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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 # 1

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. Summer and winter transports for different areas are compared

(winter apples with summer oranges). So, what do we learn when we compare different transport regimes for different seasons of the year? What is then the message? This is confusing and needs to be improved. 1. The reason why we selected the study area is a key point of the paper and we addressed it above in the general comments part. We have stressed this point 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" Comparing the same area for the summer and winter (say over the summer rout area) will result in dust clean data during half of the time.

2. Title: ..is to my opinion misleading, because during the winter season the investigated area is mainly from 0 to 10_ N, and in this area smoke (50% or more) mixed with dust (50% or less) is observed. During the summer season, the area is from 10-20_N (so different from the winter area, no overlap). In summer only dust is transported from Africa. Please check the JGR 2008 AMMA papers and the SAMUM papers. 2. Smoke is also transported with the dust. This point was stressed in the text in different places: a) Section 1, lines 127-128: "We characterize the average dust vertical distribution in the summer (2006) versus the dust and smoke in the winter (2006-7)"

b) Section 2, lines 182-185: "the high AOD (contributed mainly from dust and smoke, but also from marine aerosol) area of the winter flux is shown to have lower fine mode values surrounded by higher fine-fraction contributed by smoke from the southern parts of Africa and Brazil and pollution form North America"

c) Section 2, lines 188-189: "Therefore, for the winter analysis, we study the transport of a joint dust-smoke plumes"

Our main interest is the dust transport. Previous studies showed that during the winter months, the aerosol loading is characterized with multilayer structure, mainly composed of dust and smoke. However, there are evidences that the smoke layers are loaded with dust (e.g.: Formenti et al., 2008). Therefore, since we are following the transport of dust, we are also forced to follow the smoke. We have clarified this point in the introduction to, lines 105-115: "Ground based and aircraft measurements from the African Monsoon Multidimensional 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). Therefore, during the winter we describe the transport of plumes of dust-biomass burning aerosol mixture"

3. Abstract: ..is misleading. It is not true that the vertical distribution of dust is studied mostly by in situ measurements and models. There have been several activities (SHADE, PRIDE, ACE-2 papers on vertical Saharan dust profiling, recent AMMA and SAMUM activities), there are several lidar networks (Asian Dust Network, EARLINET in Europa) focussing on dust transport, we had the Space Shuttle lidar LITE in 1994. So, it is not true, that CALIPSO is something like the starting point for dust profiling. 3. We did not meant to say that before CALIPSO there were no vertical dust measurements. We made it clearer in the introduction, lines 116-119: "Until the launch of CALIPSO, the vertical distribution of dust over the Atlantic Ocean was studied mostly by short term in-situ (e.g.: McConnell et al., 2008; Reid et al., 2003) and remote sensing (e.g.: Karyampudi et al., 1999) measurements as well as models (e.g.: Schepanski et al., 2009)" However, those experiments were conducted during relatively short time periods. As for the lidar long term networks, the Asian Dust Network and EARLINET, they don't have stations in the Atlantic Ocean. SPALINET covers only a limited area in the northern Atlantic, and LITE was operated for 53 hours only. Over the Atlantic Ocean, none of the above is comparable to the temporal and spatial coverage of CALIPSO that

may mark a starting point for large statistics over the Atlantic Ocean.

Introduction: 4. Page 13178, line 25, regarding the dust transport to South America. . ., it seems to me that also a lot of smoke is traveling west, to Brazil (see Kaufman 2005, Ansmann 2009). 4. Indeed smoke and other types of aerosols, like marine aerosols are transported westwards. This was mentioned in the introduction in details (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 mixing"

The subject is mentioned again in section 2, lines 182-183: "the high AOD (contributed mainly from dust and smoke, but also from marine aerosol) area of the winter flux"

And again in section 2, lines 188-189: "Therefore, for the winter analysis, we study the transport of a joint dust-smoke plumes" 5. Page 13179, Line 15. . ., please check the Schepanski paper, ACP 9, 2009. 5. Schepanski et al (2009) was added to the revised manuscript in the introduction, lines 72 and 96: " Schepanski et al., 2009"

6. Page 13179, line 25, dust may extend up to 8 km . . ., I don't believe. Did you find hints for that also when you analyzed the CALIPSO observations? 6. The sentence was removed from the revised manuscript.

7. Page 13180, line 19, long range transport across the North Atlantic, check Ansmann 2009. 7. Ansmann's paper is referenced in the revised manuscript in the introduction, line 108: "Ansmann et al., 2009"

8. Page 13180, line 25, add recent SAMUM activities regarding multilayer structures, a Page 12180, line 29, Tesche JGR 2009 SAMUM paper focuses on smoke/dust mixtures 8. The SAMUM activity is described now in the revised text in the introduction, lines 105-111. "Ground based and aircraft measurements from the African Monsoon Multidimensional 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. . ."

9. Page 13182, line 22, there is also a lot of dust travelling westward and leaving Africa north of the fire areas at heights below 1.5km, Of course, dust is also transported south and crosses the fire areas before leaving Africa. 9. We agree that dust traveling also westward and leaving Africa north of the fire areas. Nonetheless, Haywood et al. (2008) showed that the biomass burning aerosol that originated from the Sahel can be transported northwards, and the smoke may mix with the northern, relatively pure dust plumes. Therefore, during the winter months we consider each plume as mixture of dust and smoke.

10. Page 13182, line 28, if there is biomass burning than there should be a strong contribution of smoke to the AOD, check the AMMA/DODO and SAMUM papers. 10. During the winter there is a major contribution of smoke to the AOD. The suggested papers were already mentioned in the text (in the introduction, lines 107-110, an in the discussion, lines 312, 316). The contribution of other aerosol to the AOD was further clarified in the revised manuscript in the introduction, lines 176-177: "The summer dust transport route is clearly shown in an area characterized by high AOD levels (contributed mainly from dust but also from marine aerosol) ", and in lines 182-183: "Nevertheless, the high AOD (contributed mainly from dust and smoke, but also from marine aerosol)" 11. Page 13183, line 6: Please provide a clear definition of how you identified the top and base heights of the lofted dust layer . . .by eye? by applying a threshold value for the range-corrected signal? Please state! 11. As we explained in the general comments part, the initial detection of the boundaries of the aerosol layer was done by using the total backscatter. Due to the high noise level of the attenuated backscatter data (especially backscatter data acquired during daytime) we could not use robust threshold value for the detection processes. However 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. We added a better explanation to the revised manuscript in the methods 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" Additional explanation is placed in lines 155-160: "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. The total attenuated backscatter at 532 nm data has shown the best contrast and served as the main reference data for classification"

12. Page 13186, line 1: Figure 7 only includes low clouds, what's about altocumulus and cirrus layers between 4-15 km height. Please state clearly that you only show low cloud. The clouds top height distribution included only shallow and mid-level clouds. 12. The clouds that were sampled for the cloud top height distribution included only low startiform clouds, including stratocumulus and stratus clouds with top height lower than 2.5 km. This point was clarified in the title of section 3.2: "3.2 Low stratiform clouds" and in the caption of figure 7, lines 640-641: "CALIOP samples covered only low clouds (lower then 2.5 km)". And in the beginning of section 3.2, line 267: "The examined clouds were low clouds (including Stratocumulus and Stratus clouds)"

13. References: There are many citations of so-called 'grey' literature: Tanaka 2008, Vaughan et al. 2004, Wendisch et al. 2008, Winker and Pelon 2003. There will

be a special issue on CALIPSO in JAOTech and another one in JGR. May be one should contact Winker for more information on that, he is certainly able to provide better CALIPSO-related references. 13. Thanks to this comment the references list was updated in the revised manuscript. The changes: Winker and Pelon 2003 was substituted with Thomason et al., 2007. Tanaka 2008, was substitute with Cakmur et al., 2006. Wendisch et al. 2008 was substituted with Haywood and Boucher, 2000. Vaughan et al. 2004 was substituted with Vaughan et al. 2005.

14. Page 13193, Figure 2: I am not convinced that the plume south of Central Africa mainly consists of dust, when keeping all the AMMA results in mind. According to MODIS the optical depth of 0.6-1 (red color) is caused by roughly 60% of dust and 40% of smoke, in this area with heavy biomass burning plumes? This must be wrong! Please check. How large is the error in the MODIS products? 14. The selection of our region of interest (ROI) for the winter months was based on the location of the seasonal dust plume, as observed in previous remote sensing studies (e.g.: Prospero 1999; Prospero et al., 2002; Herman et al., 1997; Kaufman et al., 2005b), in-situ observation (e.g.: Haywood et al., 2003), and MODIS data. In addition, according to elemental analysis of data collected during AMMA SOP0/DABEX and DODO campaign (Formenti et al., 2008) dust is dominating the biomass burning aerosol by mass. We clarified this point in the introduction, lines 112-114: "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)".

MODIS error: MODIS data (e.g. AOT and aerosol fine mode fraction) was already validated with AErosol RObotic NETwork (AERONET) ground-based sunphotometer network, over land as well as over the ocean (e.g.: Remer et al., 2002). Over the ocean the error of the AOT is smaller then 10%. In the present study we used MODIS data, only as source for initial identification of the spatial and seasonal distribution of dust over the ocean. The distribution of the dust was also validated with results of previous remote sensing studies (e.g.: Prospero 1999; Prospero et al., 2002; Herman

et al., 1997; Kaufman et al., 2005b). Recent in situ measurements, conducted during AMMA and the DODO field experiment (Formenti et al., 2008) showed that even aged biomass burning plumes are dominants (in mass) with dust.

15. Page 13194, Figure 3, there are many clouds at heights above 2-3 km height. But they are not included in the cloud statistics in Figure 7, as mentioned. 15. Figure 3 is an example for the differences between the aerosol and cloud signature on CALIOP profiles. Mid and high level clouds (higher then 2.5km) were not collected, and therefore they are not included in the statistics in section 3.2. We clarified this in section 3.2, line 267: "The examined clouds were low clouds (including Stratocumulus and Stratus clouds)", and in the caption of figure 7, lines 640-641: "CALIOP samples covered only low clouds (lower then 2.5 km)"

16. In the lower plot of Figure 3, the identification of the dust-smoke layer base height seems to be impossible. How did you overcome that problem? 16. Indeed in this type of events we couldn't locate the exact location of the layer base. This issue was discussed in the method, 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 reference to the expected error was 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".

17. Why not comparing SAME CALIPSO flight tracks (during winter and summer) to better compare summer and winter transport modes over the tropical Atlantic. There is no longitudinal overlap of both color plots. The upper one belongs to a flight track segment north of 8_N (shows the northern hemisphere), the lower one belongs to a track segment south 0_ N (shows the southern hemisphere, winter season, has almost nothing to do with the Saharan dust transport). So, nothing can be compared. Just two very different color plots are shown! Must be improved! 17. As we explained in the general comments part, in this analysis we followed the main dust transport

routes and since the general circulation is significantly different in the winter compare to the summer the transport area is different. Comparison of the same (LAT LON) location would yield many pixels with no significant dust content. Thanks to the reviewer comments, we clarified this issue 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"

18. Page 13195, Figure 4: Again, both rows are almost not comparable. The upper histograms show the top height distribution in summer for the latitudinal belt from 10-20_N (two modes for the area close to Africa, one is certainly just the MBL top height), the lower histograms show the top heights of the dust-smoke dust layers for the belt from 0 to 10_N. So, what do we compare here, what is the message when comparing different, not overlapping transport regimes? 18. As we follow the general seasonal circulation of the dust route (and as shown by previous studies, e.g.: Prospero 1999; Prospero et al., 2002; Herman et al., 1997; Kaufman et al., 2005b), our study focused on regions were the dust has the most impact on climate aspect such as the direct dust forcing estimation, the indirect impact of dust on clouds formation, supplying of minerals to the biosphere (Amazon Basin and phytoplankton) and changes of the ocean albedo. MBL top height: The height of the MBL affected from the thermohaline circulation, namely from the sea surface temperature. Along the central part of the western Atlantic Ocean, the sea surface temperature is characterized with high temperature and therefore the height of the MBL may reach several km. Closed to the African coast, sea surface temperature are less affected from the hot surface stream, and the height of the MBL is only a few hundreds of meters (Augstein et al., 1974). Figure 4 (between 26°-16° W) shows the signature of the MBL up to ~0.8 km. Nonetheless, it is most likely that the rest of the samples of the lower mode (approximately between 0.8-2.7 km) are donated by dust.

19. I think the dust is below 1500m height in the belt from 10-20_N in winter. This not presented in the paper at all. But this would be, to my opinion, the most interesting message, see the Schepansky ACP 2009 paper and the sketch in Figure 1 of that paper. Smoke and dust transport in winter and just dust transport in summer is the other important difference (as mentioned in the paper). All in all, the paper does not provide a satisfying picture of the summer/winter differences in the aerosol transport across the Atlantic west of Africa. CALIPSO observed all this! 19. Indeed during the winter season the height of the dust is low. Until the last few years the height of the dust layer (over the Atlantic Ocean) was estimated mostly by models, as well as by spares in-situ measurements. Here we present the seasonal averaged height distribution that was based on large statistics (more then 800 vertical profiles). In some cases or in other regions the dust may transport in lower altitudes. Particularly, it may be true for the suggested spatial location (10°-20° N) that is located on the northern edges of the dust pathway as it transported during the winter.

20. Page 13196, Figure 5: Here the same could be mentioned what was mentioned above regarding comparisons of results that cannot be compared. 20. As we explained in the general comments part, in this analysis we followed the general circulation of the main dust transport over the Atlantic Ocean and over seasons. Comparison of the same regions in different seasons would yield many vertical profiles with no presence of dust. The comparison enables to keep the focus on regions were dust has the most impact upon biogeochemical cycles, climatic processes and human life.

21. Another problem. I have my doubts, that CALIPSO permits an accurate determination of the base height (even if the base is separated from the MBL top) because of laser pulse (and backscatter signal) stretching by multiple scattering. So to my opinion, the lower boundaries of the layers in Figure 5 is just speculation. Should be clarified. Furthermore, I do not understand, what the lower figure in Figure 5 shows. How is that compatible to the upper plot (base height)? 21. We agree that results of plume bases height and thickness (mainly of the lower plumes) may introduce errors. We clarified it

in the methods, line 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 reference 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" The difference between Figure 5a and 5b is that while figure 5a shows the average top and base heights (of the upper plume), figure 5b shows only the average top heights (of the lower plume). Since we expect errors in the estimation of the lower plumes base heights it is not present in Figure 5b. We better explain it in the caption of figure 5, lines 629-631: "Results of plume bases height and thickness (mainly of the lower plumes) may introduce error. Due to the expected error the bases of the lower dust plumes are not presented in figure 5b".

22. Page 13197, Figure 6: dust-smoke layer top height of about 3 km west of Africa (10_N) seems to be too low. Should be close to 4 km. 22. We are aware that there are previous studies suggesting that the dust-smoke layer top height is close to 4 km (near 10° N). Indeed, our results (figure 4, lower panel) show that in many cases the dust crosses the coastline even in higher altitude. However, here we present the seasonal average value (based on 880 CALIPSO tracks) that covered also other cases when the dust crosses the coastline in low altitudes (near 2.5 km).

23. Does CALIPSO clearly detect the top height (weak traces of dust and smoke)? 23. In order to detect base and top height, CALIPSO algorithms is based on the difference between the scattering of clean atmospheric layers (only molecular scattering) and the realistic atmospheric conditions (molecular + aerosol/clouds scattering). Naturally, the edges of the transported aerosol plumes are not sharp. Therefore, we use the manual picking method that enables to detect plume edges more precisely then using a constant threshold. Our method also enables a better analysis of the noisy data. We estimate that our error in the vertical detection is on the order of 3 pixels which are equivalent to ∼100 meters. When averaging 880 granules the error in single layer

detection is much smaller than the statistical variance.

24. Why is the top height only shown over the Ocean, CALIPSO detects layer top heights over the continents, too. 24. CALIPSO detects layer top heights over the continents as well. The vertical distribution of the dust over the North Africa was studied in detailed using the CALIPSO data by Liu et al. (2008). Moreover due to land ocean circulation we do expect the local effects to be important near the land-ocean boundary and since this study is aiming to a long range transport we avoided the land area.

25. Page 13198, Figure 7: As mentioned above, altocumulus and cirrus is not included here. 25. The analyzed clouds top height distribution includes only low startiform clouds (Stratocumulus and Stratus clouds) with top heights lower than 2.5 km. We clarified this point in section 32, line 267: "The examined clouds were low clouds (including Stratocumulus and Stratus clouds)", and in the caption of figure 7, lines 640-641: "CALIOP samples covered only low clouds (lower then 2.5 km)"

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