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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Patterns of Saharan dust transport over the Atlantic: winter vs. summer, based on CALIPSO first year data" *by* B. A. Yuval et al.

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Authors' response to referee # 2

We would like to thank both referees for their beneficial remarks. We have addressed all of the reviewers' comments. We will start with a general comment part addressing two main issues that seems to be less clear in the previous version on the dust horizontal distribution and the method we used to pick the dust distribution, followed by specific reply to the reviewers point by point.

General comments: a) The main objective of this paper is to describe the seasonal vertical distribution of dust emitted from Saharan and Sahelian sources toward the

Atlantic. As the biggest dust source and transport rout, such analysis made by direct measurements has value in many climate aspects such as for the direct dust forcing estimation, dust transport and lifetime, dust interaction and modification of clouds, dust interaction with the ocean biota and with the rainforest as well as effects on air-quality. In this study we show the geometrical properties of the dust layers and the likelihood for interaction with shallow stratiform clouds. It was shown in previous studies that the dust transport routs are significantly different between summer and winter. During the summer the main dust transport rout is from the northern and central Sahara toward North-America while in the winter due to the shift south of the ITCZ the transport rout is shifted as well and the emissions are mainly from the southern Sahara and the northern edges of the Sahel toward the north part of South-America (Kaufman et al., 2005b). Analyzing the same spatial location for both seasons (say between the Sahara to North-America) would yield many dust free pixels in the winter while missing the true southern route. Therefore, in this work we specified first the dust transport routes using the MODIS AOD and aerosol fine-fraction data. This gave us a robust estimation for the area in which most of the transport occurs showing similar horizontal special location to what was shown in previous studies (e.g.: Prospero 1999; Prospero et al., 2002; Herman et al., 1997; Kaufman et al., 2005b, and many others). Indeed as the reviewer wrote there is no spatial overlap in the main dust pathways, this is not new. The aim of the study is to follow the dust plumes wherever they occur and to specify their vertical distribution. This was stressed out in the revised paper in the introduction, lines 127-130: "We characterize the average dust vertical distribution in the summer (2006) versus the dust and smoke in the winter (2006-7) along the main transport route in each season, where the impact of dust upon biogeochemical cycles, climatic processes and human life is the most significant"

b) Using Automatic vs. manual picking of the dust layers and for aerosol classification: The depolarization backscatter data and the automatic aerosol and cloud classification have been used as a first approximation for the dust layer vertical and horizontal detection. However due to the high noise level of the attenuated backscatter data (especially backscatter data acquired during daytime) we could not use a robust threshold value for the detection and for dust/smoke classification processes. When examining the patterns of each LIDAR cross-sections by eye, the dust boundaries were easy to detect and the dust layer edges were mostly robust. Similarly when we tried to use the depolarization data for final aerosol classification over the Atlantic near the Sahel coastline the noise level of most of the data was too high and we could not state if we see only smoke, only dust or a mixture and the classification process, based on this data could not be robust. We were encouraged not to distinguish dust from smoke also based on recent studies that showed that over the ocean dust and smoke are well mixed together (e.g.: Formenti et al., 2008). We have added better explanation to the revised manuscript on the picking of the dust layer in the method, lines 147-159: "For fast classification between aerosol and clouds and in order to mark the top and bottom of the dust layer, we hoped to use either the CALIPSO depolarization product or the Vertical Feature Mask (VFM, Vaughan et al, 2005). However we found out that for such detailed analysis the best results are obtained when the final aerosol layer is mask manually on each profile. Due to the high noise level of the attenuated backscatter data (especially backscatter data acquired during daytime), we used the depolarization product and the VFM as the sources for the initial classifications and then we manually determined the location of the aerosol layer. The data was not used, when the confidence level was low. The classification is based on the different backscatter patterns between clouds and aerosol. While aerosol plumes have relative weak but uniform signature, stratiform (low, marine stratocumulus or higher stratus) clouds have a much stronger and narrower backscatter signal and convective clouds has patchy backscatter pattern"

Additional reference is located in section 2, lines 190-193: "For each backscatter vertical profile within the research area the top and the base of the aerosol plumes as well as the location of the low stratiform clouds were picked (the stratiform clouds are often too thin to distinguish between their bases and tops) manually"

Specific comments: 1. This paper uses CALIPSO data to characterize the altitude

distribution of aerosol transport over the tropical and equatorial Atlantic. It shows a strong contrast between the winter and summer transports. As stated in the paper, while there has been a great deal of research on summer dust events, there is almost nothing about winter transports. The paper finds substantial differences between the winter and summer plume properties – in particular, the height of the aerosol layer top and bottom altitudes. The dynamical causes of these differences and the differences in aerosol source and composition warrant further research. 1. Thanks to this comment we added a part that discuss the dynamical causes for the seasonal differences to the section 4, line 287-292: "Presumably, the elevated plumes are a result of intensive solar heating of the bright Saharan surface that encourage lifting of dust into the deep mixed boundary layer. As the plumes cross the coastline, they override the cooler and moister maritime air layer (Karyampudi et al., 1999). The lower dust layer may be a result of a combination of fresh emission from costal dust sources toward the ocean at low altitude and sedimentation of dust from upper plumes" The seasonal variability of the sources is mentioned in the introduction, lines 68-69: "As a consequence, the location of the dust sources, their activity pattern and the transport routes are affected". Nonetheless, a deeper discussion about aerosol sources and composition is beyond the scope of this paper.

2. A shortcoming of this paper is the inability to distinguish between dust and biomass burning aerosols. This could be a significant problem in boreal winter when biomass burning is prevalent in the equatorial and sub-Saharan regions of Africa. 2. Indeed, during the boreal winter smoke is also transported with the dust and we planned to separate between the two aerosols based on their depolarization properties. This task is very challenging since the classification shown to be ambiguous. Smoke and dust layer are almost always mixed together. Based on elemental analysis of data collected during the recent AMMA SOP0/DABEX and DODO campaign (e.g.: Johnson et al., 2008a; Johnson et al., 2008b Formenti et al., 2008), we were encouraged not to classify dust from smoke. Moreover, Formenti et al. (2008) showed that the mass of aged biomass burning aerosol plumes are dominated by dust. Therefore we considered

the winter plume to be a mixture of dust and smoke. We clarified in section 2, lines 105-114: "Ground based and aircraft measurements from the African Monsoon Multi-dimensional Analyses (AMMA, Formenti et al., 2008), the Dust Outflow Deposition to the Ocean (DODO, Formenti et al., 2008), the SAharan Mineral dUst ExperiMent (SAMUM, Ansmann et al., 2009), and the Dust and Biomass-burning Experiment (DABEX, Johnson et al., 2008a; Johnson et al., 2008b) showed that the winter atmospheric column may contain a multi layers structure of low level dust layer and elevated biomass burning layer that contains dust as well (external mixing of both types of aerosols). Moreover, they estimated the contribution of the dust mass of elevated biomass burning aerosol layer to be extremely high (72 $\pm$16%, Formenti et al., 2008)"

3. Another problem has to do with the ability of CALIPSO to detect the base of the dust layer and to distinguish it from the MBL. 3. We agree with the reviewer that the ability of CALIPSO to detect the base of the dust layer and to distinguish it from the MBL is limited. When the dust or dust-smoke plumes were attached to the MBL we couldn't determine the exact location of the base, in this type of events. Therefore, we clarified in the methods, (lines 195-197) that results of plume bases height and thickness (mainly of the lower plumes) may introduce error: "When the location of the dust plume base was close to the top of the Marine Boundary layer (MBL), we couldn't determine its exact location. Therefore, results of plume bases height and thickness (mainly of the lower plumes) may introduce error". Additional explanation is placed in the caption of figure 5, line 629-630: "Results of plume bases height and thickness (mainly of the lower plumes) may introduce error"

4. The title is not strictly accurate in stating that the focus is "Saharan dust transport". First of all, there is more than dust present in these aerosol events. This is particularly true in winter when biomass burning is very strong in the Soudano region of Africa. In the introduction the authors cite a lot of literature on biomass burning but they essentially ignore it in the body of the paper. 4. We agree with the reviewer that other aerosol types are also present in the studied dust events, especially smoke during the

winter season. Nonetheless, our scientific interest is transport of dust. Therefore, the title of the paper is focused on dust. Since the contribution of the biomass burning aerosol (during the boreal winter) to the transported aerosol loading is significant, we discussed it in the introduction, lines 102-105: "During the winter months the West African Sahelian region is characterized by large areas of biomass burning fires mainly due to agricultural activities. In the same time low level easterly and north-easterly Harmattan winds transport the dust toward the biomass burning regions causing unavoidable external mixing" Later, we explain that during the winter the aerosol events are considered as transport of a joint dust-smoke plumes and we keep our focus on the dust. This explanation is placed in lines 127-182: "We characterize the average dust vertical distribution in the summer (2006) versus the dust and smoke in the winter (2006-7)". Based on this comment we changed the title of the paper to: "Patterns of North African dust transport over the Atlantic: Winter vs. summer, based on CALIPSO first year data"

5. Not all dust comes from the Sahara and the biomass burning is definitely not from the Sahara which they themselves state in the introduction. 5. Thanks to the last two comments, and in order to describe more accurately the origin of the dust, the title of the paper was changed to: "Patterns of North African dust transport over the Atlantic: Winter vs. summer, based on CALIPSO first year data".

6. In the Introduction (and restated in the Methods) they state: "Therefore, during the winter we describe the transport of plumes of dust-biomass burning aerosol mixture." But that point is not elaborated upon in the body. 6. Previus studies (Formenti et al., 2008; Johnson et al., 2008a; Johnson et al., 2008b) have already showed that during the winter the dust is mixed with biomass burning aerosol, as discussed in the introduction. However, the body of the text reflects our scientific objective in the vertical distribution of the dust. During the winter part of the dust plumes are mixed with smoke, and the separation is not possible (especially as the aerosol progress westward). In the winter we analyze dust + smoke as a whole. The relevant reference in

the body of the text is placed in lines 206-207: "... the average heights of the dust and dust-smoke plumes (and clouds) were defined statistically by analyzing the local top height distribution..." Additional explanation is placed in lines 213-214: "In the winter distribution there is a dominant dust-smoke high level plumes with a minor peak in lower altitudes" Additional explanation is placed in lines 238-239: "During the winter the upper dust-smoke plumes are lower and the mean height near the African coastline is..." Additional explanation is placed in line 256: "... the dust-smoke plumes is located south to the maximal AOD..." Additional explanation is placed in lines 263-264: "... suggesting a larger contribution from smoke on the southern part of the average plume..." Additional explanation is placed in line 328: "The winter upper dust and smoke plumes average width is..." Additional explanation is placed in lines 329-330: "A height slope of 23m per 1° longitude yielding dust-smoke plumes top height of..."

7. (With regard to "summer" and "winter", they should qualify, at least for the record, that they are talking about boreal seasons.) 7. This comment was adopted in the abstract, lines 25-27: "In this study the vertical structure of North African dust and stratiform low clouds is analyzed over the Atlantic Ocean for the 2006-2007 boreal winter (Dec - Feb) and boreal summer of 2006 (Jun - Aug)". Similar correction was done in the discussion, lines 280-282: "In this study we used the CALIOP vertical backscattering profiles to examine the seasonal dust height distribution over the Atlantic Ocean during one boreal summer (2006) and one boreal winter (2006-7)"

8. The abstract is rather superficial – it is a broad introduction rather than an abstract in the strict sense. They should put more substance in it. Also they lightly pass over profile work prior to CALIPSO. I would certainly agree that CAPLIPSO provides a huge window of vertical profile characterization. 8. Based on this comment, the abstract was changed: the part that was considered by the reviewer as "superficial" or "broad introduction" was removed from the abstract. In addition, we insert to the abstract part of our results, lines 31-34: "The higher plume top height is 5.1 km, near the African coast line in the summer and 3.7 km in the winter. The lower plume merges with the

marine boundary layer, in both seasons"

9. The paper starts with a considerable review of the history of the study of dust outbreaks. But, as pointed out be another reviewer, the interpretation of their results would benefit from linking more closely to the recent literature from the AMMA and SAMUM campaigns although the latter's focus is a bit too far north to be closely 9. This comment was adapted in the revised text that presents AMMA as well as additional studies. We agree with the reviewer that the SAMUM campaigns focused in the northern part of Africa, and therefore its results are less relevant to our study. The revised text is placed in the discussion, lines 312-315: "Comparison between the above cited AMMA results (that showed low and high concentration of dust in the lower and higher altitude respectively) to our winter results, shows that our results may over estimate the height of the bulk part (in mass) of the transported dust" The comment was also adapted in section 4, lines 293-295: "The average base and top heights of the upper dust plumes found in this study agree with results from previous studies (e.g.: McConnell et al., 2008; Myhre et al., 2003) although some deviations exist". The comment was also adapted in section 4, lines 300-307: "In situ measurements conducted in the western Atlantic (on the edge of the ROI during the summer) (Reid et al., 2002; Reid et al., 2003; Maring, 2003) showed a chaotic vertical structure of transported dust. However, Reid et al., (2003) showed that over the western Atlantic, the chaotic vertical structure of the transported dust was favored with upper and lower (in the MBL) layers. These finding suggest that our difficulties to track the structure of the dust layers over the western Atlantic, was caused by the method of seasonal averaging because of the changing nature of these layers" The comment was also adapted in section 4, lines 316-318: "In situ measurements that represent the winter months (Formenti et al., 2001) showed that the dust may reach South America either in a uniform vertical structure or as several plumes"

10. In contrast to another reviewer, I have no problem with focusing on a seasonal "plume" region. We are, after all, interested in the altitude distribution of the aerosol

in the main transport region for dust-smoke. However I do agree that there should be more of an effort to explain how these differences might arise. 10. Thanks – we tried to make this point clearer in the revised paper, lines 287-292: "Presumably, the elevated plumes are a result of intensive solar heating of the bright Saharan surface that encourage lifting of dust into the deep mixed boundary layer. As the plumes cross the coastline, they override the cooler and moister maritime air layer (Karyampudi et al., 1999). The lower dust layer may be a result of a combination of fresh emission from costal dust sources toward the ocean at low altitude and sedimentation of dust from upper plumes"

Additional explanation is placed in the discussion, lines 296-299: "Towards the western Atlantic Ocean, the apparent vertical structure is less clear, possibly due to descending and sedimentation of the upper layer and the rising of the lower layer (caused possibly by the east-west sea surface temperature gradient and its impact on the marine boundary layer depth)"

Additional explanation is placed in the discussion, lines 308-312: "During the winter season, the bi-modal trend is less clear, the dust is advected off the coastline of Africa in lower altitudes compared to the summer. This may be a result of shallower boundary layer and weaker surface heat fluxes over the Sahel, where the dust is emitted towards the ocean during the winter (compared to the Sahara region where it is emitted during the summer)"

11. Re: 13183-5: "Based on this MODIS data and taking into account the above field experiments results we decided not to distinguish between the dust and the smoke plumes during the winter. Therefore, for the winter analysis, we study the transport of a joint dust-smoke plumes." The authors discuss the use of the depolarization product earlier in the paper (Methods) and then after stating some problems (especially noise) they decline to use it. I can appreciate the problem with this product but it is still useful. In transects of North Africa across the ITCZ into the equatorial regions, one often sees the presence of extremely dense aerosol on both sides of the ITCZ. In the

depolarization product, the southern aerosol just disappears. It would seem that they could use this product at least in a qualitative way to elaborate on their results. 11. The depolarization backscatter data can add significant information that can be used for aerosol classification. However, for detection of the aerosol layer boundaries the noise level of most of the data was too high and in many cases we could not state if we see only smoke, only dust or a mixture. Therefore, the classification process, based only on this data, could not be robust. The explanation to this point is placed in section 2, lines 147-155: "For fast classification between aerosol and clouds and in order to mark the top and bottom of the dust layer, we hoped to use either the CALIPSO depolarization product or the Vertical Feature Mask (VFM, Vaughan et al, 2005). However we found out that for such detailed analysis the best results are obtained when the final aerosol layer is mask manually on each profile. Due to the high noise level of the attenuated backscatter data (especially backscatter data acquired during daytime), we used the depolarization product and the VFM as the sources for the initial classifications and then we manually determined the location of the aerosol layer. The data was not used, when the confidence level was low"

In addition, recent studies showed that over the ocean dust and smoke are mixed together. In this case it was insignificant to distinguish between both aerosol types.

12. Re: 13184: 3 Results 3.1: It seems that the discussion of the altitudes of transport could be improved by linking their results to the literature on both the African side (e.g., AMMA and related studies) and over the western Atlantic (e.g., PRIDE and some of the earlier work in BOMEX, the Carlson and Prospero papers). In particular, a number of the PRIDE papers (e.g., Reid, Maring, etc.) discuss the properties of the Saharan Air Layer (SAL), the distribution of dust, and the relative importance of transport in the SAL and in the MBL. The authors give a rather thorough overview of much of the earlier literature in the introduction but the observations reported in this literature are never really brought into the interpretation of the results in this paper. 12. Thanks to this comment, major revisions were conducted in section 4 (discussion). The revised manuscript in-

cludes interpretation of our results in the frame of results from previus studies. The revised text is placed in lines 312-315: "Comparison between the above cited AMMA results (that showed low and high concentration of dust in the lower and higher altitude respectively) to our winter results, shows that our results may over estimate the height of the bulk part (in mass) of the transported dust" The comment was also adapted in lines 293-295: "The average base and top heights of the upper dust plumes found in this study agree with results from previous studies (e.g.: McConnell et al., 2008; Myhre et al., 2003) although some deviations exist". The comment was also adapted in lines 300-307: "In situ measurements conducted in the western Atlantic (on the edge of the ROI during the summer) (Reid et al., 2002; Reid et al., 2003; Maring, 2003) showed a chaotic vertical structure of transported dust. However, Reid et al., (2003) showed that over the western Atlantic, the chaotic vertical structure of the transported dust was favored with upper and lower (in the MBL) layers. These finding suggest that our difficulties to track the structure of the dust layers over the western Atlantic, was caused by the method of seasonal averaging because of the changing nature of these layers" The comment was also adapted in lines 316-318: "In situ measurements that represent the winter months (Formenti et al., 2001) showed that the dust may reach South America either in a uniform vertical structure or as several plumes"

13. I agree with the general conclusions about the contrasts between the winter and summer transport regarding the overall thickness of the layer and the altitude distribution. A group of us obtain similar results with CALIPSO which we present in a submitted paper which focuses on a broader range of variables associated with these winter summer transport events. But I am less confident of the lower boundary results in CALIPSO for a number of reasons. One problem is the ability to discriminate between dust and sea-salt in the MBL. The other has to do with the attenuation of the incident and backscattered lidar beam; this would vary with the total column aerosol loading. This is particularly evident in Fig. 5 which shows the base of the summer SAL along the coast of Africa at about 1.5 km altitude. This is considerably higher than that obtained in earlier work (e.g., Karyampudi, Carlson, Westphal). Soundings along the

coast and in the Cape Verde Islands suggest much lower altitudes for the base of the SAL layer. In addition there is much evidence of low-level transport along the coast as well which is not seen in this figure. Thus the authors err in relating the height of the base of the SAL as they depict it, linked with the depth of the MBL. 13. a. We agree that the identification between dust and sea-salt in the MBL is a challenge. In order to avoid misclassification, the boundaries of the MBL were defined based on the location of the marine stratocumulus clouds (MSc). Aerosol tops height located below the MSc (namely sea-salt) were not included in the seasonal average height calculations. Nonetheless, we agree that results of plume bases height and thickness (mainly of the lower plumes) may introduce errors. We clarified it in the methods, lines 195-197: "When the location of the dust plume base was close to the top of the Marine Boundary layer (MBL), we couldn't determine its exact location. Therefore, results of plume bases height and thickness (mainly of the lower plumes) may introduce error" Additional explanation is placed in the caption of figure 5, lines 629-630: "Results of plume bases height and thickness (mainly of the lower plumes) may introduce error"

b. The presented results represent the average seasonal trend. We find that the results of the summer base height are in line with previous studies such as Carlson and Prospero (1972) who proposed that the dust departs the African coastline approximately between 850-550 mb, and Karyampudi et al (1999) who showed that the base height has latitudinal shift, and that it may vary between 1-2 km. c. The low level transport of dust is one of the main points in our study. Due to the expected error in the bases of the lower dust plume, the bases of the lower dust plumes are not presented in figure 5b.

14. Re Fig. 2. Aerosol optical properties over the Atlantic Ocean, for the 2006 summer (upper row) and 2006–2007 winter (lower row), from the MODIS instrument onboared Terra. Left column: the aerosol optical depth (at 550 nm). Right column: the aerosol fine mode fraction. The contours mark the center of the seasonal plume. I don't understand how the center of the ROI (plume) was defined in right column bottom (winter).

14. Reduction in the fine fraction mode (figure 2, right column) may indicate a presence of larger size aerosol, presumably dust. During the boreal winter, the signature of the dust was blurred by fine mode aerosol (smoke). Therefore, the ROI was selected (mostly) based on the AOD map (figure 2, left column) and on previous cited studied that detect the location of the dust during the winter months (e.g.: Prospero 1999; Prospero et al., 2002; Herman et al., 1997; Kaufman et al., 2005b, and many others).

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