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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 #1

GENERAL COMMENTS

The study by Barreto et al. focuses on the vertical profiles of aerosol extinction and meteorological variables over Tenerife during Saharan dust outbreaks, compared to clean scenarios. The analysis is based on 12 years of data and is differentiated between winter and summer. The dust layer and the marine boundary layer characteristics are studied separately. The direct radiative effects of both aerosol and water vapour advected during the outbreaks is assessed in both the short- and long-wave ranges based on average profiles. Finally, some considerations about ice nucleation processes are given based on cloud statistics and model results.

Although the paper is quite long and not always a compelling read, it condenses a great amount of information that the interested reader can have all in one place. Hence, the paper deserves publication on ACP. Some marginal comments follow, mainly based on the reviewer's expertise.

Authors: We appreciate these positive comments. Specific comments are addressed below.

SPECIFIC COMMENTS

1. Is the asymmetry factor the best way of representing highly forward-scattering particles? Have the authors checked whether there is any difference if the full phase function is used?

Authors: The authors find this referee's comment interesting. The aerosol phase function is a key parameter to provide information on the angular intensity distribution of the scattered light. This is particularly true in the case of mineral dust, nonspherical particles (with significantly different backscattering properties in relation to spherical particles) with a characterized high forward scattering. However, the asymmetry factor, as an integral property of the phase function, is considered a computationally efficient parameter to replace the phase function in the study of aerosol radiative transfer properties, reducing significantly the efforts to parameterise the phase function (Horvath et al, 2015). As Boucher (1998) stated, parameterizations as the Henyey–Greenstein (HG) phase function, the one used in this study, can advantageously replace the phase function in most flux calculations with a small error, being generally considered acceptable for flux calculations. Following this author, HG phase function slightly overestimates dust forward scattering, and therefore appropriate corrections dependent on the aerosol size distribution, aerosol refractive index, and solar zenith angle should be included to refine the results.

In this paper we have used the scattering properties from MOPSMAP to model the radiative effect of dust, which uses spheres, spheroids, and a small set of irregular particle shapes over a wide range of sizes and refractive indices. Therefore, natural nonspherical aerosol particles, such as desert dust particles, are expected to be correctly modelled in terms of particle backscattering, minimizing the potential errors associated with the effect of the particle shape on the aerosol direct radiative effect calculations. However, additional corrections related to the use of the HG phase function should ideally be included in future studies. The authors have not checked possible differences between full phase and modelled phase functions, but some detailed calculations can be extracted from previous publications (i.e., see Boucher 1998). We have added this information in the Sect. 3.5 of the manuscript:

*“Atmospheric heating rate calculations are performed using the LibRadtran radiative transfer model (Mayer and Kylling, 2005; Emde et al., 2016). The simulations are done with the radiative transfer solver DISORT (DIScrete Ordinate Radiative Transfer) (Stamnes et al., 1988) for spectral ranges of 280 to 4000 nm (shortwave; SW) and 4000 nm and 100 μ m (longwave; LW). The absorption parameterization REPTRAN (Gasteiger et al., 2014) included in the LibRadtran is used in both spectral ranges. Regarding the atmosphere gas composition, we use the standard midlatitude summer atmosphere model (Anderson et al., 1986). The temperature and relative humidity profiles are taken from the monthly or seasonally median profiles obtained from radiosondes (Sect. 3.3). **Henye-Greenstein parameterization is assumed for computation of the aerosol phase function using the asymmetry parameter g as an approximation of the full phase function. Small errors but not negligible are expected from this approximation, generally considered acceptable for flux calculations (Boucher et al., 1998).**”*

2. Have the authors compared the MOPSMAP output to the AERONET-derived aerosol properties within the common wavelength range?

Authors: Following the recommendation of the referee we have compared the AERONET-derived asymmetry factor values for dust in summer conditions (99 days) with the values extracted from AERONET inversions. The results are shown in the following table for the nearest common wavelengths, showing an excellent agreement between the two datasets under influence of mineral dust, which is the main objective of this study.

	<i>g</i> AERONET	<i>g</i> MOPSMAP
440 nm	0.748	0.757
500 nm	0.730	0.744
675 nm	0.742	0.715
870 nm	0.747	0.706

3. As mentioned at line 579, low cumulus clouds prevent observation of higher clouds using the lidar. Could the anticorrelation seen in Fig. 6 between low and high clouds be partly due to this limitation? In the specific case study, an all-sky camera was used to prove the presence of cirrus (not seen by the MPL-3). However, the cloud statistics in Fig.6 only rely on the lidar profiles.

Authors: The sentence “DREAM also predicts INPC on August 22 (from noon time) and 23 but the low cumulus clouds prevent observations of mid-level and cirrus clouds” (lines 578 and 579) refers to a particular case study in two specific days. In reality, with very few exceptions, both the stratocumulus layer and the altostratus/altocumulus layers (middle clouds) do not present a compact appearance. On the contrary, they are usually in the form of scattered clouds, a circumstance that allows the numerous lidar measurements carried out during daytime to detect not only low clouds but also medium and high clouds.

Given the relevance that these results have on the conceptual model of cloud-types distribution under clean and dust scenarios, and in the discussion of Sect. 7, we consider it appropriate to introduce a second approach (included in the supplement) for the determination of the frequency of different types of clouds, totally independent of the results obtained using only MPL data.

We also propose to include a new section to clarify the cloud screening calculation with MPL-3. This new section 3.6 is the following:

3.6. Methodology for obtaining cloud type distribution for dust and clean scenarios

*To determine the distribution of cloud types (low, middle and high clouds) for each clean and dust scenario in the 2007-2018 time period, we have estimated the cloud height using lidar data. Since the MPL system used in this study cannot measure particle depolarization, we are not able to directly estimate the presence of clouds and their respective altitudes. We addressed this issue by means of an indirect technique. We first extracted extinction coefficient values assuming a lidar ratio of 20 sr **in the classical Fernald-Klett inversion procedure**, close to the expected value for mid-level clouds (Yorks et al., 2011). Then, we have identified molecular (particle-free and therefore with the sole contribution of molecules) and aerosol signals **taking into account visibility and empirical thresholds in the value of the retrieved α and its quantile**. The presence of clouds is considered when **an empirical threshold in α is exceeded** and the visibility is reduced to values < 5 km if the molecular layer starts from the surface level (WMO, 2019). **Cloud is also identified when visibility is reduced to values < 10 km if the molecular layer starts above the surface level and empirical thresholds in α and in the 80% quantile of α are exceeded.** “*

In Sect. 7, the information included in the new Sect. 3.6 has been deleted. The text from line 507 to line 538 and Figure 6 have been replaced by the following information:

*Lines 507 y 525: As we have shown in Sects. 5 and 6, both SAL’s dust and humidity anomalies profoundly change the vertical radiative fluxes. **The relative frequency of cloud types from MPL data for both Saharan and clean scenarios, for winter and summer, has been calculated according to Sect. 3.6 in order to explore the effect of SAL radiative impact on cloud formation. The cloud type distribution is shown in Figures 6a and 6b, for winter and summer, respectively.** Analogous plots but from cloud climatological and total sky camera observations at 13 UTC are shown in Figures S6 of the supplementary material. Notice that these two datasets of direct and independent observations from two strategically located meteorological stations on the island of Tenerife (Tenerife North airport meteorological station at 600 m a.s.l. and Izaña meteorological station at 2400 m a.s.l.) are quite consistent with the lidar analysis. A notable reduction of low clouds in the case of the Saharan scenario (winter and summer) in comparison to clean conditions is observed using MPL data (Fig. 6 a and b). On the contrary, a higher occurrence of mid- and high level clouds under the Summer-SAL scenario are observed in Fig. 6 b*

(23 % under Saharan conditions versus 4 % in clean conditions). This pattern is corroborated, at least qualitatively, using direct cloud observations (Fig. S6). Although the reduction in low-level clouds is observed for both Winter-SAL and Summer-SAL, the reduction is more prominent in summer, when the probability of occurrence of low clouds is reduced from 40 % in summer clean conditions to 5 % under SAL conditions (Fig. 6b). In winter, this drop in low clouds is less pronounced, with a reduction from 25 % (winter clean conditions) to ~ 4 % (Winter-SAL conditions).

Lines 538-540: **We can interpret some of the previous results in terms of the impact of dust on heterogeneous nucleation and the role of dust as ice nucleation particles (INP) (Weinzierl et al., 2017).**

New Fig. S6 including subfigures a and b with relative frequency of clouds from the Oktas analysis for Tenerife Norte and Izaña, for winter and summer, respectively.

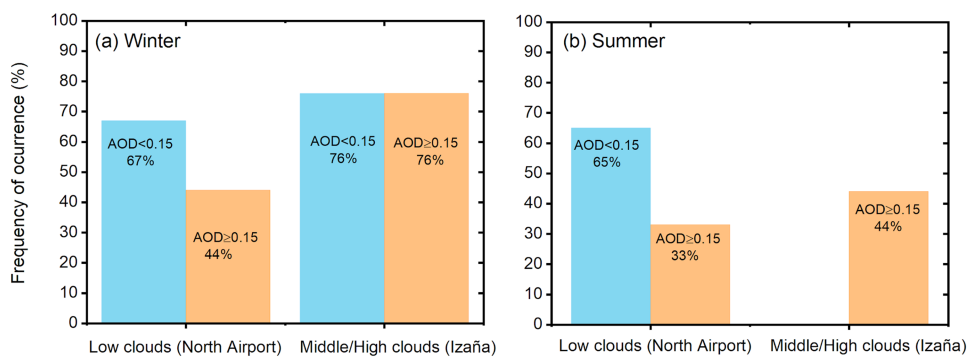


Fig S6. Frequency of occurrence (%) of low and middle/high clouds from the oktas analysis for Tenerife Norte Airport and Izaña Observatory for (a) winter and (b) summer.

New Sect. S5 in Supplementary material:

S5. Cloud observations from direct observations

In the classical approach, cloud observations in the time period 2007-2018 from two strategically located meteorological stations on the island of Tenerife have been used: the meteorological station at Tenerife North airport (WMO 60015) at 600 meters above sea level, excellent location to record low clouds (stratocumulus), and the Izaña meteorological station (WMO 60010) at 2400 m above sea level, permanently free of low clouds and therefore a very good site to observe middle (generally altostratus and altocumulus) and high clouds (cirrus). These two stations are 8 and 31 km away, respectively, from SCO. Climatological and routine observations performed at 13 UTC from Tenerife North airport provide the determination of oktas from trained staff, while an automatic determination of oktas around 13 UTC with a total sky camera was performed at Izaña. Using these two pieces of information we ensure that we can observe medium and high clouds when the low clouds do not allow us to see the first ones from the Santa Cruz station (SCO), at sea level, where the MPL is located. ”

TECHNICAL REMARKS

- **abstract: acronyms should be avoided in an abstract unless a term is used multiple times (e.g., MPL-3 is only used one and other abbreviations only twice)**

Authors: Following the referee's 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 ($< 0.022 \text{ km}^{-1}$) in the free troposphere (FT).** The Summer-SAL has been characterised as a dust-laden layer strongly affecting both the MBL ($\Delta\alpha = +48 \%$ 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 $\alpha > 0.066 \text{ km}^{-1}$ at ~ 2.5 km. Desert dust is present up to ~ 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 ~ 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 $+0.7 \text{ K day}^{-1}$) 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 $+0.7 \text{ K day}^{-1}$ 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 ($\sim 0.3\text{ K day}^{-1}$) 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.”

- I. 54: "studies... study" ("investigation" or "research" can be used instead?)

Authors: Yes, we have modified this text as follows:

“Another problematic point of the current **research** is related to the preferential study of the dust leaving Africa at tropical latitudes in the summer season when the Saharan outbreaks over the North Atlantic are mostly..”

- I. 61-69: The Introduction is very long. Maybe these lines with detailed considerations might be dropped?

Authors: We agree with this comment, these lines have been deleted from the final manuscript.

- I. 78: "Therefore" is used as a consequence of what? It is not obvious that biomass burning aerosol has specific geographical provenance

Authors: We have used the word “Therefore” in the text to express consequence. Based on our experience, dusty air masses getting the Canary Islands in winter are commonly caused by deep lows or cut-off lows that became detached from the mid-latitudes circulation located in the vicinity of the Canary Islands archipelago transporting mineral dust within a relatively short distance (see Cuevas et al. 2021 and references therein). This fast and short-distance transport is commonly originated in the Western Sahara, a desert region with very sparse vegetation, and therefore with a very low probability of being a source of biomass burning aerosols, as confirmed by our analysis of dust composition. This situation contrasts to dust transport in winter in the tropics, often mixed with species linked to biomass burning from the Sahel region during the dry season (Formenti et al., 2003; Capes et al., 2008; Rodríguez et al., 2011).

- I. 98: "from Tenerife" (Tenerife was already mentioned one line above) could maybe replaced by "in the same area"?

Authors: Done

- I. 161-163: information on how aerosol properties at slightly different wavelengths are compared (mentioned at lines 441-443) could be anticipated here

Authors: The information about MOPSMAP provided in lines 441-443 is used to compute diurnal-averaged heating rates. However, in lines 161-163, we describe the methodology to retrieve aerosol extinction profiles from MPL-3 data. The authors think these two are independent pieces of information that have been presented in different sections as it has done in the manuscript.

- I. 183: only arrival altitudes are mentioned. Does ARTI also accounts for the trajectory altitude above the Saharan-Sahel surface?

Authors: ARTI index is computed using 120-hour back-trajectories arriving at two levels, 150 m and 2400 m, which are considered the most representative levels to study air mass long transport arriving at SCO and IZO, respectively. This index expresses the percentage of the time in which the air-mass trajectory is above the Saharan-Sahel surface, so that 0% means that a specific air mass has not passed above the Saharan-Sahel region, and high values of ARTI indicate an African origin of the air mass getting SCO or IZO. So, the answer to the referee is yes, the ARTI index accounts for the trajectory of the air masses above the Sahara-Sahel surface.

- I. 189: it could be anticipated that an additional criterion based on aerosol quantities derived by AERONET (I. 247-250) is also used to identify the dust air masses

Authors: We use in this paper two independent pieces of information to discriminate between clean and dust conditions, described separately in Sect. 3.1 (AERONET) and 3.4 (ARTI). ARTI ensures clean conditions to be met (ARTI=0). This restriction, although very restrictive, ensures that we correctly select clean days. The other one is the AOD and AE extracted from AERONET, to distinguish between clean and dust conditions. The authors consider that anticipating this information in Sect. 3.4 is not enlightening but can add confusion to the reader.

- I. 228: this sentence is too general and unclear. Please, rephrase

Authors: We have clarified the sentence:

“Atmospheric scenarios have been classified using two different and independent techniques: lidar extinction profiles, able to characterize the vertical distribution of aerosols, and atmospheric soundings, necessary to characterize the atmosphere from a thermodynamic perspective. Only daytime lidar profiles and atmospheric soundings (launched at 12 UTC) have been included in this study.”

- I. 267: is the presence of residual dust a sign that 120h is a too short period for the backtrajectory calculations?

Authors: The presence of some residual dust is attributed to the maximum extinction values only sporadically observed in clean conditions during winter. Dust arrival is confined to lower levels this time of the year, as is shown in the paper. The value of 120h was selected as a compromise

between reliably detecting the origin of the air mass and limiting the increasing uncertainty as we go further back in time. The authors consider that, despite this residual dust observed in the winter clean scenario might be minimized using a longer time period, it would be counterproductive in terms of geographical uncertainty.

- I. 267-268: the two sentences are maybe a bit confusing? It sound like both the second extinction maximum and the minimum are located at the same place, i.e. near the MBL top

Authors: The authors agree with this comment. We have changed this sentence.

“Mean and median lidar profiles (Fig. 1) show a rather constant α profile within the MBL, with two secondary maximum values. The first maximum in the median profile, with $\alpha \sim 0.033 \text{ km}^{-1}$, is located at altitudes ranging from 0.6 km in summer to 0.7 km in autumn-winter. Maximum α peak values are found in winter (0.036 km^{-1}), which may be a consequence of the residual dust due to the frequent dust outbreaks at this level in this season. The second maximum ($\alpha \sim 0.023 \text{ km}^{-1}$) is located at ~ 1.5 - 1.7 km height. Minimum α values within the MBL are observed from 1.6 km in summer to 1.3 km in the other seasons.”

- I. 297: what does "500 km above Western Sahara" mean here? Is it "north of"? Same at line 358

Authors: Yes, this sentence is confusing. We propose to change these two sentences with these new ones:

“The temperature gradient in summer in the lower troposphere (e.g. 925 hPa) between Tenerife and a point located 500 km away, in the Western Sahara, is roughly 10 K ...”

“In this season, the temperature difference in the lower troposphere (e.g. 925 hPa) between Tenerife and a point located 500 km away, in the Western Sahara, is barely 2 K...”

- I. 374: please, state the altitude levels used to estimate the temperature inversion

Authors: The calculation of the height and the temperature of the inversion is performed individually (not at averaged levels) in each one of the atmospheric soundings. First, it is detected if there is inversion, when the temperature gradient acquires positive values, that is, the temperature increases with the height, according to the following equation (Carrillo et al., 2016):

$$\Gamma_{i,j}((z_2 + z_1)/2) = \frac{\Delta a_{i,j}}{\Delta z_{i,j}} = \frac{a_j - a_i}{z_j - z_i}$$

Where Γ_{ij} is the lapse rate of the “a” parameter between the z_i and z_j altitude level. The location of inversion layers where temperature lapse rate acquires positive values was considered. If there is an inversion, the base is determined as that point at which the temperature begins to increase with altitude, and the top, where it begins to decrease. At these points (base, top): height, temperature, etc. are determined. Note that the soundings are previously interpolated

linearly every 10 hPa, and that the significant points are collected in the meteorological soundings. See Carrillo et al. (2016) for further details on the temperature inversion determination.

- I. 399-400: "As a consequence" does not refer to the previous sentence, but to the one before. Please, reorder or rephrase

Authors: We agree with this comment. The paragraph has been reworded as follows:

"These r anomalies, although small as absolute values, represent a high relative variation in comparison to the extremely dry FT under clean conditions (Δr up to +332 % at 5.3 km, roughly coinciding with the altitude of the maximum cooling). As a consequence, the SAL appears as a relatively moist layer at mid-levels. The anomaly in α peaks at 2.6 km, where maximum extinction values are commonly retrieved (Fig. 3 (c))."

- I. 427: acts "in" modifying?

Authors: We have corrected the mistake as follows:

*"... this dust-laden layer acts **by** significantly modifying the thermodynamic profiles..."*

- I. 514-519: have the authors validated the cloud screening procedure described, and how? How different are thick Saharan dust layers from clouds, as seen by the MPL?

Authors: The authors have included more information in the manuscript to ensure the validity of this cloud screening. Independent observations of clouds have served as validation, as is written in the new Sect. S5 of the supplementary material (see specific comment #3).

Regarding the thickness of the Saharan dust layers, as seen by the MPL, with a vertical resolution of 75m, the MPL (using the aforementioned cloud screening procedure) is able to detect if a specified bin (layer) is affected by the molecular (Rayleigh) regime, or is affected by aerosols or clouds. The difference between aerosol and cloud is expected to be different from the lidar signal. We have based these differences on empirical thresholds determined in the extinction values (FK inversion assuming $LR=20$ sr), also dependent on visibility. If visibility is lower than 10 km (according to WMO), clouds are identified if the 80% quantile is higher than 0.3912 km^{-1} or relative humidity is higher than 70%, or extinction is higher than 0.3912 . If visibility is lower than 5 km and the layer starts from the surface level, a cloud is identified if extinction is higher than 0.7824 km^{-1} .

We have added a new Sect. 3.6 in the text and more information in the text to clarify this classification (see comment #3).

- Fig. 10: "ln10" --> "log10"

Authors: Done

References:

Horvath, H.: Extrapolation of a truncated aerosol volume scattering function to the far forward and back region, J. Aerosol Sci., <https://doi.org/10.1016/j.jaerosci.2015.08.001>, 2015.

Boucher, O. (1998). On Aerosol Direct Shortwave Forcing and the Henyey–Greenstein Phase Function, Journal of the Atmospheric Sciences, 55(1), 128-134. Retrieved Oct 21, 2021