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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Transport of Saharan dust from the Bodélé Depression to the Amazon Basin: a case study" *by* Y. Ben-Ami et al.

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Authors' response

We would like first to express our true appreciations to the referees' efforts and to thank them for their constructive and helpful remarks. We have addressed all of the comments. Before replying to the reviewers' comments point by point, we would like to start with a general reply addressing some of the important points of the reviewers that seems to be less clear in the manuscript, namely: (a) the origin of the dust, (b) transport of biomass-burning, (c) wet deposition along the transport route (d) and the significance of the presented results.

1. General comments:

1.1 The origin of the dust

We agree that the Bodélé area is not the only source, and we cannot rule out that in the discussed event there were contributions from other sources. This point was clarified in the abstract, in the results (section 3.1, 3.3.2, 3.5) and in the conclusions. We do argue that based on our analysis (in agreement with many previous studies) the Bodélé area is by far the main source. This point was addressed with additional focus on Figures 1 showing the activity of North African dust sources during the period of the study. As we know, to follow a dust plume across the Atlantic Ocean via remote-sensing measurements, the signature of the dust plume, in terms of AOD and spatial coverage, should be recognized along the entire transport route. However, in most cases processes of gravitational settling and dilution along the path diminish the signal of the dust (e.g.: Ansmann et al., 2009) and it is a challenge to follow the dust from the exact source in North Africa to its sink location over the Amazon Basin. However, the dust plumes emitted from the Bodélé depression during the period of the study (and in numerous other occasions) are extremely dense and long and therefore can be followed for long distances and maintain very high AOD (more then 4 over the source, and probably underestimated) and cover large areas (between 12×103 and 100×103 km2 near the source). The ability to follow dust from source to sink was possible due to the unique characteristics of dust emitted from the Bodélé. As suggested by the referee, to improve the justification for the presented relationship between the Bodélé dust and collected particles in the Amazon Basin, we expanded our data set, as well as additional trajectories calculations by a transport model (HYSPLIT) described in retiles in part 3.5 and in Figure 2 (Figure 9 in the revised manuscript) and 4. The trajectory analyses support the hypothesis that the dusty air originated mainly from the southern part of the Sahara, most likely from the region of the Bodélé depression.

1.2 Transport of biomass-burning

As discussed in the manuscript, the dust during this time of the year is generally mixed with biomass burning aerosol (Formenti et al., 2008). The emphasizes of transport of

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dust and not transport of biomass burning, derives from the importance of mineral dust as possible source of nutrients to the Amazon plants. Since the Amazon Basin have an abundance of biomass burning from local deforestation fires, transport of smoke from North Africa is of secondary importance. Therefore, the focus of this study is the transport of dust and not transport of biomass burning. However, we are aware of the mixing of dust and biomass-burning aerosol. This is clearly mentioned in the several places throughout the manuscript, and sown in the retrievals of the VDR (Figure 5 in the revised manuscript).

1.3 Wet deposition along the transport route

As the referees suggested, it is possible that significant washout (and dray deposition) occurs over the Atlantic Ocean as well over the Amazon, which was subjected to the wet season during the period of the study. However, here we show clear evidence for the arrival of dust, despite the wet and dry deposition. As a first approximation for the importance of wet deposition during this case study we estimated the likelihood for washout by the occurrence of optically thick clouds along the transport rout. To do so we used MODIS cloud optical dept products. The new analysis shows that during the period of the study, between 26 February and 1 March, the entire oceanic transport route was relatively free from large clusters of tick clouds (Figure 3a). This can be a reflection of the hot and dry air that carried the dust package. At 2 March the corridor from North Africa to the Amazon basin started to be closed by thick clouds that where forming along the ITCZ, approximately between 5° N and the equator (and later spread to 5° S) (Figure 3b). The transport route over the northern part of South America was frequently covered by thick cloud, especially during 5 March (Figure 3).

Although we can not estimate the real washout, this analysis suggests that during the case study time, wet deposition is less likely to be important. It proposed however that the likelihood to washout increase as dust plume reached close to the coast and over the Northern part of South America.

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1.4 Significance of the results

The presented report is a case study that follows dust plumes from source to sink using in-situ data that was collected during the AMAZE campaign. We were motivated to study this by the fact that a significant emission occurred during this period. As a detailed and limited in time case study this research cannot test whether the reported results are representing a common type of events. Based on analysis of many winter strong dust events, we have a reason to estimate that such event is not uncommon. Specifically to this study, although the data were limited, we were able to analyze data from vast spectrum of sources (space and ground based instruments as well as transport model) and to show clear link between source in North Africa and sink over the Amazon forest. Based on referee's comments, the revised manuscript includes major improvements which strengthen the link between dust emitted from the Bodélé area and its sink over the Amazon Basin. The main improvements in the revised manuscript includes backwards and forwarders trajectory analysis and demonstration of the dominance of the Bodélé, e.g.: section 3.5 and Figure 1 and 9 in the revised manuscript.

2. Referee # 1

2.1 Specific comments by referee # 1

1. 4347/18-27: In this chapter, a little vaguely "minerals" are mentioned as "nutrients" (probably soluble ones, referring to 4347/15-17): can you specify which particular minerals can act as nutrients for rainforest? Aluminum and titanium are named, but it is hard to think of an aluminum shortage in the rainforest, or how the plants can make use of titanium, which is most probably oxidic in Saharan dust.

1. The elements mentioned in the manuscript are used as markers for the arrival of mineral dust and they do not necessarily serve as essential elements for plants growth. Thanks to the comment of the referee, this issue was addressed in the revised manuscript in page 5 lines 107-110: "The above elements serve as markers for the arrival of mineral dust and they are not necessarily essential for plants growth. The

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bioavailability of elements contained in mineral dust to plants is beyond the scope of the paper"

The main objective of the study was to link the dust source and sink locations. To do so, we have looked at elements in collected particles that serve as tracers of mineral dust. We do not, however, discuss the availability of these elements to plants because it was not tested and is beyond the scope of the paper.

2. Fig. 3: Figure is hard to read, because the vertical profiles are mapped horizontally, e.g., it is quite difficult to follow the height evolution of the plume. If a 3D graph is really necessary, a suggestion would be to "flatten" the earth – distortions should be low due to closeness to the equator – and display only outlines of the continents. But as the scans are rather equidistant, the most readable way of this graph would be simply a set of 6 2D plots (latitude versus altitude), like to lower graphs. Also, the image quality is low - take care that the quality is higher in the final publication!

2. We agree with the referees that Figures 3 in the manuscript was difficult to read. The reason that CALIPSO profiles were not presented in Cartesian projection is that the usage of spherical projection enables a better alignment between the vertical profiles of CALIPSO to the surface of the Earth. In order to improve the quality of the Figure, and respond to the suggestions of both referees, Figures 3 was separated and enlarged.

3. Fig. 4: The numbers given of the x axis are probably geographic coordinates? Please specify. If so, only a part of the track shown in the small image is displayed. Then, maybe it could be colored/marked, including the direction of flight.

3. The X axis is indeed geographic coordinates. The necessary labels were added a to the X axis. In addition, the Figure was enlarged, the relevant part of the satellite track and the direction of flight were marked, and a scale bar was added (Figure 4).

4. Fig. 5: What is "pollution (P)"? Does this mean a variety of anthropogeneous aerosol? If so, does this aerosol show a consistent depolarization?

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4. A. The letter "P" marks anthropogenic aerosol. Thanks to this comment, the letter "P" was corrected to "A" and this point was clarified in the revised manuscript, and in the caption of Figure 5 in the manuscript.

B. Based on previous studies (e.g.: Liu et al., 2008c) the volume depolarization ratio of anthropogenic aerosol has a consistent value between 0 and 0.02. In our case, it is most likely that the anthropogenic aerosol was already mixed with other types of aerosol along the transport route. The aerosol is not "pure" anthropogenic, and therefore the volume depolarization peak shifts to higher values, centered between 0.03 and 0.09.

5. Fig. 6a: Explanation for the blue color should be added.

5. The blue color marks regions of the original VDR that are not highlight in red (DR between 0.25 and 0.4) or in green (0<DR<0.25). This is now stated in the Figure caption in the revised manuscript.

6. 4355/9-10: Is the dust really mixed with BB smoke, or is this just a vertical superposition in different layers? It is hard to see from Fig. 3.

6. The mixing state / layering of aerosols types cannot be derived from Figure 3. This information can only be deduced from the polarization components. Nevertheless, close to the dust source, one can differentiate between dust (characterized by higher backscatter attenuation), to the biomass-smoke. Please see our detailed answer on the mixing of both types of aerosol in the general comment.

7. 4355/17-18: Is the change from 0.19 to 0.22 significant?

7. The change in VDR from 0.19 to 0.22 was based on one case study. Despite the limited amount of data based on the sharp changes in the VDR between the different regimes (0.28-0.31 versus 0.15-0.22) we think that it is significant. In the revised manuscript we add the standard deviation of the different regimes as another measure in Figure 6a (in the revised manuscript) and in the caption of Figure 6a: "Average VDR

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(± one standard deviation)..."

8. Fig. 7a, caption line 2: omit ", and 50 W-10 E", as it is not averaged over this area.

8. Figure 7 in the manuscript shows latitudinal average for a rectangle region between 10° N - 5° S and 50° W - 10° W. This is now clarified in the caption of Figure 7.

3. Referee # 2

3.1 General comments by referee # 2

1. What is missing in the introduction are clear statements concerning: What has been done before in this field of research? This point needs to be more properly and carefully elaborated in the introduction. The submitted paper is obviously not the first one that reports on the transport of dust (AND OF SMOKE the authors should clearly mention that) towards South America. Kaufman et al. 2005 (JGR) demonstrated how dust and smoke is transported across the Atlantic based on MODIS observations. Liu et al 2008 (JGR, CALIPSO, long range transport paper) showed dust and smoke plumes over the tropical Atlantic. Ansmann et al. demonstrated how dust and smoke is transported to America during the winter season.

1. We are definitely not saying that this is the first paper that reports on transport of dust and smoke from Africa to South America. In fact some of this paper authors did report on this in the past. This paper shows a detailed case study that follows a dust package from the emission in the Bodélé area to the Amazon. To make this point clearer, the introduction of the revised manuscript includes a review regarding what has been done before in this field, including the studies of Kaufman et al., 2005a, Liu et al., 2008 and Ansmann et al., 2009. In addition, we clarified in the text that the dust is mixed with biomass-burning aerosols in the abstract: "The lofted dust, mixed with biomass burning aerosols..." And in page 4 lines 90-91: "...North African dust, mixed with biomass-burning aerosols from the Sahel region..."

2.The paper presented here is similar to the Ansmann paper.

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2. This paper shows different things. Ansmann et al., 2009 (GRL) analyzed the transport of dust and biomass-smoke from Cape-Verde to the Amazon using lidar data, back trajectories and retrieval of AOD. Cape-Verde islands are located west from the Saharan coast and in their paper they do not deal directly with source. In our paper the source is an important component of the paper. Moreover, Ansmann et al., 2009 (GRL) did not show clear evidence for the arrival of dust as far as the Amazon forest: following the relevant quoting from Ansmann et al., 2009 (GRL): 1. "the aerosol over Manaus was almost well-mixed, reached up to 3.5 km, and mainly consisted of aged biomass burning smoke". 2. "The observed particle depolarization ratios, shown in Figure 4j, are low with values of 0.04–0.05, and indicate that dust was almost absent over Manaus".

Our manuscript shows that the source for most of the dust of the studied event comes from the Bodélé area. Special attention is devoted to detailed analysis of the emission flux and pattern. It follows the dust package along the African continent and provides detailed description from the CALIPSO LIDAR of the dust transport along the entire trajectory. Finally the last part of this paper analysis shows in-situ measurements of elements in collected dust samples that verify the arrival of dust to the Amazon forest. We do discuss the finding of Ansmann et al., 2009 in the following parts: Page 4 lines 84-85: "Nevertheless, not all dust outbreaks reach the Amazon forest (Ansmann et al., 2009)." Page 4 lines 90-91: "... aerosols from the Sahel region (Formenti et al., 2008; Ansmann et al., 2009)..." Page 4 lines 96-98:"... satellite remote sensing (Karyampudi et al., 1999; Torres et al., 2002; Kaufman et al., 2005a; Liu et al., 2008a and b; Generoso et al., 2008; Ansmann et al., 2009..." Page 8 lines 195-196:"...and biomass-burning aerosols from the Sahel region (Andreae et al., 1994; Formenti et al., 2008; Ansmann et al., 2009)". Page 17 line 424: "..., in agreement with Ansmann et al. (2009)." Pages 18-19 line 454-456: "... were almost depleted of dust particles when they reached the Amazon region (Ansmann et al., 2009)"

3. Another essential point to be clarified and changed is: Schepanski et al. 2009

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(JGR?) recently introduced a mechanism how dust is mobilized. Large amounts are emitted into the lower atmosphere when the nocturnal low level jet dissolves in the morning hours and hits the ground. And according to the Schepanski paper dust mobilization takes place almost everywhere in the southern Saharan area, not only in the Bodélé area. Thus the statement . . ..Given the Bodélé depression is the largest. . ..' cannot be interpreted as the only source of dust identified in the Amazon Basin.

3. We agree with the referee that the Bodélé is not the only source. However, during the period of the study the Bodélé was bay far the dominance active dust source. This point was clarified in the revised manuscript, as discussed in details opening part. In order to clarify the dominance of the Bodélé area, Figure 1 was substituted with an improved Figure (Figure 1 here), showing dust activity from numerous dust sources over North Africa during the period of the study. The improved Figure clearly emphasizes the dominance of the Bodélé as the major source.

3.2 Specific comments by referee # 2

1. Title has to be improved! The paper does not provide any solid data set (measurements, model simulations) that clearly shows a direct relationship between Bodélé dust and the Amazon Basin particles. This is not acceptable. Speculation is not tolerable.

1. Following the general discussion from the opening part, and in order to improve the justification for the presented relationship between the Bodélé dust and collected particles in the Amazon Basin we expanded our data set (satellite images of North Africa, measurements from AERONET station, space lidar measurements along the path and in-situ measurements taken over the canopy of the Amazon forest), as well as additional trajectories calculations by a transport model (HYSPLIT). Due to the large distance between the source and sink locations (∼9000 km) and the long time of transport, the transport model can not provide very accurate results but a general idea about the possible route of the dust plume. A. Forward trajectories (Figure 9a in the revised manuscript and Figure 2 here), starting over the Bodélé depression between 14 and 15

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February 2008 (at height levels of 0, 500 and 1000 m), show that air parcels reached the Amazon forest between 24 and 29 February. B. Forward trajectories (Figure 9b in the revised manuscript and Figure 2b here), starting over the Bodélé depression between 18 February 2008 (at height levels of 0, 500 and 1000 m) when extensive emission of dust began, show that the air parcels are commonly transported to the southwest and pass near Ilorin (Nigeria) at ∼20 February. The air parcel crossed the African coast line and continued to move southwestwards. It reached the Amazon forest at the beginning of March. C. Back trajectories (Figure 4a and b here, not shown in the revised manuscript), starting at several locations over the Amazon forest for the period of the arrival of the dust (between 22 February and March 5 2008, at height levels of 500, 1000 and 1500 m), show that most air parcels originated from the regions of the south of the Sahara and the Sahel. Note that only trajectories from 26 February originated from the central and northern part of the Sahara (Figure 4a and b here). Some trajectories passed near the Bodélé depression. Both trajectories support the hypothesis that the dusty air originated mainly from the southern part of the Sahara, most likely from the region of the Bodélé depression area. The contribution of additional dust sources along the trajectories is undoubted. Figure 2 (here) was added to the revised manuscript as Figure 9.

2. Page 4346, line 5: Abstract: . . .Given the Bodélé depression area . . .is the main inter dust source. . ... yes that may be true but is certainly not the only one.

2. We agree with the referee that the Bodélé is one among other dust sources that were activated in the southern Sahara. This point was addressed in the abstract in page 2 lines 49-50: "…(most likely with contribution from other dust sources in the region)…"

3. Page 4346, line 8-13 must be rephrased according to the discussion above (..speculative argumentations are not tolerable in scientific papers). Provide unambiguous facts, or leave it out. More alternative positions are not acceptable.

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3. We clearly mention now the contribution of other dust sources in the abstract.

4. Page 4347, line 18-27, in this paragraph one should review the literature, what has been done, what is known from previous work (Formenti, 2001, Kaufman 2005, Liu 2008, Ansmann 2009), before one introduces the new approach. To my opinion the approach here (use of CALIPSO lidar data to indicate WINTER TRANSPORT pattern, height dependent transport, depolarization ratio analysis) is similar to the Ansmann work (lidar in Africa and South America, WINTER SEASON transport pattern, dust and smoke transport, height dependent. . ., depolarization ratio). That needs to be mentioned in the introduction!

4. A. The introduction of the revised manuscript was modified and it now includes a more comprehensive review describing previous studies, including the studies of Formenti et al. (2001), Kaufman et al. (2005a), Liu et al. (2008) and Ansmann et al. (2009).

B. We agree with the referee that the approach presented here is not conceptually new. Nevertheless, as mentioned above, the main result of the study is innovative. In contrast to Ansmann et al. (2009) who followed the transport of dust and biomass-smoke from North Africa, and showed no clear evidence for arrival of dust to the Amazon region, this study follows the dust from its source and presents clear evidence for its arrival to the Amazon Basin. C. We now relate to the Ansmann et al. (2009) study in several places throughout the revised manuscript: Page 4 lines 84-85: "Nevertheless, not all dust outbreaks reach the Amazon forest (Ansmann et al., 2009)." Page 4 lines 90-91: "... aerosols from the Sahel region (Formenti et al., 2008; Ansmann et al., 2009)..." Page 4 lines 96-98:"... satellite remote sensing (Karyampudi et al., 1999; Torres et al., 2002; Kaufman et al., 2005a; Liu et al., 2008a and b; Generoso et al., 2008; Ansmann et al., 2009..." Page 8 line 195-196:"...and biomass-burning aerosols from the Sahel region (Andreae et al., 1994; Formenti et al., 2008; Ansmann et al., 2009)". Page 17 line 424: "..., in agreement with Ansmann et al. (2009)." Pages 18-19 lines 454-456: "... were almost depleted of dust particles when they reached the

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Amazon region (Ansmann et al., 2009)"

5. Page 4347, line 29: Koren. . .. has suggested that the Bodélé depression . . .. is the main source for the dust transport. . ... As mentioned above, Schepanski et al. 2009 show that this may not be true at all. So this phrase appears too speculative. Please rephrase (or better leave it out). Why not just stating, dust from the southern Saharan area is transported to South America (mixed with smoke..). Why do the authors try to emphasize 'Bodélé' so much?? The message of the paper is clear and does not change if they remove their key word 'Bodélé. . ..'.

5. The importance of the Bodélé as a main dust source was emphasized by numerous studies, as well as by Schepanski et al. (2009). According to Schepanski et al. 2009 it is most likely that transport of dust from North Africa is dominant by dust emitted from the Bodélé. Following two relevant quotations from Schepanski et al. 2009: 1. " . . .mineral dust from the Bodélé Depression is able to reach higher tropospheric levels (Fig. 9) which is a precondition for long distance transport as crossing the Atlantic. For transport to South America, two preconditions are fulfilled during winter: wind regimes over the tropical Atlantic have a southwestward component and the Bodélé is most active during this season." 2. "Considering the dust source activity controlling the atmospheric dust concentration, the Bodélé is most active during winter. Consequently the contribution of Bodélé dust to the Saharan dust load is maximum in winter months. Considering long-range transport as towards the Amazonian rain forest, preconditions are the best during winter months."

Unlike previous studies of dust transport from North Africa to the Amazon forest, the objective of this study is to show evidence for the exact dust source and its deposition in the Amazon. The revised Figure 1 shows that during the period of the study, the Bodélé Depression is the dominant visible dust source in North Africa.

6. Page 4348, line 23 to Page 4349, line 4: Why do the authors not present a more relaxed, more realistic discussion, i.e., why do they not tell that dust and smoke plumes

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are transported (this is later clearly seen in the CALIPSO depol data). Why do they focus on dust only.

6. Following the detailed discussion in the general comments from the opening part, the mixing of dust and biomass smoke is sown in the retrievals of the VDR (Figure 5 in the revised manuscript) and it is clearly mentioned throughout the entire revised manuscript, e.g.: In page 2, line 53: "The lofted dust, mixed with biomass burning aerosols. . ."

Additional explanations are placed in the following pages: Page 4 lines 90-91:". . .North African dust, mixed with biomass-burning aerosols from the Sahel region. . ." Page 8 lines 193-195: "Over the Atlantic Ocean. . . dust particles are mixed with. . .and biomass-burning aerosols from the Sahel region" Page 13 lines 316-317: "As the dust propagated southwest from the Bodélé, it mixed with biomass burning smoke" Page 15 line 363: "the biomass smoke is mixed with dust particles."

7. Page 4349, line 23: ..dust mass was estimated. . .over the Ocean. . ..! Where over the Ocean? Provide exact location information, show trajectories that the dust at this oceanic site is linked to the Bodélé depression area.

7. The exact location of the area over the Atlantic Ocean was determined based on the spatial coverage of the MODIS AOD over the Atlantic Ocean during the period of the study. The exact location (between 20° N - 15° S and 50° W - 15° E) is clearly stated now in the manuscript in page 8 lines 199-200, and in the caption of Figure 7 in page 22, lines 554-555. We do not attribute all the observed dust loading to the Bodélé. This issue was addressed in section 3.3.2 in the revised manuscript. The dominance of the Bodélé, during the period of the study is addressed via the revised Figure 1. Figures 1 and 9 (in the revised manuscript) link the oceanic dust to the Bodélé.

8. Page 4349, line 25. . ., Conversion of AOD to dust mass,. . .. I speculate that 50% of the mass is smoke related! So, this conversion computation is rather uncertain! Must be mentioned.

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8. The conversion of AOD to dust mass is based on disintegration of the observed AOD to its main components: maritime, anthropogenic and dust aerosol. This issue was introduced in the method; section B, pages 8-9 lines 193-219: "Over the Atlantic Ocean, it is likely that dust particles are mixed with marine aerosol ...and biomass-burning aerosols from the Sahel region ... τdu was extracted from the total AOD ..."

We agree with the referee that in a case of conversion of the total retrieved AOD to mass, part of the mass should be attributed to smoke. However, the disintegration process, which is still needs to be improved, enables to use the part of AOD that is attributed to dust only. As a consequence, the error of the estimated mass (over the ocean) reduces significantly. The uncertainty in the mass calculations ($\pm$30%) is now addressed in the revised manuscript in page 8 lines 189-190: "The uncertainty in the mass calculations is $\pm$30%..." and in the caption of Figure 7, pages 22-23, lines 555-556: "the mass estimate is calculated based on $\pm$30%"

9. Page 4350, line 9: I have not found any indication for biomass burning aerosols in Andreae 1986, why is that referenced here?

9. Corrected. The wrong reference was corrected to Andreae et al. (1994).

10. Page 4350, line 15 – line25: What is f (without index) in the formula? How is it explicitly related to f-m, f-a, f-d. Is Eq(2) ok? Is f always smaller than f-a (otherwise tau-du is becoming negative).

10. A. f is the total fine fraction, namely, aerosol fraction with diameter smaller than 1 μm, as retrieved by MODIS. Equation 2 was based on the assumption that one can disintegrate f to the following main component: f = fa + fm +fd, were fa + fm +fd are the fine fraction attributed to anthropogenic, maritime and dust aerosol. The meaning of f is now clarified in the revised manuscript. B. Following Kaufman et al. (2005a), f is bounded by: fa $\geq$ f $\geq$ min {fm , fd}. Values outside these bounds were set to the limit value: f = fa for f > fa and min {f m , fd} for f < min {fm , fd}. In case of dust storm, as presented here, f <fa.

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11. Page 4350, line 27: The use of CALIPSO depol to separate dust and smoke is similar to the approach presented by Tesche et al. (JGR, 2009), should be referenced!

11. Thank to this comment, the results of Tesche et al. (2009) is now mentioned in the revised manuscript.

12. Page 4351, line 6: use 'depolarization ratio' . . . instead of 'depolarization signal'.

12. Corrected throughout the entire revised manuscript.

13. Page 4351, line 9: Add Freudenthaler et al., 2009 (Tellus, SAMUM special issue) to the reference list regarding dust depolarization ratios. Murayama (2001) reports observations that are frequently disturbed by anthropogenic particles over eastern Asia, and thus these values are much lower than the values for pure dust.

13. Corrected. Freudenthaler et al. (Tellus, 2009) are now cited in the revised manuscript. We acknowledge that the results of Murayama (2001) were lower than the values for pure dust. However, the result presented in this manuscript are also not of pure dust.

14. Page 4351, line 25. . .: I miss one point: Backtrajectories arriving at Amazonia (Manaus area),. . ...clearly showing the link to the Bodélé area! I can image why this point is left out. Because such an analysis will show rather uncertain and not convincing results. But without such an analysis the hypothesis 'Bodélé dust found in the Amazon Basin' is just speculation! And looking at the bullet list in section 3.

14. Based on the referee's comments, and as discussed in details earlier, we introduced results of transport model (HYSPLIT) of forward trajectories (Figure 9 in the revised manuscript, Figure 2 here), starting over the Bodélé depression. The results of the model show that the dust-containing air parcels from the region of the Bodélé depression, cross the Atlantic Ocean towards the Amazon forest. The increase in the crustal elements in particles collected in Manaus occurred simultaneously with the arrival of the dusty air parcels, which was followed from the source region!

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15. What about cloud effects, thunderstorms in the tropics during the winter season along the transport route, washout? Did you check the satellite images along the transport path for cloud clusters (indicating washout). There must be also significant washout over the Amazon Basin (during the wet season). Please discuss this impact.

15. As discussed in details in the opening part and based on additional spatial distribution of clouds optical thickness along the transport route (Figure 3 here), we do not expect significant washout over the Atlantic. The likelihood to washout increase as dust plumes reached the cost of northern South America.

16. Page 4353, line 17: I checked the AERONET web page. . .! So large aerosol optical depths up to 4(!), and obviously always a large contribution (30-50%) by biomass burning smoke. Can optical depths accurately be measured above AOD=3? Is the CIMEL still able to find the exact position of the sun? Over 14 days the optical depth was larger than 2!. The Angstroem exponents are always between 0.2 and 0.8 (clearly indicating a large contribution by smoke). Why did the observations stop on March 1, 2008? Multiple scattering effects must be large so that the single scattering AOD is then obviously often larger than 5! More explanations are required here to convince readers that proper observations are presented! Unfortunately there is no other AERONET site that shows such dramatically high AODs in that biomass burning area.

16. Figure 2 (in the revised manuscript) presents measurements of AOD from AERONET station, attributed mostly to emissions of dust from the periods between 11-16 and 18-27 February. Observations were stopped on 1 March, after the arrival of those dusty air parcels to Ilorin station (between 14-17 and 20-22 February) was observed. We agree with the referee that part of the AOD should be attributed to biomass smoke. However, based on the reduction of the Angstrom Exponent and based on MODIS images (showing the propagation of the dust plume towards Ilorin), it is suggested that the significant increase of the AOD was dominated by dust and not by biomass smoke particles. The AOD, during the passage of the dusty air parcel, was indeed very high. Measurements of AERONET, which were conducted in similar con-

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ditions of massive AOD, were validated by Schmid et al. (2003), who found remarkable agreement between AOD measured by AERONET and AOD measured by airborne sun photometer (with RMS between 6 to 15%). Nevertheless, we agree with the referee, that in such conditions of AOD>3, AERONET underestimates the true AOD. This is now clarified in the revised manuscript in page 12 line 302: "...significantly increased AOD, (most likely underestimated)..."

17. Page 4353, line 24. . ..: It is demanding to provide information regarding the CALIPSO data quality (uncertainties) in such situations with so high AOD (larger than 2). How trustworthy are all the shown CALIPSO products. Can I trust the depolarization ratio profiles down to the ground? . . . at such high AOD values? What about multiple scattering by dust in such cases, must be large? CALIPSO lidar is not just a powerful lidar. I am surprized about the shown results. Please provide a bit larger discussion regarding uncertainties. Ask the CALIPSO peopleto provide uncertainty information for situations with such high AOD.

17. The performances of CALIPSO in similar conditions of dense dust were demonstrated in numerous studies (e.g.: Generoso et al., 2008; Liu et al., 2008a, b and c), and the presented results of VDR has remarkable agreement with known VDR values from numerous studies. Naturally, in conditions of high AOD, the data quality may be reduced due to signal saturation. Although saturation was not observed, the possible error due to conditions of high AOD are now addressed in the revised manuscript in page 14 lines 336-338: "...in a case of high AOD the signal of CALIPSO, obtained from the lower part of the aerosol plume, may have a lower quality."

Multiple scattering is discussed in page 14 lines 334-336: "...more signal at the perpendicular band of CALIOP, derived from the irregular shape of the dust and from multiple scattering", and in page 14 lines 339-340: " Water clouds located near or within the aerosol plume, have higher VDR values (between 0.4 to 1) due to multiple scattering..."

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18. Figure 3 is one of the main figures and shows the full advantage of a spaceborne lidar! BUT Figure 3 is rather small (must be increased by at least factor of 2). May be it is then necessary to split the figures in two plots.

18. Corrected. Figures 3 in the manuscript was enlarged and spited.

19. Most parts of Figure 4 can be omitted. Concentrated on CALIPSO observations that a relevant for this paper. Then more details can be seen. Figure4 is also too small!

19. Corrected. The Figure was enlarged. We agree that part of the data shown in the lower panel of Figure 4 (in the revised manuscript) is not necessarily needed. Nevertheless, in order to mark the exact track of CALIPSO (as shown on the upper part of the panel) it is necessary to keep the size (from south to north) of the “curtain”.

20. Page 4354, line 20: Add Tesche et al (JGR, 2009, SAMUM results) to the references and compare their results with the CALIPSO findings. I guess, agreement is reasonable. This comparison will help to convince the reader that CALIPSO data are trustworthy!

20.Corrected. The results of Tesche et al. (JGR, 2009) are now addressed in the revised manuscript in pages 13-14 lines 330-331: " These VDR values, which are typical for dust (. . . Tesche et al., 2009). . ."

21. Page 4355: Volume depolarization ratios are always not easy to explain. They are influenced by the strength of particle backscattering (in comparison with Rayleigh backscattering) and by the influence of the different scatterer types. So this complicates the discussion. On the other hand, it is certainly too difficult to show color plots in terms of particle depolarization ratios. But add some sentence and explain this. It must be clear to the reader why the depolarization ratio is so variable. According to the Tesche (2009) paper dust particle depolarization ratio is obviously around 30-35% and the particle depolarization ratio of smoke (fine mode particles) is obviously close to 0%. That should be mentioned very clearly.

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21. A. Accepted. The complexity of the VDR retrieval, caused by different types of scattering, is now emphasized in the revised manuscript in page 13 lines 325-328: " VDR, retrieved from the vertical profiles of CALIOP, is a function of CALIPSO wavelength and the size and shape of the targets particles and air molecules. Therefore, the acquired VDR is in fact a result of different types of interactions."

Additional explanation is placed in page 14 lines 334-336: "The relatively high values. . .derived from the irregular shape of the dust and from multiple scattering"

Additional explanation is placed in page 14 lines 339-343: "Water clouds . . . have higher VDR values . . . due to multiple scattering . . . Anthropogenic aerosols, . . . which are much smaller compared to the CALIOP wavelength, have low (between 0 to 0.1) VDR values . . .

B. Corrected. The results of Tesche et al. (2009) are now addressed in the revised manuscript in pages 13-14 lines 330-331: "These VDR values, which are typical for dust (. . . Tesche et al., 2009). . ."

22. Page 4355, line 4: I can not believe that European haze can make it down to central Africa. There are many other sources of pollution, e.g., from northern Africa. Do the trajectories indicate such a haze transport? Please check, if yes, mention this (trajectories support this hypothesis), if no, remove the hypothesis.

22. Thanks to the reviewer comment we calculated back trajectories from HYSPLIT model, starting at ground level (red), 500 (blue) and 1000 (green) m above ground level for several coordinates along CALIPSO route (for 200 hours). The back trajectories show that the anthropogenic aerosol may originate from North Libya and/or Europe (Figure 5 here). The results of HYSPLIT model are mentioned in the revised manuscript in section 3.5 in the revised manuscript.

23. Page 4355, line24: The AOD is so large, and at such favourable conditions MODIS has difficulties, over the Ocean? Please explain!

23. MODIS AOD was validated over the ocean in numerous studies, generally by comparison to AERONET stations, for example: Remer et al. (2005) showed that one standard deviation of MODIS AOD $\leq$1 retrievals at 550 nm, fall within the predicted uncertainty of $\pm$0.03$\pm$0.05τ. Tanre et al. (1997) compared between MODIS algorithm to ground based measurements and showed remarkably good agreement with MODIS retrieval for AOD >2. Validation of MODIS algorithm over land, which are less accurate then retrievals over the Ocean, showed that MODIS underestimates AOD for high aerosol loading conditions. Therefore, it is most likely that the AOD, shown in the manuscript is underestimation of the true AOD. This is now clearly clarified in the revised manuscript in page 12 lines 282-283: "The average AOD of the plumes varied between 2 and 3.9 (most likely underestimated)..."

Additional explanation is placed in page 19 lines 457-458: "The Bodélé emission rates might be underestimated due to saturation of the AOD inversion algorithm..."

24. Page 4356, line14: After section 3.3.2 another subsection is required, not to say demanded. What do transport models show? Are DREAM model runs for this case? Please check!. What about HYSPLIT trajectories. We need support by air mass transport simulations! Without such a support, all statements that follow are (almost) pure speculation and are thus unacceptable to be presented in a scientific paper. Furthermore, the authors want to create a link from Bodélé to Amazonia. That has to be shown!!! Demonstrated by air mass transport simulations!!! If such simulations are highly uncertain, then the hypothesis is highly uncertain, too. But even such a result would be a result worthwhile to be presented as a quality criteria for the highly speculative hypothesis.

24. Following the reviewer's comment and the detailed discussion from the opening part, results of forward trajectories were inserted to the revised manuscript. The new results support the hypothesis that dusty air parcels, originated from the Bodélé depression, indeed reached the Amazon Basin. However, trajectory analysis can not provide very accurate results but a general idea about the possible route of the dust

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plume. Since trajectory analysis is not among the objective of the study, and following the convincing result of the detailed trajectory analysis (forwards and backwards trajectories for different locations, heights and dates), conducted with HYSPLIT model, we believe that the presented results satisfies the general idea about route of the dust plume, and that additional results are not necessary.

25. Page 4356, line17. . .: Arrival of dust. . .? Please show that this hypothesis is supported by air mass transport simulations.

25. The arrival of the dust is supported by air mass transport simulations, calculated by the HYSPLIT transport model. Results of the model are presented in Figure 2 (Figure 9 in the revised manuscript) and discussed above.

26. Brazil observations from 22-26 February are related to dust emissions from 18-27 February. This is nonsense, what went wrong? Please clarify.

26. The ground based measurements have limited time resolution (between 3 and 5 days). Therefore they integrate several parcels and are unable to specify the exact arrival day. It is clear, however, that the arrival of the air parcel occurred between 22 and 26 February, and that the presence of the dust was observed until 4 March. Analysis of back trajectories suggest that the increase of crustal elements between 22 and 26 February is attributed to dust emitted from the Bodélé (and the nearby sources) between 14 and 15 February. Similarly, the increase of crustal elements between 26 February and 4 March can be attributed to emission of dust on ∼18 February. This issue is now mentioned in the manuscript in page 17-18 lines 427-432: "Forward trajectories, calculated using the HYSPLIT transport model, . . .propose that the increase of crustal elements between 22 and 26 February was contributed to dust emitted from the Bodélé (and the nearby sources) between ∼14 and ∼15 February (Figure 9a). Similarly, the increase of crustal elements between 26 February and 4 March can be attributes to emission of dust from ∼18 February and the following days. . ."

27. Page 4356 line22: Ok, large particles identified. Source: Sahara! Are there

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potentially other sources for large particles?

27. Other potential sources for large particles of crustal elements are located in Manaus and other places in southern and northeastern Brazil (Martin et al., 2010). Backward trajectories, taken from Manaus, for the period of the arrival of the dust are consistent with arrival of the air parcels from the Atlantic Ocean (Figure 6 here).

28. Do the chemical analysis during AMAZE allow to identify smoke, too? Would be confusing, if you only identified the dust, but not the smoke.

28. Elemental analysis from the AMAZE shows increase in Potassium, in the fine and coarse fraction that may be attributed to the contribution of biomass burning aerosol, possibly originating from the Southern Sahel region. This issue is now mention in the revised manuscript in page 17 lines 416-418: "Potassium, in the fine and coarse fraction, may be attributed either to arrival of dust or to a contribution of biomass burning aerosol, possibly originating from the Southern Sahel region"

29. Measurements are done during the wet season. Can you estimate the washout effect? Check satellite imagery for the last two days of the travel across the rain forest.

29. As discussed in details in the opening part and based on additional spatial distribution of clouds optical thickness along the transport route (Figure 3 here), we do not expect significant washout over the Atlantic. The likelihood to washout increase as dust plumes reached the cost of northern South America.

30. Page 4357, line 10: Ansmann et al (2009, GRL) provide similar conclusions (3-4 km top height). Should be mentioned, too

30. Corrected. These results are now clearly mentioned in the revised manuscript.

31. Page 4355, line 14: . . . that closely follows dust emitted from the Bodélé depression AND MANY OTHER AREAS OF THE SOUTHERN SAHARA.....

31. We agree with the referee that part of the dust was emitted from additional dust

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sources. This issue is discussed in details in the opening part. The contribution of additional dust sources is emphasized in the revised manuscript and with the revised Figure 1.

32. Page 4361, line 25: Liu, D 2008a, Liu, Z 2008b, Liu D 2008b, better a,b,c? ignoring D or Z?

32. Agree. The comment was adopted in the revised manuscript.

33. Page 4362, line 13: Martin et al. . . .. as long as the paper is not published (at least in press) it should not show up in the references.

33. The reference was corrected.

34. Fig1: Use star or closed circle symbol in Fig 1a to indicate the site

34. Adopted. The location of the source was marked on Figure 1a.

35. Fig2a: Use linear scale for Angstrom from 0. to 0.7 (presently one number, log scale?, is insufficient).

35. Agree. Figure 2a in the manuscript was improved based on this comment.

36. Fig2b: Use more contrasting colors for the trajectories. Hard to identify them in Fig 2b. Use yellow star or bullet to indicate the AERONET site.

36. Agree. Figure 2b in the manuscript was improved based on this comment.

37. Fig 3a,b top: Figures are too small, where is the equator?...indicate some latitudes! Symbols 'a' for Fig 3a and 'b' to indicate Fig 3b are missing. Fig3a,b bottom: Figures are too small , unsufficient height and longitude information. Enlarge the plots, use other colors to clearly indicate the areas and Bodélé (with star or bullet symbol).

37. Corrected. Figures 3a and 3b in the manuscript were separated and enlarged. The necessary labels and markers were added.

38. Fig4: Figure is too small, provide axis text and units. Vertical profile of WHAT

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attenuated backscatter?). 60% of the data (latitudinal belt) shown are not needed here!

38. Corrected. The Figure was enlarged and we added axis, labels a scale bar and units. In addition, we marked the relevant part of the track and the direction of the flight. We agree that part of the data shown in the lower panel of Figure 4 (in the manuscript) is not necessarily needed. Nonetheless, in order to mark the exact track of CALIPSO (as shown on the upper part of the panel) it is necessary to keep the size (from south to north) of the curtain.

39. Fig 5: x-axis: Volume depolarization ratio, y axis: Occurrence frequency (Cases). Data set is based on 18-26 Feb 2008 (for the seven CALIPSO curtain like measurements)? Area from 20E-60W, 30N-30S? Please provide this information! Avoid . . .depolarization signal. . .

39. The labels of Figure 5 were corrected based on the comment. The dataset for Figure 5 was based on 6 vertical profiles, as seen in Figure 3a. This issue was clarified in the revised manuscript. The area covered by CALIPSO's curtains was clarified in revised manuscript.

40. Fig 5: Almost pure dust causes volume depolarization ratios of 25% at 532nm, pure dust causes more than 30%, what is the impact of multiple scattering here?

40. The volume depolarization is a ratio (VDR) of the perpendicular and the parallel attenuated backscatter signal. Dust is characterized by no spherical particles which increase the signal of the perpendicular band. As the referee mentions, in cases of high AOD, the signal of the perpendicular band may increase due to multiple scattering. Therefore, the VDR is expected to increase with purer dust particles and higher AOD. The separation between the effects of multiple scattering versus non-sphericity on the VDR is beyond the scope of our paper. This issue is mention in page 14 lines 334-336: "The relatively high values, namely more signal at the perpendicular band of CALIOP, derived from the irregular shape of the dust and from multiple scattering"

41. Fig6: Figure is too small, Occurrence frequency in percent? State that clearly, improve also: Volume depolarization ratio

41. Agree. The Figure was modified according to the recommendations.

42. Fig7: At least 30% of the AOD is caused by biomass burning smoke.

42. We agree that part of the AOD may be attributed by biomass smoke. The uncertainty regarding mass calculation was addressed in the caption of Figure 7.

43. Fig7b x axis: Daily dust mass (Tonne). E", as it is not averaged over this area.

43. Corrected. The area covered by Figures 7a and b is not the same. This is now clarified in the revised text.

44. ig. 8: As probably iron or maybe phosphorous or potassium play an important role for nutrient input, they should be displayed in that graph.

44. As mentioned above, the elements shown in the Figure serve as markers for arrival of mineral dust and they are not necessarily essential elements for plants growth. The arrival of Potassium was addressed in the manuscript. It was not shown in the Figure since Potassium may be attributed to a contribution of biomass smoke aerosol.

45. 357/1: "Chlorine"

45. ”chloride” was corrected to chlorine.

46. 358/12-15: Can this conclusion really be drawn from the present case study?

46. The statement that "events with early emission starting time . . . are likely to be strong dust events and are more likely to be transported and to reach the Amazon forest" was based on one case study, and it is far from being significant. However, in the frame of the unknown meteorological conditions which are necessary for transport of dust as far as the Amazon Basin, this statement may open a new insight regarding arrival of dust to the Amazon. In order to address this point the statement was restricted

and we clearly mention that further studies are needed. This issue is mention in page 19 line 471: "Although further studies are needed, our study suggests that..."

4. References

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5. Figure caption

Figure 1: (a) The location of the Bodélé depression (marked with red); (b) The Bodélé depression (composed of two main dust sources, marked in red) on a clear day (5 March 2008); (c-d) daily images of north Africa as seen by the MODIS instrument on board the Aqua satellite (collection 005) for 18 and 19 February, for the region between 37°N-5°S and 17°W-35°E. Blue regions marked area with no satellite coverage. The

gaps between two aerosol plumes are equivalent to emission less periods (usually nighttime). The images are taken from http://modis-250m.nascom.nasa.gov/.

Figure 2: Forward trajectories calculated using the HYSPLIT model, starting from several locations over the region of the Bodélé depression from the period between (Figure 2a here and Figure 9a in the revised manuscript) 14 and 15 and (Figure 2b here and Figure 9b in the revised manuscript) for 18 February 2008. The green, red and blue lines mark the height of the starting point at 0, 500 and 1000 m above ground level. The region near Manaus is marked by a white circle.

Figure 3: Cloud optical dept (total) for the region between 40° N-20° S and between 70°E-15°W, retrieved from Aqua instrument, for (a) 26 February, (b) 2 March and (c) 4 March 2008.

Figure 4 (not shown in the revised manuscript): a. Backward trajectories calculated by the HYSPLIT model, starting from several locations over the region of the Amazon Basin. The red, blue and green colors mark trajectories started at level height of 500, 1000 and 1500 m above ground level between 22 February and 5 March 2008. The region of Manaus and the Bodélé are marked by a white circle and triangle respectively; b. same as Figure 4a, but without trajectories from 26 February.

Figure 5 (not shown in the revised manuscript): Backward trajectories from HYSPLIT model, showing that the northern part of the aerosol plume (mostly donated to anthropogenic aerosol) originated from the northern part of Libya or/and Europe. Region of starting point was marked with white ellipse.

Figure 6 (not shown in the revised manuscript): Backward trajectories calculated from HYSPLIT model, originated near Manaus (Lat -3, Long -60) for height levels 100 m (red), 1000 m (blue), and 2000 m (green) above ground, for the period between 22 February and 4 March 2008.

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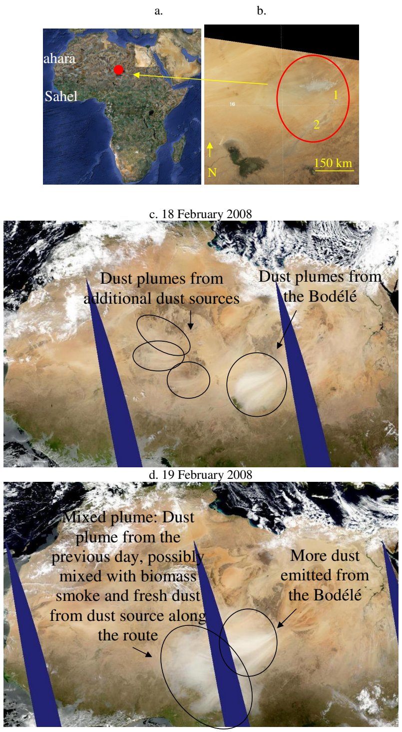

Fig. 1.

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Discussion Paper

a. b.

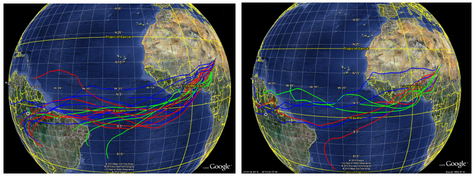

Fig. 2.

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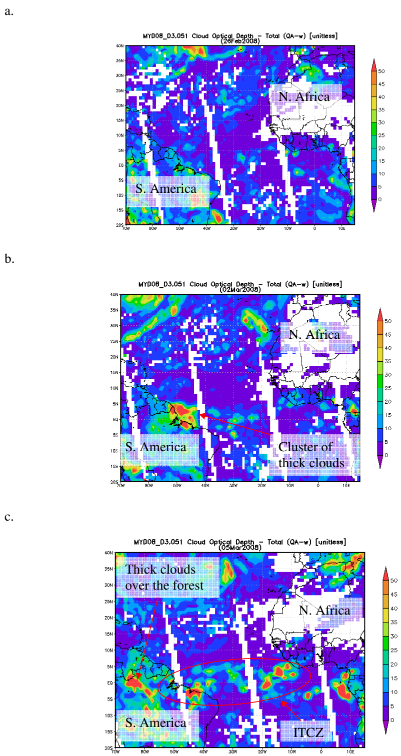

Fig. 3.

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a. b.

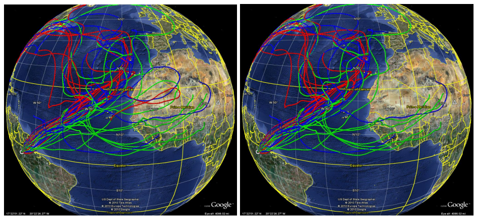

Fig. 4.

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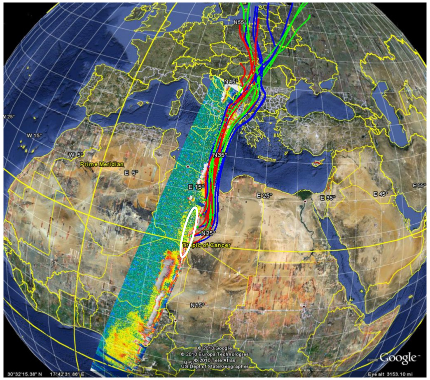

Fig. 5.

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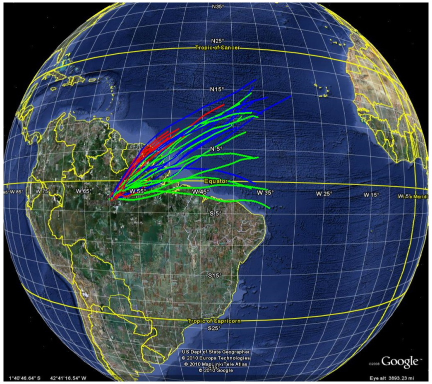

Fig. 6.