ACPD-2021-508

Interactive comment on "Long-term characterisation of the vertical structure of Saharan dust outbreaks over the Canary Islands using lidar and radiosondes profiles: implications for radiative and cloud processes over the subtropical Atlantic Ocean" by África Barreto et al.

Anonymous Referee #2

The manuscript presents the seasonal evolution of meteorological vertical profiles and lidar-derived extinction coefficients using long-term observations in Tenerife. Data were analysed under the clean scenario, the summer-Saharan scenario, and the winter-Saharan scenario. Both dust and water vapour impacts in the radiative balance were investigated.

The ice nucleation processes were also discussed. The dataset is interesting, and the manuscript is well written. The manuscript is worthwhile to be published, after addressing all the points raised by reviewers.

Authors: We acknowledge the referee's positive and constructive comments. Below we respond to his/her general comments.

Please see below some suggestions and comments:

The manuscript is long, and with too many acronyms. The Appendix A helps a bit, but I had to continuously go back and forth to remind myself what all those acronyms represent. Maybe reduce some used of abbreviations, e.g. clean FT (CFT). Besides, it would help if some important abbreviation definitions were added in the figure captions.

This comment is similar to the referee's 1 technical comment #1.

Authors: Following these two suggestions, we have reduced the number of acronyms in the abstract. However, we consider the acronym MPL must be used since it is the common name of the most important instrument used in this study.

> *"Every year, large-scale African dust outbreaks frequently pass over the Canary Islands (Spain). Here we describe the seasonal evolution of atmospheric aerosol extinction and meteorological vertical profiles at Tenerife over the period 2007 – 2018 using long-term Micropulse Lidar (MPL-3) and radiosondes observations. These measurements are used to categorise the different patterns of dust transport over the subtropical North Atlantic and, for the first time, to robustly describe the dust vertical distribution in the Saharan Air Layer (SAL) over this region. Three atmospheric scenarios dominate the aerosol climatology: dust-free (clean) conditions, the summer-Saharan scenario (Summer-SAL) and the winter-Saharan scenario (Winter-SAL).*
>
> ***A relatively well-mixed marine boundary layer (MBL) was observed in the case of clean (dust-free) conditions; it was associated with relatively constant lidar extinction coefficients (α) below 0.036 km^{-1} with minimum α (< 0.022 km^{-1}) in the free troposphere (FT).*** *The Summer-SAL has been characterised as a dust-laden layer strongly affecting both the MBL (Δα = +48 % relative to clean 10 conditions) and the free*

troposphere. The Summer-SAL appears as a well-stratified layer, relatively dry at lower levels but more humid at higher levels compared with ***clean FT conditions*** *($\Delta r \sim$ -44 % at the SAL's base and $\Delta r \sim$ +332 % at 5.3 km, where r is the water vapour mixing ratio), with a peak of α > 0.066 km^{-1} at $\sim$ 2.5 km. Desert dust is present up to $\sim$ 6.0 km, the SAL top based on the altitude of SAL's temperature inversion. In the Winter-SAL scenario, the dust layer is confined to lower levels, below 2 km altitude. This layer is characterised by a dry anomaly at lower levels ($\Delta r \sim$ -38 % in 15 comparison to the clean scenario) and a dust peak at $\sim$1.3 km height.* ***FT clean*** *conditions were found above 2.3 km.*

Our results reveal the important role that both dust and water vapour play in the radiative balance within the Summer- and Winter-SAL. The dominant dust-induced shortwave (SW) radiative warming in summer (heating rates up to +0.7 K day^{-1}) is found slightly below the dust maximum. However, the dominant contribution of water vapour was observed as a net SW warming observed within the SAL (from 2.1 km to 5.7 km) and as a strong cold anomaly near the SAL's top (-0.6 K day^{-1}). The higher water vapour content found to be carried on the Summer-SAL, despite being very low, represents a high relative variation in comparison to the very dry clean free troposphere in the subtropics. This relevant aspect should be properly taken into account in atmospheric modelling processes. In the case of the Winter-SAL, we observed a dust-induced radiative effect dominated by SW heating (maximum heating of +0.7 K day^{-1} at 1.5 km, near the dust peak); both dust and atmospheric water vapour impact heating in the atmospheric column. This is the case of the SW heating within the SAL (maximum near the r peak), the dry anomaly at lower levels ($\Delta r \sim$ -38 % at 1 km) and the thermal cooling (~0.3 K day^{-1}) from the ***temperature inversion*** *upwards.*

*Finally, we hypothesise that the SAL can impact heterogeneous ice nucleation processes through the frequent occurrence of mid-level clouds observed near the SAL top at relatively warm temperatures. A dust event that affected Tenerife in August 2015 is simulated using the regional DREAM model to assess the role of dust and water vapour carried within SAL in the ice nucleation processes. The modelling results reproduce the arrival of the dust plume and its extension over the island and confirm the observed relationship between the Summer-SAL conditions and the formation of mid- and high-level clouds.****"***

We have also reduced the abbreviations in the figure captions:

- ***Figure 1.- Lidar total extinction at each level*** *(mean and median,* ***km above the sea level)*** *and vertical profiles (median) of temperature (T), potential temperature (θe), equivalent potential temperature (e) and water vapour mixing ratio (r) for (a) spring, (b) summer, (c) autumn and (d) winter clean scenarios. The black horizontal broken line represents the IZO altitude. The blue solid line represents the* ***Marine Boundary Inversion*** *(MBI) and the* ***Transition Inversion*** *(TI) tops detected from vertical soundings. The green horizontal line indicates the average 0ºC (isozero) level extracted from vertical soundings. The grey shaded area is bounded by the 20^{th} and 80^{th} percentile values of lidar total extinction at each level. 2D-field of wind profiles with arrows (wind direction) and magnitude in m s^{-1} (color bar) are also presented on the right.*

- ***Figure 2.-*** *The same as Fig. 1, but for Saharan scenarios in (a) summer and (b) winter. Dark and light blue areas in summer indicate the **Trade Wind Layer** (TWL) and the **Marine Boundary Layer** (MBL), respectively. Orange shaded areas indicate the presence of the SAL. Orange shaded areas with black spots in winter indicate a mixture of the **Saharan Air Layer** (SAL) with the MBL.*

- ***Figure 3.-*** *Differences between Saharan and clean scenarios in summer and winter in terms of temperature (T) and water vapour mixing ratio (r), both magnitudes retrieved from radiosondes; and extinction coefficient (α) from **Micropulse Lidar** (MPL) elastic backscatter lidar. Orange shaded areas indicate the presence of the **Saharan Air Layer** (SAL). Orange shaded area with black spots in winter, indicates a mixture of SAL with **Marine Boundary Layer** (MBL).*

- ***Figure 4.-*** *(a) Median potential temperature (θ) and water vapour mixing ratio (r) profiles extracted from the radiosondes, and median lidar extinction (α) profiles, for summer-clean and Summer-SAL scenarios. (b) Diurnal averaged heating rates simulated with Libradtran using MOPSMAP inputs for the scenarios Summer-SAL (solid lines) and summer-clean* (dashed lines). Dust contribution to total heating is also included with dotted lines. The orange shaded area indicates the presence of the **Saharan Air Layer** (SAL), while the dark and light blue areas represent the **Trade Wind Layer** (TWL) and the **Marine Boundary Layer** (MBL), respectively.*

- ***Figure 5.-*** *The same as Fig. 4, but for winter-clean and Winter-SAL scenarios. The orange shaded area indicates the presence of the **Saharan Air Layer** (SAL), while the orange shaded area with black spots indicate a mixture of the SAL with the **Marine Boundary Layer** (MBL).*

In the abstract (l 8) and conclusion (l 600), "it was associated with lidar extinction coefficients ~ 0.030 km-1". Please clarify this "extinction coefficients" (max at which height? mean with standard deviation?). In line 265, you mentioned the maximum in the median extinction profile is ~0.033 km^{-1}.

<u>Authors</u>: We agree with this comment. The sentence is confusing. We propose to change the two sentences with these ones:

> ***"A relatively well-mixed marine boundary layer (MBL) was observed in the case of clean (dust-free) conditions; it was associated with relatively constant lidar extinction coefficients (α) below 0.036 km^{-1} with minimum α (< 0.022 km^{-1}) in the free troposphere (FT)."***
>
> ***"The results of this study have revealed that, in the case of clean conditions, the MBL is relatively well-mixed with α values below 0.036 km^{-1}, and significantly clean conditions are observed in the free troposphere (α < 0.022 km^{-1})."***

l 9 add "+" for 48%

Authors: Done

l 10-11 clarify "lower levels" and "higher levels"

Authors: We agree with this referee comment. The information about the levels is included at the end of the sentence and can be confusing to the reader. We propose to reorder the sentence as follows:

> *"The Summer-SAL appears as a well-stratified layer, relatively dry at lower levels* ***(Δr ∼-44 % at the SAL's base, where r is the water vapour mixing ratio)*** *but more humid at higher levels compared with clean FT conditions* ***(Δr ∼+332 % at 5.3 km)****, with a peak of α > 0.066 km−1 at ∼2.5 km."*

l 128-131 this paragraph is more related to the section 2 "site"

Authors: We have moved this paragraph to the Section 2: Experiment Site.

l 154-158 The full overlap of MPL-3 is at ~ 5km agl. I assume you have applied overlap corrections in this study, was the same overlap correction applied to all profiles? The lower limit of the reliable backscatter / extinction profiles after the overlap correction is 300 m? With the uncertainty of only 10 % near ground? "a relative uncertainty in the overlap correction between 5 % and 10 %", do you mean uncertainty on the NRB or derived optical profiles?

Any vertical smoothing was applied in the profiles?

Authors: During the 12 year period with MPL-3 data a total of 6 overlaps have been performed at Izaña high altitude Observatory, ranging the full overlap altitude from 3.5 to 6.1 km. Different overlaps have been applied to the signal, considering the observed decay in the signal.

The lower limit of 300 m has been set taking into account both uncertainties due to overlap and afterpulse.

Regarding the uncertainty due to the overlap correction. Following Figure 5 in Welton and Campbell (2002), fractional percent uncertainty in the overlap correction is typically lower than 10%, from 3% to 6% between ground level to 6 km, where the full overlap is usually reached. However, following Sicard et al (2020), a non-appropriate overlap function applied in the retrieval of the backscatter coefficient yields errors up to 60% in the first 0.5 km and up to 20% above. We will update this information in the text:

> *"Furthermore, the corrected profiles are hourly averaged to increase the signal-to-noise ratio (SNR). The MPL-3 installed at SCO station achieves a full overlap at an average of ∼5 km. Welton and Campbell (2002) estimated a relative uncertainty in the overlap* ***calculation typically below 10 %. Sicard et al (2020) estimated the errors of applying a non-appropriate overlap function to be up to 60% in the lowermost atmospheric layers and up to 20% above. Due to the overlap effect*** *in addition to the saturation of the*

detector in the near range caused by the afterpulse phenomenon, the information below 300 m is disregarded."

We have not applied any vertical smoothing in the profiles.

l 159-167 LR were estimated using two-layer approach, and then applies to derive extinction coef. What were the LR values? These are interesting information to present.

Authors: We agree that LR is an important information to be included in the text, since these values have been used to derive the extinction coefficients. We propose to include the following information in the text:

Sect. 4.1: "... We used a total of 10658 lidar profiles corresponding to 610 days in the case of the extended spring scenario, 5341 (217 days) for summer, 3842 (240 days) for autumn, and 1532 (136 days) for winter. ***Average LR between 16 sr and 18 sr have been retrieved for the first layer, and between 48 sr and 50 sr for the second layer. These values are in agreement with previous studies performed by Berjón et al. (2019) in Tenerife with the same two-layer analysis.****"*

Sect. 4.2: "... We used a total of 3529 lidar vertical profiles (173 days) for summer, and 2437 lidar profiles (corresponding to 105 days) for winter. The main features of each dust scenario are shown in both Fig. 2 and Table 2. ***Average LR of 19 sr (summer) and 15 sr (winter) have been retrieved for the first layer, and 47 sr (summer) and 51 sr (winter) for the second layer. These LRs are in agreement with the analysis performed by Berjón et al. (2019)."***

What is the error/uncertainty on the derived extinction coefficients? Can it be added in the median extinction profile (e.g. by error bar)? I assume in the overlap region (below 5km), this uncertainty has higher value.

Following Bösenberg and Hoff (2007), typical relative errors in the retrieved backscatter and extinction profiles of 10 % and 20 % are assumed for the combined elastic lidar–photometer technique, which is low enough for climate impact studies. However, as many authors have shown (e.g. Kovalev, 1995; Barnaba and Gobbi, 2001; Pelón et al., 2002; Ansmann, 2006), considerably higher errors may be expected in the case of complex aerosol distributions such as under the presence of different aerosol layers in the vertical or horizontal inhomogeneous aerosol layers. Extinction coefficients have been retrieved in this paper following the two-layer approach published by Berjón et al. (2019). This methodology, an inversion method based on the Fernald–Klett method, combines Micropulse Lidar and photometric information considering two layers of aerosol with two different lidar ratios, one in the MBL and another one in the FT. This method is expected to better match the real lower-troposphere vertical structure of the North Atlantic subtropical region, commonly affected by the presence of a complex vertical layering because of the transport of Saharan dust. Since no specific uncertainty analysis was developed in the mentioned article, and considering this calculation is out of the scope of the present study, it is plausible to estimate the maximum uncertainty in the extinction retrieval at 20%, the highest typical error of the common inversion techniques.

These errors have been estimated without considering overlap. They are expected to be higher when the rest of the source of errors are included, such as the incomplete overlap, which is expected to be more important below the full overlap region.

Fig.1 Mean extinction profile is not in the grey shaded area, especially in fig.1b. Do you have an explanation?

Authors: It is true that, in the clean scenario at summertime above 4 km, mean values exceed the 20-80 percentile area. The authors attribute this departure to the presence of outliers in the extinction dataset at these altitudes, probably due to residual dust recirculated from previous dust outbreaks. In these conditions, ARTI=0 discards that the origin of the air mass in the previous 5 days is over Africa. However, given the high frequency of dust outbreaks in summer time, and considering the low-efficiency wet deposition processes to remove aerosols from the atmosphere in summer, residence time of dust injected above the MBL is considerably higher than in other seasons.

Please specify "lidar total extinction at each level".

Authors: We have added this information in the caption.

Is the height asl in all figures?

Authors: Yes. We have added this information in the caption.

Table2, for winter "and summer" seasons.

Authors: Done

Fig. 4,5 add "523nm" in the caption for extinction.

Authors: Done

l 547 fig.6b not a

Authors: Done, it was a typo.

l 563-564, information was not shown in fig.7b, add the reference of Fig S8 here. "-" are not visible in fig.7b, change the figure as in Fig S8.

Authors: We have modified this sentence as follows:

> *"...The model predicts that most of the dust mass is in a layer between 2 and 6 km, in agreement with the MPL-3. Maximum concentrations (>100 µg/m^3) were reached on the afternoon of 20 August (see Fig. **S8**)..."*

Fig.7 change "nINP"

Authors: Done

l567 m³

Authors: Done, it was a typo.

fig S7, 1h time averaged MPL-3 profile centred on 10:54? please clarify.

add the time for the DREAM extinction profile. What's the shaded area for DREAM profiles?

*Authors: MPL-3 profile was retrieved at 10:54. However, DREAM outputs are recorded every 3h, and therefore +3h (15 UTC) and -3h (9 UTC) DREAM profiles (centered around 12 UTC) are used to determine the shaded area to represent variability of the model results around measurement time. These profiles are bilinearly interpolated to the observation station latitude and longitude, because the model resolution is 0.1*0.1 degrees.*

We have added this information in the figure caption.

References:

Ansmann, A.: Ground-truth aerosol lidar observations: Can the Klett solutions obtained from ground and space be equal for the same aerosol case?, Appl. Opt., 45, 3367–3371, https://doi.org/10.1364/AO.45.003367, 2006.

Barnaba, F. and Gobbi, G. P.: Lidar estimation of tropospheric aerosol extinction, surface area and volume: Maritime and desert-dust cases, J. Geophys. Res., 106, 3005–3018, https://doi.org/10.1029/2000JD900492, 2001.

Bösenberg, J. and Hoff, R.: Plan for the implementation of the GAW Aerosol Lidar Observation Network GALION, Tech. Rep. WMO/GAW No. 178, World Meteorological Organization, available at: http://library.wmo.int/pmb_ged/wmo-td_1443.pdf (last access: 12 December 2018), 2007.

Kovalev, V. A.: Sensitivity of the lidar solution to errors of the aerosol backscatter-to-extinction ratio: Influence of a monotonic change in the aerosol extinction coefficient, Appl. Optics, 34, 3457–3462, https://doi.org/10.1364/AO.34.003457, 1995.

Pelón, J., Flamant, P., León, J. F., Tanrè, D., Sicard, M., and Satheesh, S. K.: Characterization of aerosol spatial distribution and optical properties over the Indian Ocean from airborne LIDAR and radiometry during INDOEX'99, J. Geophys. Res., 107, 8029, https://doi.org/10.1029/2001JD000402, 2002.

Sicard, M.; Rodríguez-Gómez, A.; Comerón, A.; Muñoz-Porcar, C. Calculation of the Overlap Function and Associated Error of an Elastic Lidar or a Ceilometer: Cross-Comparison with a Cooperative Overlap-Corrected System. Sensors 2020, 20, 6312. https://doi.org/10.3390/s20216312.