Interactive comment on “Transport of dust particles from the Bodélé region to the monsoon layer: AMMA case study of the 9–14 June 2006 period” by S. Crumeyrolle et al.

Anonymous Referee #2
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We thank referee #2 for his detailed and constructive comments on our manuscript. We have revised the manuscript attempting to take into account all the comments raised by both reviewers. We apologize for the delay due to the time required to perform the requested additional analysis.

Major comments

<u>1 Set up and diagnosis of the model</u> : The authors make a good case for correlating observations of a dusty PBL above the croplands with increased entrainment driven by locally high H. A similar case is not well made in the model. This of course is not helped by the use of what the authors imply is an inappropriate vegetation map, which does not capture the variability around 11N. I'm left somewhat confused about the discussion of the latitude of the dust maximum in the model and its relation to local vegetation cover (p5068-5071). The model does have locally reduced forest cover between 7 and 8N, though no local increase in PBL aerosol is evident there in Figure 9.
The authors have not presented clearly the evidence that the ECOCLIMAP forest cover field is controlling sensible heat flux and inversion height, and hence aerosol concentration. Other factors may also influence the sensible heat in the model, notably the surface model formulation and its sensitivity to vegetation cover, the underlying soil moisture, and incoming radiation. A much cleaner set of simulations would greatly benefit this study, one which assesses the sensitivity of dust to land cover in the region where it was observed. The authors themselves concede in their response (C4012) that this would be a better way of demonstrating the impact of the land cover on dust. Such simulations could be performed over a single diurnal cycle to minimise the impact of feedbacks and drifts that they note there.

We agreed with the referee that we have not presented clearly the evidence that the surface cover heterogeneities are controlling dust sedimentation process via the control of sensible heat flux and inversion height. To prove our hypothesis, the representation of the surface cover used in Meso-NH needs to be improved. Indeed, ECOCLIMAP-I corresponds to the period 1992–1993 using 1-km re-sampled datasets from the Advanced Very High Resolution Radiometer (AVHRR) instrument. Natural ecosystems typically vary on a decadal basis and therefore ECOCLIMAP-I is likely to be valid for the 90s. Updating ECOCLIMAP-I into ECOCLIMAP-II land cover map over West Africa is now performed on the basis of observations from MODIS (Kaptue et al., 2010). Unfortunately, the upgraded climatology is not yet operational with the version of the mesoscale model used in this study. Thus, a new simulation has been done using a manually modified surface cover and has been compared to the previous ones using ECOCLIMAP-I surface cover. Indeed, the Shrub fraction is quite significant along the ATR-42 flight track except between 7-8°N. In the same area, the crop fraction increases abruptly while the forest fraction seems to be negligible in this area. Then, the surface cover modification mainly affects the shrub and crop fractions. Indeed, all the vegetation type defined in the model, except the bare soil, are changed to crop .

Considering that boundary layer height evolution is related to surface heterogeneities, the comparison of both simulations should highlight differences in PBL dynamics and in particle concentration in the PBL. Figure 1 represents the shrub fraction from ECOCLIMAP I along the ATR flight track together with the difference of vertical wind speed between the initial simulation (ECOCLIMAP I, VAR) and the simulation including surface cover modifications (CROP). The shrub cover maximum heterogeneity occurs between 6.5 and 7.5°N exactly in the same zone where the maximum amplitude of the ΔW is observed. Moreover, in this specific area the covariance values are highest which implies that both parameters are not independent from each other. The same conclusions could be made regarding the meridional and zonal wind speeds. Figure 1 and the discussion above have been added in the revised version of the manuscript.

We also have added the difference of dust particle concentration at 1000m between the simulation using fixed soil cover and the simulation using ECOCLIMAP data. Negative concentrations correspond to particles which are present in the boundary layer in the case of surface heterogeneities and not present in the case of constant soil cover. One can see that the concentrations are negative in an area running from 6.5 to 9°N, exactly where the surface heterogeneities are located. As no dust outbreaks have been observed in the simulation between Niamey and Cotonou, these dust particles are coming from long range transport by the Harmattan flux. Thus, the surface heterogeneity seems to be linked with a maximum of vertical wind speed heterogeneities at the top of the PBL (i.e. entrainment) and with a maximum sedimented dust particles from the SAL into the PBL.

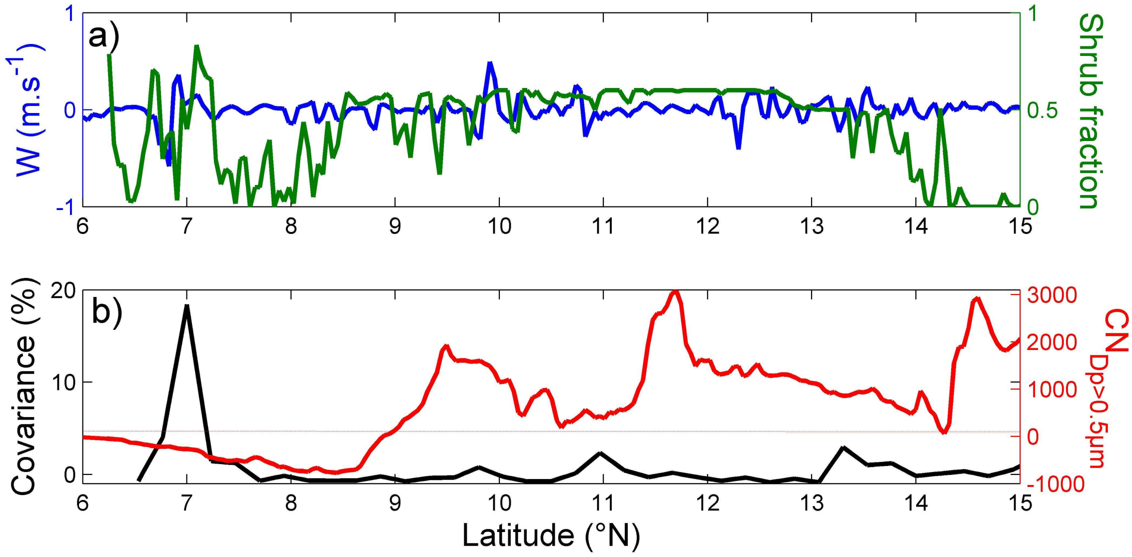

Figure 1: (a) Difference of vertical wind speed between the initial simulation (ECOCLIMAP I, VAR) and the simulation including surface cover modifications (CROP) and Shrub fraction (b) Covariance between both tendencies shown in Figure 1a and $CN_{Dp>0.5\mu m}$ (at 1000 m) concentration as a function of latitude at 1200 UTC on 13 June.

<u>2 Linking Dust to Land Cover Maps</u> : The authors make a critical distinction between the land cover north of 12.5N and the cover around 11N (p5065). They make this distinction based on calculating wood/shrub cover from the GlobCover classification, _20% around 11N compared to less than 10% north of 12.5N. (Note that in the manuscript, the authors comment, and figures 8 and 12, there is an inconsistency in the units of forest shrub cover – e.g. I think the axis on Fig 8 should go up to 70 rather than 0.7%). The authors are of course well aware from their comparison of ECOCLIMAP with GlobCover (which gives both regions 40+% woody cover) that global land cover maps may not be particularly accurate in terms of defining this property. There could also be a seasonally varying component in the emission of aerosol from croplands, with more exposed soil in June than later in the growing season. This is particularly true in 2006 when NDVI shows a delay of 1 month in the growing season relative to the longer term mean. I therefore think they need to justify much better their assertion that there is no local emission of aerosol around 11N and discuss explicitly the shortcomings of using a single global land cover map to determine woody cover. This is an important part of their story. Also on this issue, the authors refer to observations at Djougou – is the vegetation cover there similar to the extensive cropland at 11N?

We agreed with the referee that the comparison of ECOCLIMAP with Globcover is not a trivial work. Indeed, the definitions of the different vegetation types in both surface cover maps are not similar. The forest and shrub fractions are define separately in ECOCLIMAP and at the same time in GlobCover which may involve some discrepancy. However, these divergences have no consequences on the general trend of vegetation and therefore on the strong heterogeneities.

The 2006 monsoon season was characterized by a 10-day delayed onset compared to climatology, with convection becoming developed only after 10 July. This onset delay impacted the continental hydrology, soil moisture and vegetation dynamics as well as dust emission. During June 2006, the Normalized Difference Vegetation Index (NDVI) shown in Janicot et al. (2008) are between 0.3 and 0.4 in the area running from 10 to 12°N. This NDVI corresponds to a vegetation cover larger than 18%. Kimura and Wang (2009) study the relation between dust outbreak and vegetation cover on the Loess Plateau, a significant dust source area of East Asia. The soil properties in this region are comparable to the one of the Sahelian region. Their results show that the threshold NDVI for preventing dust outbreaks was about 0.2 when the wind speed ranged from 7 to 8 m s^{-1}. In June 2006, the average wind speeds, reported by Janicot et al. (2008), don't exceed $5 m.s^{-1}$. Then, the averaged conditions are not faciliting dust outbreaks. Only the passage of a mesoscale convective system leading important wind speed (> $9 m.s^{-1}$) may involved dust outbreaks. Looking to the SEVIRI satellite pictures, the last MCS passage over this region was observed on 11 June 2006 19:00 UTC. Moreover, no dust plume have been observed over the region of interest on 13 June 2006 on MODIS pictures (Figure 2).

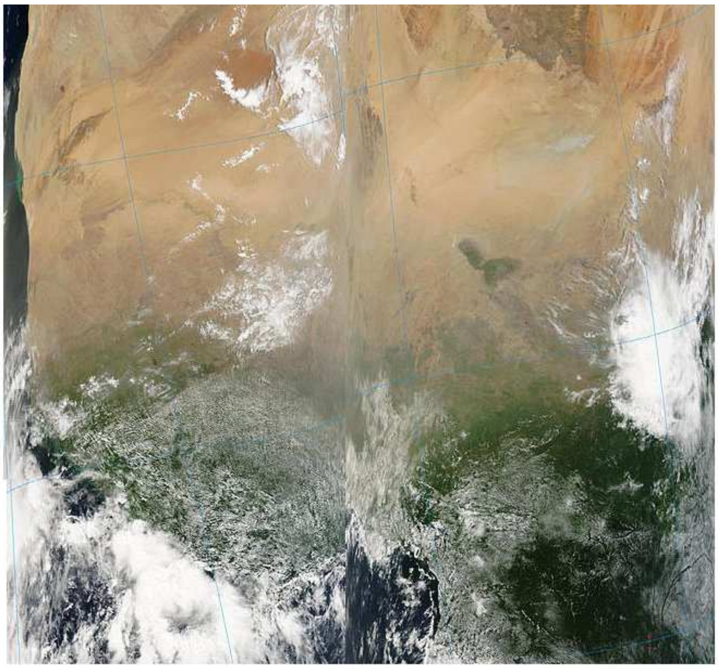

Figure 2: Satellite images from MODIS over West-Africa domain on 13 June 2006 at 11:10 UTC (right side) and at 09:30 UTC (left side).

<u>3. Boundary Layer Processes:</u> There is a lack of clarity in the manuscript about the boundary layer processes linking spatial variability in dust to vegetation. The abstract claims "The goal of the present study was to determine the process that facilitates the sedimentation of dust particles from the Saharan Air Layer (SAL) to the boundary layer". The study highlights the observed correlation between aerosol concentration and forest cover, and uses the model to try to confirm this. However they have not isolated the dynamical process(es) responsible for the correlation. Two likely causes which the authors highlight are (i) entrainment of aerosol-rich air into the PBL above a surface with high sensible heat fluxes and (ii) additional entrainment associated with mesoscale circulations driven by horizontal variations in sensible heat flux. The second effect is discussed (p5066), and is further emphasised by the authors in the opening section of their response to Referee 1 (C4005), yet no evidence of coherent circulations is presented, either in the model or observations. This needs to be clarified with more detailed model diagnosis.

The main process that leads to the presence of dust particles in the boundary layer is the entrainment of aerosol-rich air into the PBL above a surface with high sensible heat fluxes. This point has been clarified in the text. More detailed model diagnoses have been used to illustrate the effect of surface heterogeneities on the PBL dynamic. The difference in vertical wind speed as well as the covariance (Figure 1 above) highlight a relationship between the surface and the dynamical parameter in the BL.

Moreover, we compared three simulations with different surface cover :
- VAR: ECOCLIMAP data
- C30: Constant surface cover (only cropland surface)
- TRE: Constant surface cover (only forest surface)

The height of the boundary layer has been defined using the turbulent kinetic energy (TKE) and the temperature inversion criteria (Stull, 1988). The top of the monsoon flux is defined by the wind shear criterion (Lamb 1983). The PBL evolution resulting from the TKE criterion as well as the monsoon flux top are shown on Figure 3. In this exercise of comparison, it is important to take into account the trend of each curve, not absolute values. Indeed, the boundary layer height values in cases of constant surface cover are not representative of the reality. Looking only at PBL fluctuations, two regions may be distinguished: the northern part of the domain (10-15°N) and the southern part of the domain (6-9°N). In the Northern part, the height of the boundary layer is similar for the VAR and C30 simulation while TRE simulation results are different between 13-15°N. This is probably a consequence of the more intense water exchange over forest than for other types of vegetation. In the southern part of the domain, the boundary layer height shows clearly a different tendency for VAR simulation results than for the two others. Indeed a strong increase is observed at 7°N (heterogeneity area) as opposed to the PBL for the constant surface cover simulations, which remains more or less constant. Moreover, the boundary layer height is observed only one time above the monsoon flux top which means that exchanges between SAL and PBL occurs only when the surface cover is variable between 7 to 9°N. Thus, this figure is highlighting a clear effect of surface cover heterogeneities on the PBL dynamics and therefore on the dust sedimentation. Figure 3 and the discussion above have been added in the revised version of the manuscript.

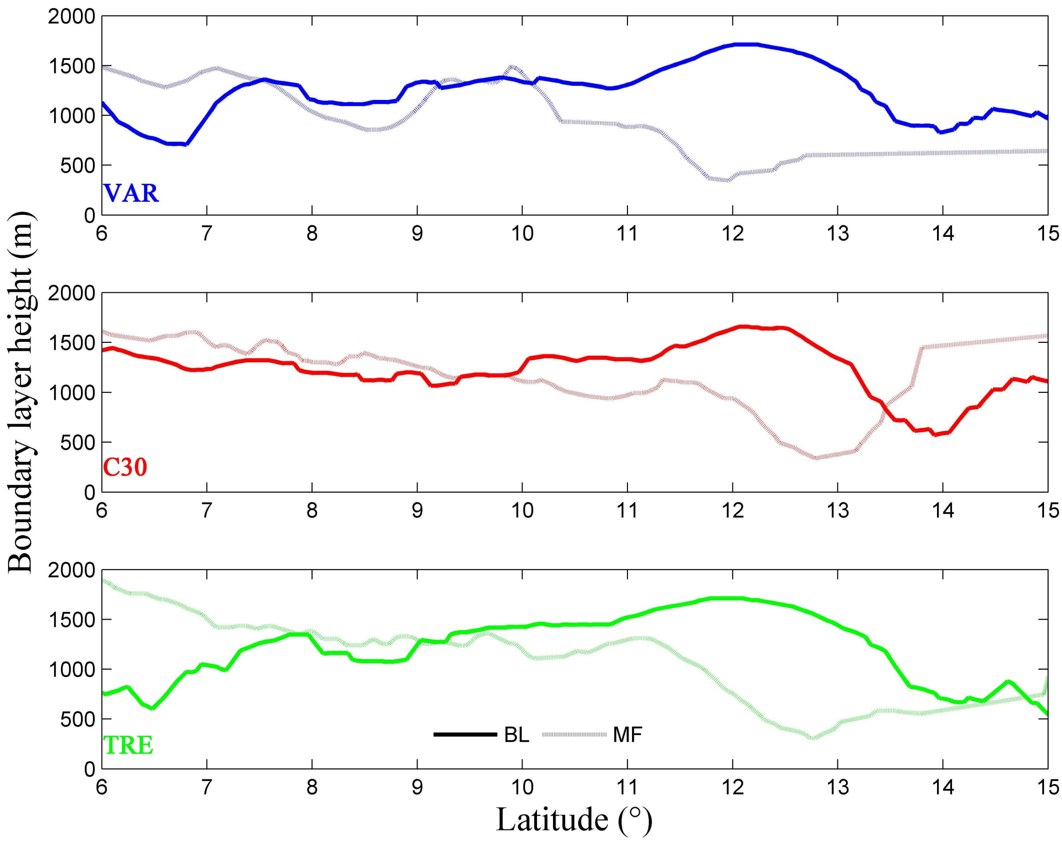

Figure 3: Height of the boundary layer (BL, solid line) and the monsoon flux (MF, dashed line) as a function of latitude for three simulation runs on 13 June 2006 12:00 UTC. VAR : variable vegetation cover, C30: constant surface cover of cropland, TRE: constant surface cover of tree.

Minor comments

<u>4. Initialisation of the surface:</u> It is not stated explicitly (p5057), but I assume that soil moisture was initialised from the ECMWF analysis. It is not good practice to translate soil moisture values directly from one land model to another, as discussed by e.g. Koster et al, J Clim 2009. This could impact the results as the sensitivity of H to vegetation cover depends, amongst other things, on soil moisture. A far-preferable alternative would be to use the offline ALMIP generated soil moisture from the ISBA model to initialise the model and minimise soil moisture spin-up issues.
The reviewer is correct in saying that soil moisture could impact our results via the sensitivity of H or the vegetation cover. In our study case, we use the ECMWF data to generate soil moisture. As it was not specified in the text, we added a sentence in the paragraph Description of the mesoscale model. Unfortunately, this line of work has not been considered but it seems certain that the use of soil moisture, from ISBA, could yield better results. However, most simulations with MesoNH routinely use soil data from ECMWF and experience shows that results are representative of reality.

<u>5. Discussion of profiles (p5064) :</u> "These key dynamical and thermodynamic parameters are well represented in the simulation, although at 10_ N (Fig. 6b) the top of the monsoon layer is overestimated by 400 m. The observed and simulated wind speed profiles are similar; nevertheless the simulated values are most often underestimated in the monsoon layer (2–4ms−1) as well as in the Harmattan layer (2ms−1). The simulated and observed 10 potential temperature profiles are almost the same for the four dropsondes." The height of the inversion is critical for studying entrainment. Whilst it is true that the comparison of potential temperature is pretty good over the lowest 7km of the atmosphere, an inversion height error of_400m (compared to the observed value _1500m) should not be swept under the carpet as it might influence the results.
There are differences on some profiles, and this may influence the BL top but the majority of the observed BL heights are the same in simulation. Moreover the inversion height error of 400m is located at 10°N and not exactly in the zone of interest (7-9°N).

<u>6 It would greatly</u> help the reader if a measure of aerosol from Figure 7 was included on Figure 8.
The evolution of the concentration of particles with diameter larger than 0.5µm has been added on the Figure 9.

<u>7. "Recent studies</u> investigated the impact of vegetation heterogeneities on the dynamics within the planetary boundary layer (Taylor et al., 2003, 2007; Garcia-Carreras et al., 2010). These studies highlighted a strong relationship between the boundary layer temperatures, the boundary layer top, the meridional wind velocity and the fraction of forest or shrub cover" (p5066). Only the latter study investigated woody cover, the other two focused on soil moisture forcing.
This has been changed to:" Recent studies investigated the impact of soil moisture and vegetation heterogeneities on the dynamics within the planetary boundary layer (Taylor et al. 2003; Taylor et al. 2007; Garcia-Carreras et al., 2010). Moreover, Garcia-Carreras et al. (2010) highlighted a strong relationship between the boundary layer temperatures, the boundary layer top, the meridional wind velocity and the fraction of forest or shrub cover."

<u>8 The use of Bowen ratio (p5066)</u> is misleading given the contrasts in roughness and albedo between forest and cropland which will affect the total turbulent flux and surface temperature. "The boundary layer temperature anomalies caused by variations in sensible heat flux or Bowen ratio at boundaries between forest/shrub and cropland lead to an increase in the boundary layer top" and "Over the area running from 9.9_ N to 12.3_ N, the forest/shrub cover diminishes (15%) from 9.9_ N to 11.1_ N, and as a consequence of an increase in Bowen ratio, the surface temperature increases."

The reviewer is correct in stating that roughness and particularly albedo are also crucial in determining surface fluxes. Aircraft data presented in Garcia-Carreras et al. (2010) which cover a similar region of Benin showed that regions of cropland were in fact associated with higher PBL temperatures (and therefore higher PBL heights). Given that the forested regions tend to be darker than the cropland, this suggests that variations in Bowen ratio are in fact the dominant mechanism via which the surface affects PBL temperatures in the region. This has been clarified in the text.

9 "Thus, the BL height has been estimated using the method described in Hopkins et al. (2009)" (p5066). An additional sentence here would be helpful to describe the method.

New sentences:

“Thus, the BL height has been estimated using the method described in Hopkins et al. (2009). This method is based on the fact that the temperature and depth of a convective boundary layer are related to the stratification above the boundary layer top : if we assume that this stratification is relatively invariant with position, then boundary layer depth are directly related to the mixed-layer temperature. »

10 "Garcia-Carreras et al. (2010) show that the vegetation anomalies are related to the vertical transport of isoprene from the surface to the upper layers" (p5067). Cause and effect are not clear in this phrase.

This has been changed to: “Garcia-Carreras et al. (2010) show how vegetation anomalies can lead to mesoscale circulations which in turn control the vertical transport of isoprene from the surface to the upper layers.”

11. The discussion of Figure 10 is confused for me by referring to an “evolution as a function of latitude”. Is this an evolution as the air mass travels south, or as the southbound aircraft launched sondes?

This has been changed in: “Figure 11 shows the evolution of the dust mass size distribution as a function of launched sonde latitudes for both simulations SED and NOSED (line and dashed line, respectively).”

12. What is the time of day in Figure 11?

The time of day in Figure 11 is 1200 UTC on 13 June. This has been added to the capture of this figure.

13 "The top of the monsoon flux, marked with the black line (Fig. 11), has been delineated using the method given by Lamb (1983)" (p5068). "Monsoon flux"? The height of the inversion would be a useful property to show here.

The height of the inversion has been added to the figure instead of the top of the monsoon flux.

14 "Furthermore, this sedimentation process leads to the presence of dust in the boundary layer down to 800 m, corresponding to the higher altitude of the ATR-42 flight plan, between 7.3_ N and 8.8_ N" (p5068). I would have expected the dust concentration to extend throughout the PBL here, as it does between 10 and 12N in Fig 11.

The homogenization of particle concentrations in the boundary layer may take time, at least one day. In the area of interest, it seems that this phenomenon had just happened and therefore the particle concentrations have not yet homogenized via turbulent fluxes.

Reference :

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Kimura R., Bai L., Wang J. Relationships among dust outbreaks, vegetation cover, and surface soil water content on the Loess Plateau of China, 1999-2000 (2009) Catena, 77 (3), pp. 292-296.

Stull, R.B. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, 666 pp., 1988