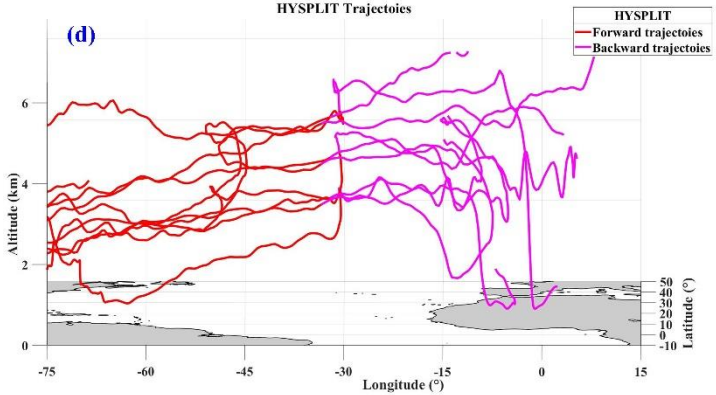
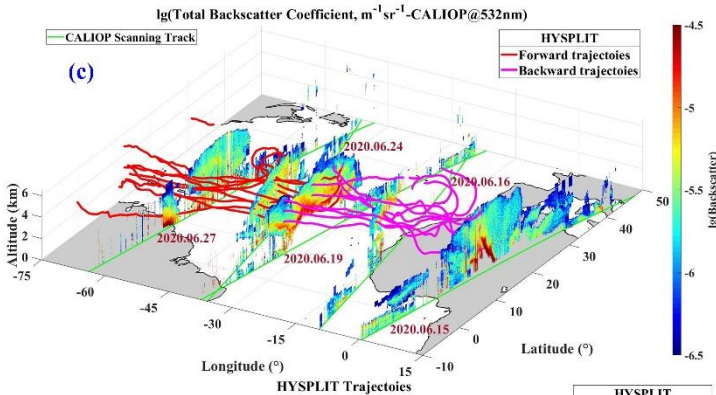
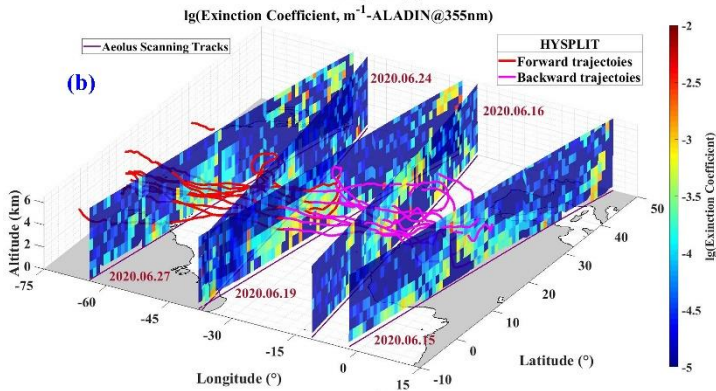
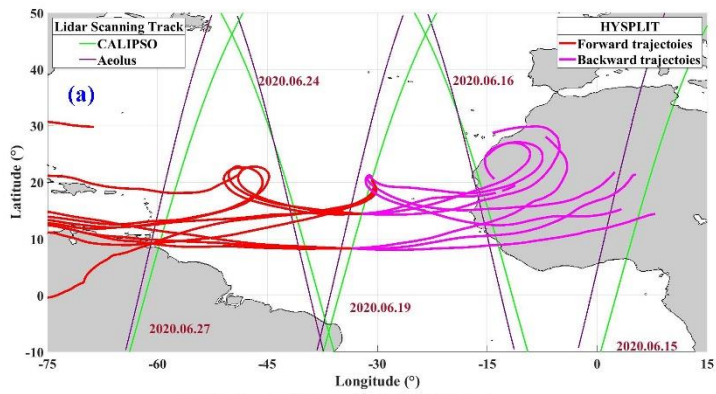
Date	15 June	16 June	19 June	24 June	27 June
Mean mass concentration, $\text{mg} \cdot \text{m}^{-3}$ (retrieval method)	<del>0.19</del> <u><math>0.30 \pm 0.23</math></u>	<u><math>0.27 \pm 0.24</math></u> <del>0.20</del>	<u><math>0.26 \pm 0.24</math></u> <del>0.17</del>	<u><math>0.27 \pm 0.24</math></u> <del>0.19</del>	<u><math>0.22 \pm 0.19</math></u> <del>0.17</del>

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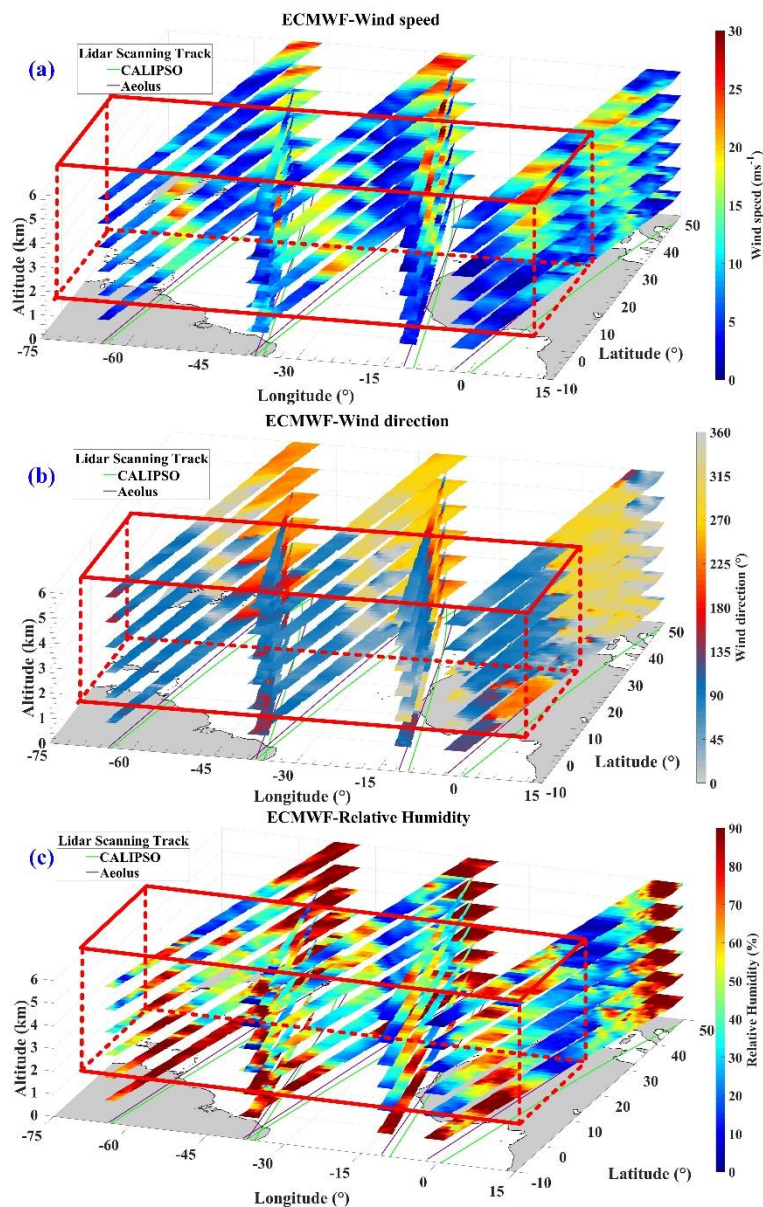
Mean mass concentration, $\text{mg} \cdot \text{m}^{-3}$	<u>0.26 ± 0.17</u>	<u>0.39 ± 0.24</u>	<u>0.40 ± 0.25</u>	<u>0.42 ± 0.21</u>	<u>0.34 ± 0.20</u>
(factor method)	<del>0.23</del>	<del>0.27</del>	<del>0.26</del>	<del>0.30</del>	<del>0.25</del>

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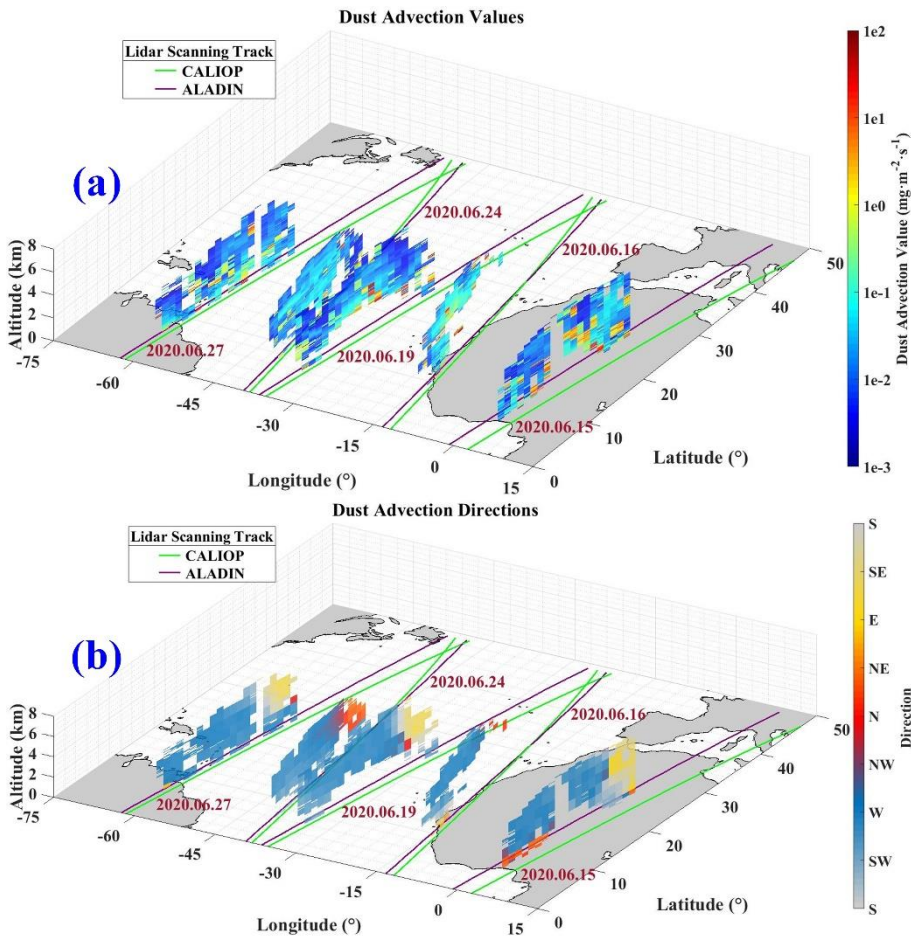


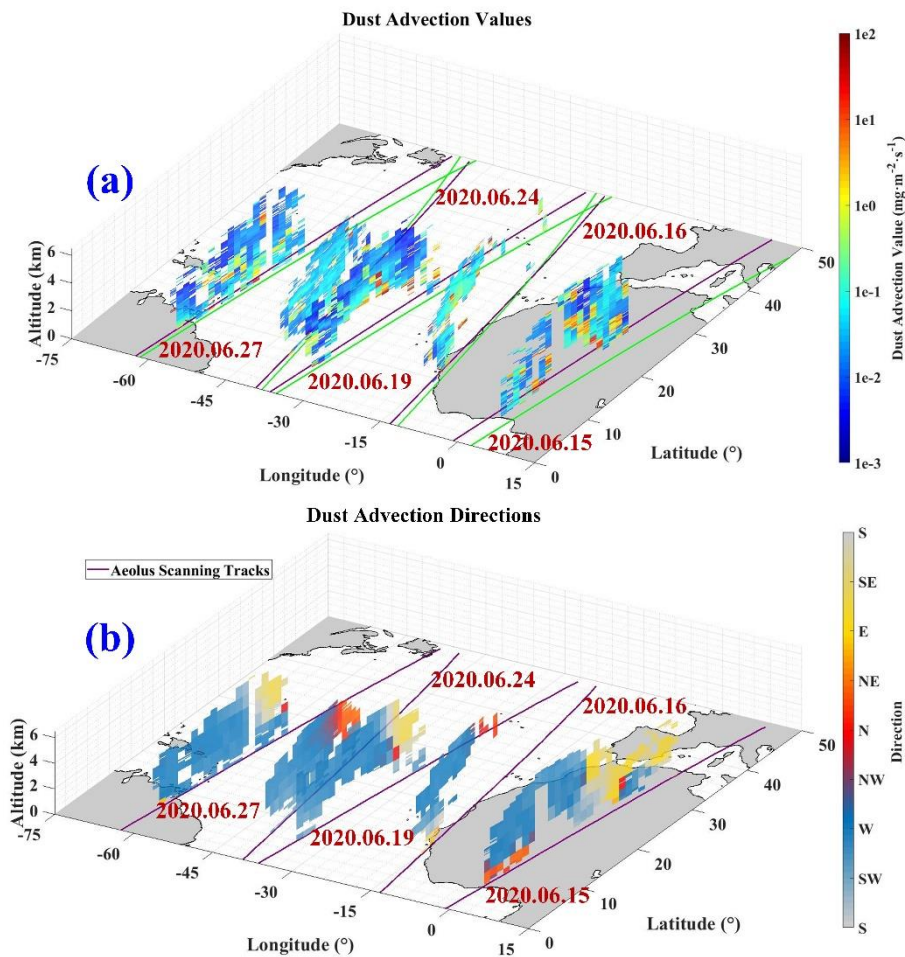


**Figure 98.** Observation of dust event during 15 and 27 June 2020 with ALADIN and CALIOP and the corresponding HYSPLIT trajectories. (a) Vertical view of ALADIN Aeolus and CALIOP scanning CALIPSO-tracks and HYSPLIT trajectories; (b) Extinction coefficient cross-sections measured with ALADIN and HYSPLIT trajectories; (c) Total backscatter coefficient cross-sections measured with CALIOP and HYSPLIT trajectories and; (d) Side view of HYSPLIT trajectories. In (a) and (d), the solid lines, the dot lines and the dot dash lines of the HYSPLIT trajectories represent the trajectories modelled from the altitudes of 3 km, 4 km and 5 km.



**Figure 10.** The wind speed, wind directions and relative humidity between the quasi-synchronization observation tracks of Aeolus and CALIPSO provided by ECMWF. The red frames indicate the transport region of the dust plume.



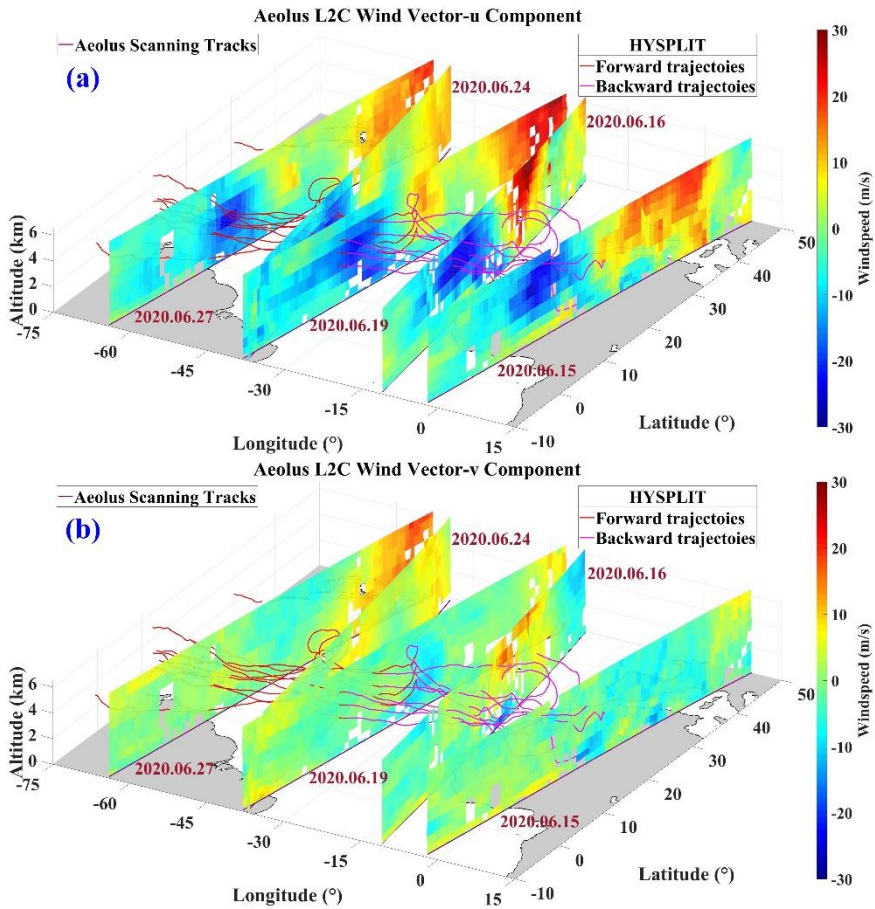


445 **Figure 119.** The dust advection calculated with data from ALADIN, CALIOP and ECMWF (a) dust advection values at different cross-sections and at different times during the dust transport and (b) dust advection directions at different cross-sections and at different times during the dust transport.

In Fig. 119, the dust advections at different heights of all the cross-sections during the dust transport are presented. In Fig. 119(a), the mean dust mass advection values are about  $1.51 \pm 1.03 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.50 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 15 June 2020,  $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.41 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 16 June 2020,  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 19 June 2020,  $1.60 \pm 1.08 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.01 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 24 June 2020 and  $1.03 \pm 0.60 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.15 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~  on 27 June 2020. From this trend, it appears that the mean advection value ( $1.51 \pm 1.03 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  ~~around  $1.50 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~ ) on 15 June when the dust originated is lower than that ( $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  ~~around  $2.41 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~ ) on 16 June. It has to be emphasized that, according to Fig. 98(a), Aeolus and CALIPSO quasi-synchronously observed the dust plumes on 15 June only over part (not whole) of the emission regions. The emission part from West Africa is missed and thus leads to the lower mean dust

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advection value on 15 June than that on 16 June. With the development and enhancement of the dust event, the mean advection value gradually increases and reaches the peak value ( $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  ~~around  $2.41 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~ ) on 16 June. Then, during the transport of the dust plume over the Atlantic Ocean, the mean advectons decreased on 19 June and 24 June. Ultimately, resulting from the dispersion and deposition of the dust plume to the west part of Atlantic Ocean, ~~the Americas~~ Central/South America and the Caribbean Sea, the dust advection on 27 June becomes the lowest ( $1.03 \pm 0.60 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.15 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$~~ ) of the whole dust transportation.



**Figure 1210.** The u and v components provided by Aeolus and the HYSPLIT model for the dust event.

From Fig. 10, the L2C wind vectors including u and v components from Aeolus at different times are plotted. In Fig. 10a, the dust plumes are trapped in the Northeastery Trade-wind zone (indicated by the blue colour at different cross-sections) between the latitudes of  $5^{\circ}\text{N}$  and  $30^{\circ}\text{N}$  and altitudes of 0 km and 6 km. The u component values of the wind vectors in the trade-wind zone are high, reaching  $20 \text{ m} \cdot \text{s}^{-1}$ . Dominated by the trade-wind, the dust plumes are mainly transported to the



west. Therefore, it can be considered that Aeolus provided the observations of the dynamics of this dust transport event in the Saharan air Layer (SAL), which is a hot, dry, elevated layer originating from the Sahara Desert and covering large parts of the tropical Atlantic (Carlson and Prospero, 1972; Prospero and Carlson, 1972). From Fig. 10b, the v component values of the wind vectors are presented as well. Affected by the small wind towards south, the dust plumes are slightly shifted to the south part of Atlantic Ocean in this case.

## 5. Summary and conclusions

In this study, a long-term large-scale Saharan dust transport event that occurred between 14 June and 27 June 2020 is tracked and its mass advection is calculated with the remote measurement data from ALADIN and CALIOP, the reanalysis data from ECMWF, and HYSPLIT. This allows us to (1) evaluate the performance of the ALADIN and CALIOP on the observations of dust optical properties and wind fields and (2) explore the capability of tracking the dust events and in calculating the dust mass advection.

We identified the dust plumes with AIRS/Aqua Dust Score Index and with the Vertical Feature Mask products from CALIOP. The emission, dispersion, transport and deposition of the dust event are followed using the data from HYSPLIT, CALIOP and AIRS/Aqua. With the quasi-synchronized observations from ALADIN and CALIOP, combined with the wind field and relative humidity from ECMWF, the dust advection is calculated.

From this study, it is found that the dust event generated on 14 and 15 June 2020 from the Sahara Desert in North Africa dispersed and moved westward over the Atlantic Ocean, finally being deposited in the west part of Atlantic Ocean, the Americas and the Caribbean Sea. During the transport and deposition processes, the dust plumes were trapped and transported in the Northeasterly Trade-wind zone between the latitudes of  $5^{\circ}\text{N}$  and  $30^{\circ}\text{N}$  and altitudes of 0 km and 6 km (~~we name this space area as “Saharan dust westward transport tunnel”~~). Aeolus provided the observations of the dynamics of this dust transport event in the SAL. From the measurement results on 19 June 2020, the dust plumes are captured quasi-simultaneously over the emission region (Western Sahara), the transport region (Middle Atlantic) and the deposition region (Western Atlantic) individually, which indicates that the dust plume area over the Atlantic on the morning of this day is quite enormous and this dust transport event is massive and extensive. The quasi-synchronization observation results of 15, 16, 19, 24 and 27 June by ALADIN and CALIOP during the entire transport process show good agreement with the “Dust Score Index” data and the HYSPLIT trajectories, which indicates that the transport process of the same dust event is tracked by ALADIN and CALIOP, verifies that the dust transport spent around 2 weeks from the emission to the deposition and achieved the respective observations of this dust event’s emission phase, development phase, transport phase, descent phase and deposition phase. ~~influenced by the hygroscopic effect and mixing with other types of aerosols, the backscatter coefficients of dust plumes are increasing along the transport routes, with  $3.88 \times 10^{-6} \pm 2.59 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “dust portion during emission phase”~~,

~~$7.09 \times 10^{-6} \pm 3.34 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “dust portion during development phase” and  $7.76 \times 10^{-6} \pm 3.74 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1}$  in “dust portion during deposition phase”.~~

Finally, the advection at different dust parts and heights on 19 June and on the entire transport routine during transportation are computed, ~~as shown in Fig. 7 and Fig. 10,~~ respectively. On 19 June, the mean dust advection values are about  $1.91 \pm 1.21 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.06 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  during over the emission phaseregion,~~  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  during over the development transport phase region and  $0.75 \pm 0.68 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   $0.95 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  during over the deposition phaseregion,~~ from which we can infer the quasi-simultaneous transport of the dust plumes over the emission region, the transport region and the deposition region on this day. In the whole life-time of the dust event, the mean dust advection values are about  $1.51 \pm 1.03 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.50 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 15 June 2020,~~  $2.19 \pm 1.72 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.41 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 16 June 2020,~~  $1.38 \pm 1.28 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.47 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 19 June 2020,~~  $1.60 \pm 1.08 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$2.01 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 24 June 2020~~ and  $1.03 \pm 0.60 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$   ~~$1.15 \text{ mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$  on 27 June 2020.~~ During the dust development stage, the mean advection values gradually increase and reach the maximum value on 16 June with the enhancement of the dust event. Then, the mean advection values decrease since most of the dust was deposited in the Atlantic Ocean, the Americas and the Caribbean Sea.

#### Data availability.

The Aeolus data are downloaded via the website <https://aeolus-ds.eo.esa.int/oads/access/collection> (last access: 10 January 2022). The Aeolus L2A and L2C data we used in this paper are not available publicly at the time the article was submitted. We are allowed to access the data through our participation as a Calibration and Validation team. The CALIOP data can be downloaded from <https://eosweb.larc.nasa.gov/project/CALIPSO> (last access: 10 January 2022). The ECMWF reanalysis ERA5 wind data can be accessed from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form> (last access: 10 January 2022). The backward trajectory and forward trajectory of HYSPLIT can be run at [https://www.ready.noaa.gov/HYSPLIT\\_traj.php](https://www.ready.noaa.gov/HYSPLIT_traj.php) (last access: 10 January 2022).

#### Author contributions.

G. Dai and S. Wu conceived of the idea for the dust transport and mass advection measurement with spaceborne lidars ALADIN, CALIOP and model reanalysis data; G. Dai and K. Sun wrote the manuscript; K. Sun, G. Dai, S. Wu, B. Liu and Q. Liu conducted the data analyses; X. Wang helped in programming, X. E downloaded the ECMWF data, and all the co-authors discussed the results and reviewed the manuscript.

## 525 **Competing interests.**

The authors declare that they have no conflict of interest.

## **Special issue statement.**

This article is part of the special issue “Aeolus data and their application”. It is not associated with a conference.

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