

## ***Interactive comment on* “Observations of mesoscale and boundary-layer circulations affecting dust uplift and transport in the Saharan boundary layer” by J. H. Marsham et al.**

**J. H. Marsham et al.**

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We would like to thank the reviewer for taking the time to make detailed and useful comments. The paper has been revised accordingly (and also to reference relevant papers published after this paper was submitted).

In the revised paper, only cospectral analysis from B302 is presented in detail (where lower along-track winds gave clearer relationships between land surface temperatures and boundary-layer properties, Section 3.2). Observed effects of such processes are also discussed for B301, but these are less clear due to the stronger along-track winds (Section 3.3). The old Figure 9, which showed coherence between boundary-layer variables from flight B301 on scales between 4 and 10 km has been removed, since, as

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described below, the analysis of these observations is beyond the scope of the paper and not required for the LEM simulations based on data from this flight. The COSMO simulations of the Saharan boundary layer are also now evaluated using aircraft data from flights B301 and B302 (thus including a new Figure 5).

A region of the low-level flight-track from B301, where it appears that dust was being uplifted is then identified. Large eddy modelling is then used to investigate the expected contribution to dust uplift made by the boundary-layer circulations resolved by the LEM, that would not be resolved by a regional or global model (Section 3.3.1). The LEM simulations shows boundary-layer rolls, with boundary-layer convection contributing to dust uplift. The analysis of the any possible linear organisation of the boundary-layer convection in reality is beyond the scope of this paper, and perhaps expected to be complex, since the flight-track was oriented almost along the axes of the modelled rolls. The LEM results are, however, consistent with the larger scale peak in the power spectrum of vertical winds from B301 compared with B302 and the observation of dusty updraughts on the scale of this peak during flight B301. The results from and limitations of this approach are clearly described in Section 3.3.1 as well as in the conclusions.

Finally, the nomenclature used in this paper has been revised to aid clarity and make it consistent with the rapidly developing meteorological literature on this region. CBL is used to refer to the convective boundary layer that is directly coupled to the land surface, SRL is used to refer residual boundary layer that this is often observed above this in the Sahara (Saharan Residual Layer). Where the Saharan boundary layer is advected over colder boundary layers (e.g. the monsoon) the elevated dry almost well mixed layer is referred to as the SAL (Sahara Air Layer). Before, in the submitted paper, SAL was used instead of SRL. These terms are now introduced in the introduction, “Over the Sahara, large surface sensible heat fluxes and deep dry convection can result in a summertime boundary layer that is up to 6 km deep (Gamo, 1996). However, profiles from the Sahara in summer typically show a shallower active convective boundary layer (CBL), with a near neutrally stratified residual layer above (the Saharan

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Residual Layer, SRL). This is typically capped by a strong inversion at approximately 5.5 km. Where a colder boundary layer (e.g. from the monsoon or the ocean) has undercut the Saharan boundary layer, the resultant elevated dry layer is referred to as the Saharan Air Layer (SAL). The deep dry SAL layer allows much of the Saharan dust plume to avoid rain-out over the Atlantic, allowing the dust to be transported globally. Furthermore, it has also often been observed that the SAL and SRL can contain distinct sub-layers, each with different water vapour and dust contents.”  
and the remaining text has been revised accordingly to use these terms.

Details of the changes made are now given in reply to the specific comments made.

#### 0.1 General comments

**The authors consider two flights in the Sahara during the GERBILS campaign to study the effect of land surface temperature variation on boundary-layer (BL) mesoscale spatial variability in wind and temperature and on dust uplift, at scales  $> 2$  km and  $< 20$  km. They are stating that they observe convective boundary-layer rolls that increase the dust uplift and they use a mesoscale model and a Large Eddy Simulation to lend further support to their analysis and to estimate the contribution of the rolls.**

**The subject is of practical interest and challenging. Convection definitely lifts and transports dust within the BL through the turbulence associated with thermal activity and shear at surface. Structures at larger scale participate to their mixing and transport. In the global models, the uplift rate is parameterized and deduced from the wind at the first level. No-wind situation, as pointed by the authors, will typically raise issues, since they will be cases with potential large role of convectively driven boundary layers, with large wind gusts due to thermal**

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activity. So that the GCM will have to represent correctly the subgrid turbulence kinetic energy and friction velocity to properly estimate the dust uplift.

However, the authors often seem precipitate to draw conclusions from their observations and numerical simulation. Several arguments are uncorrect or not sufficiently convincing, although crucial for the conclusions drawn.

**1. When considering weak winds with convection as the main contributor of dust uplift, it is likely more due to triggering thermals and especially dust-devils than due to rolls and mesoscale organization. The later are found above surface layer and even higher, and they have a major contribution to vertical transport, and also to the spatial distribution of dust, but probably not directly to dust uplift. Unless the shear associated with them plays a crucial role that would then need to be proven and estimated. Note that Koch and Renno (2005) whom the authors quote found a contribution of 34 % due to convection, including 26 % due to dust devils. That is within the convection contribution, more than 75 % is due to dust devils rather than non vortex thermals.**

The case presented is from B301 and has high mean windspeeds (10 to 15 ms<sup>-1</sup>. Figure 11(b) shows the sensitivity of the results presented to halving the windspeed, to a moderate 5 ms<sup>-1</sup>. Low wind situations, where triggering thermals and especially dust-devils are expected to dominate are not modelled. Their significance is discussed however,

“the windspeed variations from boundary-layer convection become more significant as the speed of the mean boundary-layer wind is decreased. However, at low-windspeeds processes such as dust devils, which would not be resolved by the LEM setup used, are expected to dominate (Koch and Renno, 2005).”

**2. In any case (weak wind or moderate wind), the occurrence of the convective rolls need to be better proved in the present study, as well as their direct con-**

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**tribution (through the shear associated with them for example) or the authors should not focus on well organized rolls specifically (if neither the observations nor the LEM convincingly show their existence). See several specific comments below for this aspect.**

As described above, the paper does now not focus on rolls specifically and this aspect of the paper has been substantially revised. The aim here was: (i) having identified a region on the flight-track of B301 where much of the dust observed was probably uplifted close to the flight track, (ii) to evaluate the contribution of eddies resolved by an LEM (but not a GCM) to the dust uplift for an LEM simulation based on this observed case (please see specific comment 42). The pdf of winds at the flight-level in the LEM is evaluated using the observations, and the pdf of winds at the lowest level in the LEM is used to estimate dust uplift. This analysis is now in its own subsection, 3.3.1, "The contribution to dust uplift from boundary-layer convection evaluated using LEM simulations".

The cospectral analysis of B301 has been removed since this analysis was incomplete and unnecessary for our objectives, although it is briefly referred to, "Cospectral analysis of data from B301 is not shown, but at scales between 5.5 to 12.5 km, which includes the 10 km scale of the peak in the power spectrum of vertical winds observed for B301, it showed a significant (90%) coherent relationship between nephelometer scattering data, WVMRs and vertical winds. Both WVMRs and the scattering were in phase with the vertical winds showing moist dusty updraughts and cleaner drier downdraughts on these scales. This is consistent with dust uplift occurring at the surface and the entrainment of cleaner air into the CBL from the SRL above."

This is shown by the Figure 1 (in [http://homepages.see.leeds.ac.uk/~lecjmACP-2007-0539/acp-2007-0539-add\\_figs.html](http://homepages.see.leeds.ac.uk/~lecjmACP-2007-0539/acp-2007-0539-add_figs.html)).

We note that the LEM shows linearly organised boundary-layer convection, and it is possible that such organisation is responsible for the larger scale peak in the power

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spectrum of vertical winds from B301 compared with B302. A more complete evaluation of any possible rolls is beyond the scope of this paper (and expected to be difficult as the flight-track was probably oriented close to the roll axes).

The abstract has been revised accordingly,

“A region of local dust uplift, with strong along-track winds, was identified in one low-level flight. Large eddy model (LEM) simulations based on this location showed linearly organised boundary-layer convection. Calculating dust uplift rates from the LEM wind field showed that the boundary-layer convection increased uplift by approximately 30%, compared with the uplift rate calculated neglecting the convection.”

Similarly, the conclusions now state,

“A region of the flight-track where dust was occurring locally was identified from this day, and LEM simulations based on this case showed linearly organised boundary-layer convection. This organisation may explain the observation that the power spectrum of vertical winds on this day had its peak at a approximately 10 km, a larger scale than observed on the next day (B302), and significantly larger than the modelled CBL depth from COSMO ( $\approx 1.5$  km). There was also a significant coherence between aerosol scattering, WVMRs and aerosol scattering on this scale (scales between 5.5 to 12 km), showing moist dusty updraughts. This is consistent with dust uplift at the surface and the entrainment of cleaner drier air from above.”

**3. The authors do not consider scales smaller than 2 km in their study. It is very interesting to consider scales  $> 2$  km and  $< 20$  km for studying the impact of LST heterogeneity on wind circulation in the boundary layer and possible impact on aerosol transport, but since the authors are considering the role of convection, and albedo anomalies that are responsible for varying potential temperature and depth of the BL, it seems important to consider the smaller scales of the associated processes (with for example an analysis of the variability of turbulent**

**kinetic energy, heat fluxes, and other variables that can estimated during the low level leg). An analysis of the turbulent kinetic energy and turbulent fluxes would enrich and lend further support to their analysis of the BL larger scale variability in wind, temperature and dust lift and transport.**

No coherent relationship between LSTs and CBL properties were observed on scales smaller than 2 km. This is stated,

“cospectral analysis showed that there was a significant relationship between albedo and LST for all scales where a relationship between LST anomalies and boundary properties were observed (*i.e.* >10 km, but in fact for all scales >2.5 km, not shown).”

Processes occurring on scales smaller than 2 km are expected to affect dust uplift. A grid-spacing of 200 m was used in the LEM, and the limitation of this are noted,

“an LEM simulation is used to investigate the expected contribution to dust uplift made by the boundary-layer circulations resolved by the LEM, that would not be resolved by a regional or global model.”

“ Figure 10(a) shows linearly organised boundary-layer convection (“rolls”) in the LEM oriented approximately east-west. The roll-spacing of approximately 2.5 km is well resolved by the LEM grid-spacing of 200 m.”

“At low windspeeds processes such as dust devils, which would not be resolved by the LEM setup used, are expected to dominate (Koch and Renno, 2005).”

“It is not clear to what extent parametrisations and thresholds used by Cakmur et al (2004) and Marticorena et al (1997) are applicable on the small spatial and temporal scales resolved by the LEM. Therefore the quantitative details of the enhancement discussed above remain somewhat uncertain. In addition, scales smaller than those by the LEM may be significant for dust uplift (Koch and Renno (2005). However, despite these uncertainties, the estimated enhancement of uplift, support the other existing evidence that boundary-layer convection plays a significant role in driving dust uplift in the Sahara (Cakmur et al, 2004)”

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**4. Before leaning on the COSMO mesoscale modelisation to deduce some processes of dust transport, the authors need to validate the simulation. The validation of the LEM is also short.**

COSMO is now evaluated using the low-level aircraft legs and the only profile available that was unaffected by the monsoon flow. A new Figure 5 has been added to show this profile, from the eastern end of the low-level leg of B302. Figures 4 and 8 (old Figure 7) now show the corresponding COSMO data in addition to the aircraft data from the low-level legs.

These comparisons are now discussed in the text,

“Dashed lines in Figure 4 are from the COSMO forecast. This shows potential temperatures within 2 K of those observed, WVMRs within  $1 \text{ gkg}^{-1}$  and along-track winds typically within  $1 \text{ ms}^{-1}$ . However, the windspeeds in COSMO were up to  $6 \text{ ms}^{-1}$  lower than observed, since the across-track northerly winds in COSMO were too weak. Northerly winds were stronger further north in COSMO, suggesting that the low-level convergence of the ITD may have been too far north in the model. Despite this, the location of the windspeed maximum, at around  $8^\circ\text{W}$  was well captured by the COSMO forecast.”

The implications of this for the analysis are now stated,

“The land surface in COSMO includes an albedo feature at  $8^\circ\text{W}$ . In the model, this feature has an albedo of approximately 0.18 compared with 0.2 elsewhere on the aircraft flight-track (Saharan albedos in COSMO are lower than observed from the aircraft or from MODIS). The atmosphere in COSMO responds to the change in albedo, orography and soil at  $8^\circ\text{W}$ , showing a weak local temperature maximum and WVMR minimum (Figure 4). This supports the hypothesis that the local temperature maximum seen at  $8^\circ\text{W}$  in the observations is due to the change in land surface there.”

“Figure 5 shows the aircraft profile upwards from the eastern end of the low-level transect of B302 (the western profile was affected by the monsoon flow). Figure 5(a) shows that the boundary layer in COSMO was approximately 1 K too cold and  $1 \text{ gkg}^{-1}$  too moist, but the modelled boundary-layer depth was very close to that observed.

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Above the boundary layer, the SRL is observed to contain three main sub-layers (1500 to 2400 m, 2400 to 3300 m and 3300 to 5700 m). The lower two layers have similar dust and moisture contents, while the upper layer is drier and less dusty. Figure 5(b) again shows a more accurate representation of the westerly winds than the southerly winds in COSMO, although the trends with height are good and below 3 km values are typically within  $3 \text{ ms}^{-1}$ . The accuracy of the CBL depth shown by COSMO in Figure 5(a) lends some support to its accuracy elsewhere along the low-level transect of B302. Figure 5(d) shows this CBL depth (shown by the dashed black line and determined as the lowest model level where the potential temperature was not more than 0.5 K than the modelled mixed-layer depth). This shows that B302 was within the lower part of the CBL (0.18 to 0.35 times the CBL depth), which is consistent with the observed convergence over warm land surface anomalies. ”

and

“This is consistent with advection of dust into the flight-track from a location upstream, where the windspeed maximum was further to the east than the windspeed maximum on the flight-track. Such an eastwards displacement of the upstream windspeed maximum is shown by the COSMO model (Figure 4(b)), although as noted there are significant errors in the COSMO wind field.”

Similarly, for B301,

“As a result [of profiles being affected by the monsoon], both profiles to and from the low-level leg were not of use in evaluating the representation of the Saharan CBL in COSMO. Marsham *et al* (2008) show that for the profile at the eastern end of the low-level leg, which was affected by the monsoon, COSMO gave a good agreement with the broad features of this profile, but not the fine-structure of the layerings observed in the SAL). CBL depths from COSMO suggest that the low-level leg from B301 was at an altitude approximately in the middle of the CBL (Figure 8(d)), which is expected to make identification of convergence or divergence over land-surface anomalies difficult.”,

“Figure 8 shows windspeeds (which are dominated by the along-track winds) increas-

ing from west to east, which is consistent with the COSMO simulation (dashed lines in Figure 8 and also see Figure 3(c)). COSMO gives an accurate forecast for the low-level leg, with temperatures within 1 K of those observed, WVMRs approximately  $2 \text{ gkg}^{-1}$  too moist and east of  $8.3^\circ\text{W}$ , windspeeds within  $1 \text{ ms}^{-1}$  of those observed. The errors in windspeed increase towards the west, reaching approximately  $4 \text{ ms}^{-1}$  at  $9.5^\circ\text{W}$  (Figure 8).”

and

“Dust loadings west of  $8.8^\circ\text{W}$  were low, but are observed to increase towards the east with the increasing windspeeds (Figure 8(b)). Winds were oriented from approximately  $260^\circ$  *i.e.* almost along the west to east flight track. Windspeeds upstream were lower than those at the point of observation and COSMO simulations showed 10 m windspeeds increasing from midnight to the time of observation. East of  $8.5^\circ\text{W}$  there was a strong positive correlation between observed windspeeds and aerosol scattering (Pearson correlation coefficient = 0.8, not shown). Therefore, it is likely that the dust observed was uplifted locally along the flight-track, in the area of higher windspeeds shown by COSMO to be oriented along the flight track (Fig. 3(c)).”

These evaluations of COSMO with the available observations are now mentioned in Section 2,

“COSMO forecasts are evaluated using aircraft observations from the Saharan boundary-layer in Section 3.”

The LEM is used to investigate the expected impacts of BL convection on dust uplift. It is an idealised simulation based on a region where observations from B301 suggested that dust uplift was occurring locally. The pdf of BL winds — which at the lowest level is the pdf that controls the enhancement of dust uplift by the BL convection — compares well with observations (Figure 10). Since this is the process we are investigating this is a sufficient evaluation for our purposes. This is now stated in the text,

“ The LEM was initialised using a profile from  $7.5^\circ\text{W}$ , in a region where dust uplift was probably occurring (as discussed in Section 3.2). The probability density function of

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the windspeeds from the LEM is very similar to that observed (Figure 10(b)), with a standard deviation of  $0.97 \text{ ms}^{-1}$  for LEM and  $0.87 \text{ ms}^{-1}$  for the observations. This supports the use of the LEM for investigating the role of boundary-layer circulations in dust uplift in this case, although the LEM will fail to capture features with scales of less than approximately 1 km (five times the grid-spacing).”

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