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## Surface wind accuracy for modeling mineral dust emissions: Comparing two regional models in a Bodélé case study

B. Laurent,<sup>1</sup> B. Heinold,<sup>1</sup> I. Tegen,<sup>1</sup> C. Bouet,<sup>2,3</sup> and G. Cautenet<sup>2</sup>

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[1] After a decade of research on improving the description of surface and soil features in desert regions to accurately model mineral dust emissions, we now emphasize the need for deeper evaluating the accuracy of modeled 10-m surface wind speeds  $U_{10}$ . Two mesoscale models, the Lokal-Modell (LM) and the Regional Atmospheric Modeling System (RAMS), coupled with an explicit dust emission model have previously been used to simulate mineral dust events in the Bodélé region. We compare LM and RAMS  $U_{10}$ , together with measurements at the Chicha site (BoDEx campaign) and Faya-Largeau meteorological station. Surface features and soil schemes are investigated to correctly simulate  $U_{10}$  intensity and diurnal variability. The uncertainties in dust emissions computed with LM and RAMS  $U_{10}$  and different soil databases are estimated. This sensitivity study shows the importance of accurate computation of surface winds to improve the quantification of regional dust emissions from the Bodélé. **Citation:** Laurent, B., B. Heinold, I. Tegen, C. Bouet, and G. Cautenet (2008), Surface wind accuracy for modeling mineral dust emissions: Comparing two regional models in a Bodélé case study, *Geophys. Res. Lett.*, 35, L09804, doi:10.1029/2008GL033654.

### 1. Introduction

[2] Mineral dust is produced by aeolian erosion over desert areas when surface wind speed exceeds a threshold value. The surface-atmosphere interactions control the frequency of occurrence and the intensity of dust emissions. The radiative and biogeochemical impacts of intense dust pulse events on the environment differ from the dust background impact due to frequent but less intense events. To simulate the time and space variability of dust concentration, the emission processes have to be described rigorously with sub-daily and fine spatial resolutions.

[3] The explicit dust emission models [Marticorena and Bergametti, 1995; Shao, 2001] provide a physical description of the main processes involved in dust production (erosion threshold, saltation and sandblasting). They allow describing the spatio-temporal variability of the non-linear phenomenon of dust production if their input parameters (surface and soil features, surface winds) are accurately described.

[4] Specific efforts have been made to characterize soil properties of desert areas [e.g., Tegen *et al.*, 2002; Laurent *et al.*, 2008]. Accurate surface roughness ( $Z_0$ ) databases derived from satellite products are now available for desert areas [Marticorena *et al.*, 2004; Prigent *et al.*, 2005] and have improved the dust emission description [Marticorena *et al.*, 2004; Laurent *et al.*, 2006].

[5] While much research has been done to improve soil properties, the accuracy of the surface winds in dust modeling requires attention as horizontal emission flux is commonly defined as a third power function of the wind friction velocity. Surface winds from global models do not always allow to well describe the surface dynamics observed, nor to correctly simulate mineral dust emissions as shown for the Bodélé region, Chad [Koren and Kaufman, 2004; Bouet *et al.*, 2007; Laurent *et al.*, 2008]. Mesoscale models (e.g., Lokal-Modell LM, Regional Atmospheric Modeling System RAMS) are thought to be better suited to describe small-scale surface-atmosphere interactions, but do not always reproduce satisfactorily the 10-m wind speeds,  $U_{10}$  [Tegen *et al.*, 2006; Bouet *et al.*, 2007].

[6] This study aims at evaluating the LM  $U_{10}$  compared to RAMS  $U_{10}$  and in-situ measurements in the Bodélé, and its implication on the modeling of dust emissions over this region. To well simulate the intensity and diurnal variability of  $U_{10}$ , new LM  $U_{10}$  and new RAMS  $U_{10}$  are computed using different surface features and soil schemes. Dust emissions are computed for several wind and soil configurations, and uncertainties on mesoscale modeling are quantified.

### 2. Measurements and Modeling in the Bodélé Region

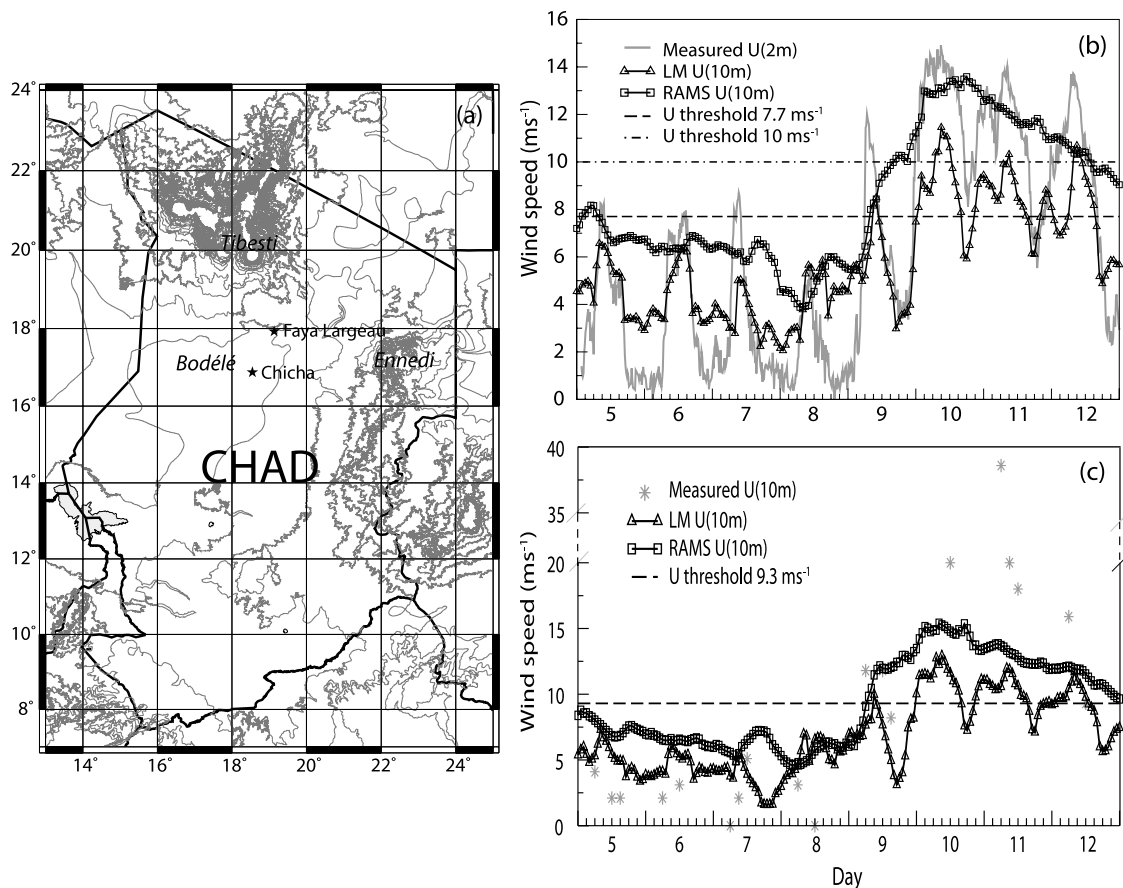
[7] The Bodélé is the most active Saharan dust source [Prospero *et al.*, 2002]. It is located in a topographic depression between the Tibesti and Ennedi mounts (Figure 1a). A characteristic of its boundary layer is the predominant Low Level Jet. The aim of the Bodélé Dust Experiment (BoDEx 2005), which took place in February-March 2005 at the Chicha site (16°53'N-18°33'E), was to establish the local conditions that account for high dust emissions [Washington *et al.*, 2006]. The 2-m wind speeds and temperatures (2 minute averaged values), and Aerosol Optical Thickness (AOT) were measured [Washington *et al.*, 2006; Todd *et al.*, 2007]. A severe dust event was observed during March 10–12. Moreover, the Faya-Largeau meteorological station (17°56'N-19°08'E) provides  $U_{10}$  and horizontal visibility measurements (every 3 hours, but data are often missing).

[8] Tegen *et al.* [2006] (hereafter T06) and Bouet *et al.* [2007] (hereafter B07) tested the ability of the LM and

<sup>1</sup>Leibniz-Institut für Troposphärenforschung, Leipzig, Germany.

<sup>2</sup>Laboratoire de Météorologie Physique, UMR 6016 CNRS, Université Blaise Pascal, Aubière, France.

<sup>3</sup>Now at Laboratoire Interuniversitaire des Systèmes Atmosphériques, UMR 7583 CNRS, Universités Paris, Créteil, France.



**Figure 1.** (a) Chicha and Faya, Bodélé region. (b) Measured 2-m wind speeds at Chicha (grey, data from *Washington et al.* [2006]) and (c)  $U_{10}$  at Faya (grey star), hourly LM  $U_{10}$  (triangle), and RAMS  $U_{10}$  (square) for March 5–12. The dashed lines correspond to the wind speed thresholds estimated for Chicha and Faya.

RAMS v.4.3.0 non-hydrostatic meteorological models to reproduce small-scale features associated with a dust event during the BoDEx period. LM is the operational weather prediction model of the German weather service Deutscher Wetterdienst (DWD) [*Doms and Schättler, 2002*]. It is operated with initial and boundary conditions from the Global Modell Europa (GME) of the DWD. RAMS was developed at the Colorado State University with the Mission Research Corporation MRC/ASTeR [*Cotton et al., 2003*]. It is initialized and laterally nudged every 6 hours by European Centre for Medium-range Weather Forecasting (ECMWF) reanalysis data.

[9] These two models were coupled with an explicit mineral dust emission scheme (MB95) [*Martcorena and Bergametti, 1995*]. T06 used as input parameter the surface roughness derived from POLDER-1 surface products ( $Z_{OP1}$ ) [*Martcorena et al., 2004*], the soil size distribution database developed by *Tegen et al.* [2002], and the LM  $U_{10}$ . B07 used the same  $Z_{OP1}$ , the soil size distribution database developed by *Laurent et al.* [2008], and the RAMS  $U_{10}$ .

[10] T06 performed the first dust mesoscale study over the Bodélé using LM  $U_{10}$  at  $7 \times 7$  km<sup>2</sup> resolution during March 1–13, 2005. The model domain, centered on Chicha, extends over  $2100 \times 1400$  km<sup>2</sup>. The model has 40 vertical levels with the first level centered at 33.5 m. Although LM underestimates the highest wind speeds occurring on March 10–12, the spatio-temporal evolution of a dust cloud could

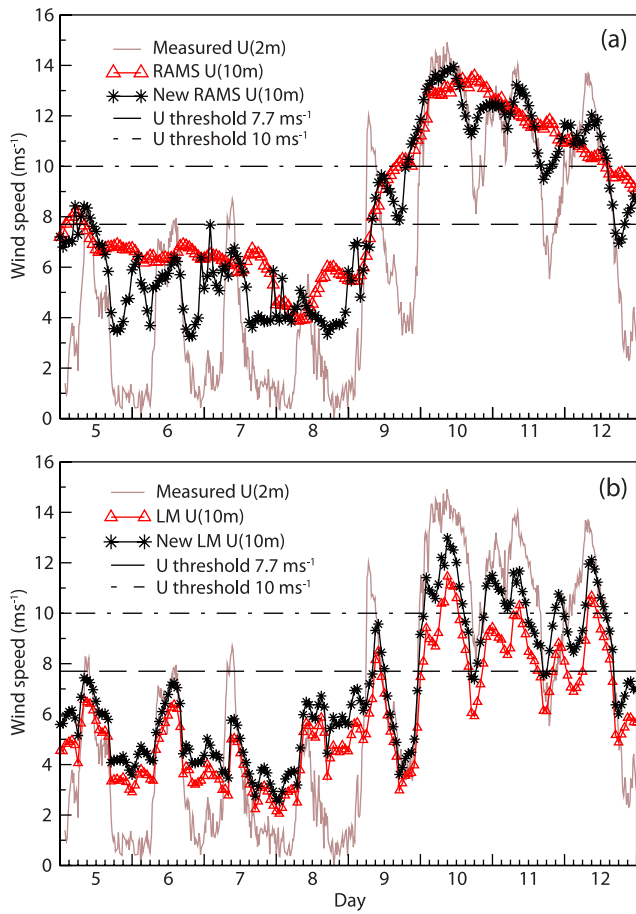
be reasonably well-reproduced in comparison with MODIS and BoDEx observations.

[11] B07 investigated the RAMS  $U_{10}$  versus the  $0.5^\circ \times 0.5^\circ$  ECMWF  $U_{10}$  to simulate dust emissions over the Bodélé during March 5–15, 2005. The model domain, centered on Faya, extends over  $1200 \times 800$  km<sup>2</sup> with a  $10 \times 10$  km<sup>2</sup> resolution. The model has 30 vertical levels with the first level centered at 23.9 m. RAMS captures the maximum measured wind speeds at Chicha, and allows simulating dust emission pattern on March 10–12 in the complex topography of the Bodélé.

### 3. Evaluation of the Modeled 10-m Wind Speeds

[12] For March 5–12, 2005, the LM  $U_{10}$  are compared with the RAMS  $U_{10}$  and the measurements at Chicha and Faya (Figures 1b and 1c). There is a very weak spatial variability of the LM and RAMS  $U_{10}$  for the pixels around Chicha and Faya. The simulated wind speeds presented in Figures 1b and 1c are thus representative of  $20 \times 20$  km<sup>2</sup> areas around Chicha and Faya, respectively.

[13] The LM  $U_{10}$  are underestimated during daytime at Chicha but their diurnal cycle agrees well with BoDEx measurements (Figure 1b). They do not exceed  $11.5$  ms<sup>-1</sup>, while in 15% of the time intervals during the BoDEx period the measured 2-m wind speeds are above  $10$  ms<sup>-1</sup>. The higher wind speeds measured at Chicha on March 10–12



**Figure 2.** Measured 2-m wind speeds ( $\text{ms}^{-1}$ ) at Chicha (grey, data from *Washington et al.* [2006]), (a) hourly RAMS  $U_{10}$  (red triangle) and new RAMS  $U_{10}$  (black star), and (b) hourly LM  $U_{10}$  (red triangle) and new LM  $U_{10}$  (black star). The dashed lines correspond to the estimated wind speed thresholds.

are captured by RAMS (max.  $13.6 \text{ ms}^{-1}$ ) but the diurnal cycle is not well-simulated. At Faya, the spaced measurements for the studied period make difficult to characterize the wind diurnal variability (Figure 1c). Nevertheless, the higher wind speeds are better simulated by RAMS (max.  $15.7 \text{ ms}^{-1}$ ) than by LM (max.  $12.9 \text{ ms}^{-1}$ ).

[14] To illustrate the potential dust emission, the estimated wind speed thresholds for dust emissions are also reported in Figures 1b and 1c. The thresholds estimated by B07 using the MB95 and  $Z_{OP1}$  are  $7.7 \text{ ms}^{-1}$  at Chicha and  $9.3 \text{ ms}^{-1}$  at Faya. *Todd et al.* [2007] estimated a higher threshold of  $10 \text{ ms}^{-1}$  at Chicha measuring the surface wind speeds associated to observed dust events. The LM  $U_{10}$  hardly exceed the thresholds and are not always able to simulate intense dust emission. The RAMS  $U_{10}$  could potentially overestimate dust emissions during the nighttime for March 10–12. The modeled winds can then lead to errors in the simulation of dust event occurrence and intensity.

[15] Possible reasons for these discrepancies in wind intensity and temporal variability are difficulties to represent the surface-atmosphere interactions, the subgrid scale topography, and to form a well-defined boundary layer in the models. Previous mesoscale model studies also pointed out the horizontal and vertical resolutions as critical issues to

simulate surface winds [*Hanna and Yang*, 2001; *Barthlott et al.*, 2006; *Fay and Neunhäuserer*, 2006].

[16] The RAMS  $U_{10}$  are computed from the 1st level (23.9 m) wind speeds using a corrective factor of 0.92 [*Bouet et al.*, 2007]. This empirical coefficient was established from an adjusting method comparing dust emissions simulated with RAMS and Météosat dust index products. There is thus a decrease of 8% of the RAMS wind speeds between the 1st and 10-m levels. We compute new RAMS  $U_{10}$  in the same conditions as RAMS  $U_{10}$  computed by *Bouet et al.* [2007] but using RAMS v.6.0 instead of the former RAMS v.4.3.0. An improved soil scheme (Land Ecosystem-Atmosphere Feedback model 3, LEAF3) is now implemented in RAMS v.6.0. Figure 2a shows that the new RAMS  $U_{10}$  present a well-marked diurnal wind variability in agreement with wind measurements, contrary to the former RAMS  $U_{10}$ . Even if the new RAMS  $U_{10}$  are still overestimated during the night, the use of the new RAMS v.6.0 soil scheme allows to better account for the diurnal soil energy budget and appears to be a key point to simulate diurnal variability of surface winds.

[17] The diurnal cycle being well-reproduced by the LM  $U_{10}$ , the underestimation of these winds compared to the RAMS and measured winds is a critical problem to study a threshold phenomenon like dust emission. The LM  $U_{10}$  are computed from the 1st level (33.5 m) wind speeds using a logarithmic wind profile depending on atmospheric stratification:

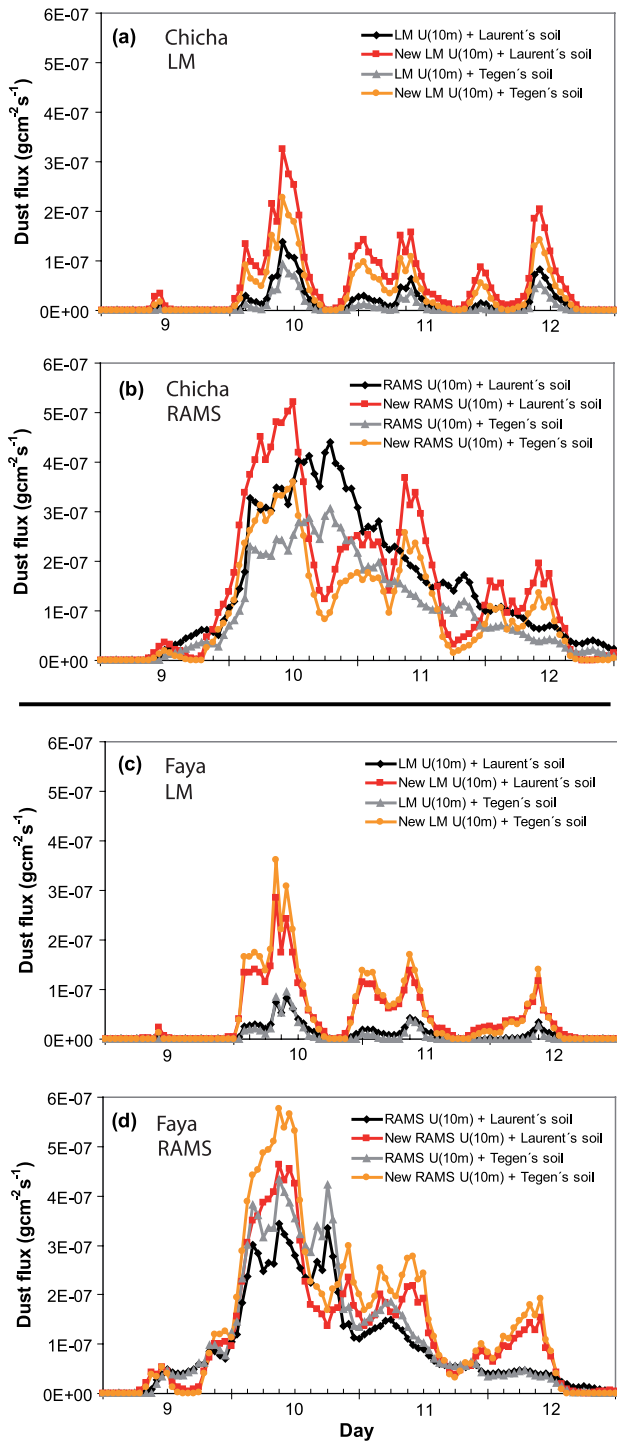
$$|U_{10}| = \frac{U^*}{K} \left\{ \ln \left( \frac{10}{Z_0} \right) + \psi_m(10, z_0, L) \right\} \quad (1)$$

with  $U^*$  the wind friction velocity,  $K$  the Von Karman's constant,  $L$  the Monin-Obukhov length, and  $\psi_m(10, Z_0, L) = 0$  in neutral stability conditions.

[18] For the studied period, linear relationships are obtained for Chicha ( $y = -0.22 + 0.79x$ ,  $r = 0.99$ ,  $n = 193$ ) and Faya ( $y = -0.21 + 0.78x$ ,  $r = 0.99$ ,  $n = 193$ ) between LM 1st level and 10-m wind speeds. A decrease of more than 20% is found between the 1st level and 10-m winds for LM.

[19] *Abu Bakr and Wieringa* [1988] analyzed the sensitivity of the wind speed in the Central Sudan as a function of  $L$ ,  $Z_0$  or  $U^*$ . They showed that the computation of wind speed is very sensitive to  $Z_0$  whereas the influence of  $L$  is limited. In the LM surface database,  $Z_{OLM}$  depends on the subgrid-scale variance of orography and land-use. The two contributions are added to obtain  $Z_{OLM}$ , which is approximately 5 cm for Chicha and Faya desert surfaces. This value is 2 or 3 orders of magnitude higher than  $Z_{OP1}$  at Chicha ( $Z_{OP1} = 0.42 \cdot 10^{-2} \text{ cm}$ ) and Faya ( $Z_{OP1} = 0.19 \cdot 10^{-1} \text{ cm}$ ) [*Laurent et al.*, 2008].  $Z_{OLM}$  database is used to compute mesoscale meteorological parameters, but to compute the 10-m wind speeds from the 1st level wind speeds, the use of the  $Z_{OP1}$  database, which characterizes the aerodynamic surface roughness length with a fine resolution and well-represents the surface roughness variability at Chicha and Faya, seems more relevant. New LM  $U_{10}$  are computed using a logarithmic profile in neutral stability conditions (equation (1)) and  $Z_{OP1}$  instead of  $Z_{OLM}$  at Chicha and Faya. The new LM  $U_{10}$  are 12% higher than the original LM  $U_{10}$  (Figure 2b), and better agree with the highest wind speeds measured during daytime. The increase in the nighttime wind





**Figure 3.** Hourly dust fluxes ( $\text{g cm}^{-2} \text{s}^{-1}$ ) computed for March 9–12 using Laurent's soil and Tegen's soil at (a, b) Chicha and (c, d) Faya, with LM  $U_{10}$ , new LM  $U_{10}$ , RAMS  $U_{10}$  and new RAMS  $U_{10}$ .

discrepancy does not affect emission too much because winds are more likely to be below the emission threshold.

#### 4. Implication on the Mesoscale Modeling of Dust Emissions

[20] While the ability of the LM and RAMS models to reproduce the AOT measured during a dust event was

discussed by T06 and B07, we investigate here the implication of the mesoscale wind representation on the modeling of dust emissions. Following T06 and B07, LM and RAMS are coupled with the MB95, and  $Z_{0P1}$  is used. Dust emissions are computed for several wind and soil configurations (Figure 3 and Table 1): with the LM  $U_{10}$ , new LM  $U_{10}$ , RAMS  $U_{10}$ , new RAMS  $U_{10}$ , and two soil databases [Tegen *et al.*, 2002; Laurent *et al.*, 2008].

[21]  $U^*$  can be considered as the relevant parameter to quantify the stress provided by wind to an erodible surface.  $U^*$  computed during the dust period of March 10–12 in the simulation configurations range from  $0.10$  to  $0.58 \text{ ms}^{-1}$  and are comparable to measurements for dust emissions in desert areas in the USA ( $0.19 \text{ ms}^{-1} < U^* < 1.0 \text{ ms}^{-1}$ ) [Gillette, 1979], and Niger ( $0.28 \text{ ms}^{-1} < U^* < 0.50 \text{ ms}^{-1}$ ) [Rajot *et al.*, 2003].

[22] For Chicha and Faya, large differences in intensity but also in the temporal evolution of the simulated dust emissions are observed. At Chicha, the hourly dust fluxes computed with Laurent's soil are higher than the ones computed with Tegen's soil (Figures 3a and 3b). Several dust events are simulated with the LM  $U_{10}$ , new LM  $U_{10}$ , and new RAMS  $U_{10}$  on March 9–12, with a maximum value on March 10 in the morning ( $1.4 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$ ,  $3.3 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$ , and  $5.2 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$  with Laurent's soil, respectively). Using the RAMS  $U_{10}$ , dust emissions are simulated continually for the same period with maximum fluxes on March 10 at noontime and in the afternoon ( $4.5 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$  with Laurent's soil).

[23] At Faya, the dust fluxes computed with the 2 soil datasets are similar for low winds, the fluxes computed with Tegen's soil being larger for the high winds (Figures 3c and 3d). The dust flux temporal variability is also more pronounced with LM winds than with RAMS winds, even if the dust event peaks are now more marked using the new RAMS. The maximum flux is simulated on March 10 in the morning with the LM, new LM, RAMS and new RAMS winds ( $9 \cdot 10^{-8} \text{ g cm}^{-2} \text{ s}^{-1}$ ,  $3.5 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$ ,  $4.4 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$ , and  $5.8 \cdot 10^{-7} \text{ g cm}^{-2} \text{ s}^{-1}$  with Tegen's soil, respectively). The AOT measurements at Chicha and the horizontal visibilities measured at Faya are insufficient to determine which simulation is more realistic.

[24] Table 1 presents the dust emissions simulated for March 10–12. The total emissions range from 29 to 502  $\text{g m}^{-2}$  at Chicha, and from 24 to 489  $\text{g m}^{-2}$  at Faya. For the same period, Todd *et al.* [2007] estimated an emission of 324  $\text{g m}^{-2}$  ( $\pm 40\%$ ) from sunphotometer retrievals of dust volume at Chicha and assuming the total exposed diatomite layer ( $\sim 10.8 \cdot 10^9 \text{ m}^2$ ) being a dust source. T06 simulated a dust emission of 104  $\text{g m}^{-2}$  using a corrective factor on the erosion threshold to compensate for the too low LM  $U_{10}$ . In fact, the emission simulated at Chicha using the original LM winds (29 to 56  $\text{g m}^{-2}$ ) seems to be underestimated. The emission computed with the new LM  $U_{10}$  and Tegen's soil is 122  $\text{g m}^{-2}$ , slightly higher than the estimation of T06. The new LM  $U_{10}$  thus provides satisfactory dust emission without lowering the erosion threshold using a corrective factor. The emissions simulated with the new LM (122 to 191  $\text{g m}^{-2}$ ), RAMS (344 to 502  $\text{g m}^{-2}$ ), and new RAMS (341 to 496  $\text{g m}^{-2}$ ) winds are in the same range as the previous estimations. Using RAMS v.6.0, the diurnal variability of the winds is more pronounced and leads to larger

**Table 1.** Dust Emissions Computed Using Laurent's Soil and Tegen's Soil and LM  $U_{10}$ , New LM  $U_{10}$ , RAMS  $U_{10}$ , and New RAMS  $U_{10}$  at Chicha and Faya During the Dusty Period, March 10–12, 2005<sup>a</sup>

	LM $U_{10}$	New LM $U_{10}$	RAMS $U_{10}$	New RAMS $U_{10}$
Chicha-Laurent's soil	56	191	502	496
Chicha-Tegen's soil	29	122	344	341
Faya-Laurent's soil	35	151	306	396
Faya-Tegen's soil	24	169	368	489

<sup>a</sup>Dust emissions are given in  $\text{gm}^{-2}$ .

dust emissions during the day and lower during the night than using the former RAMS v.4.3.0 (Figures 3b and 3d).

[25] The emission difference due to the two soil databases is around 35% at Chicha and 20% at Faya for the largest simulated emissions and can reach 50% and 30% for the lowest emissions, respectively. The emission difference due to the four wind databases is more than a factor 11 at Chicha and a factor 20 at Faya. If we just consider the emissions computed with the new LM  $U_{10}$  and new RAMS  $U_{10}$ , which better agree with in-situ surface wind measurements than the former LM and RAMS  $U_{10}$ , the dust emission difference is around 65%. These results confirm the importance of representing as accurately as possible the  $U_{10}$  to simulate dust emissions.

## 5. Conclusion

[26] The comparisons of  $U_{10}$  from simulations by LM and RAMS mesoscale models as well as in-situ measurements highlight the limitations of such models to reproduce correctly both the intensity and the diurnal cycle of the 10-m winds in the Bodélé. Nevertheless, the new RAMS  $U_{10}$  computed using the RAMS v.6.0 new soil scheme better reproduce the diurnal wind cycle in agreement with in-situ measurements. Moreover, the new LM  $U_{10}$  computed using  $Z_{OP1}$  values are 12% higher than the original LM  $U_{10}$  and better agree with the maximum wind speeds measured at Chicha and Faya during daytime dust events. The soil scheme (and then the soil-atmosphere heat budget) appears as a key parameter to model the diurnal variability of surface winds. We also highlight that  $Z_0$  is a key parameter to compute  $U_{10}$ . As already mentioned in mesoscale studies, further investigations on the subgrid scale topography (horizontal resolution), and the developing boundary layers (parameterizations, vertical resolution) would be also benefit to accurately represent the surface meteorological parameters, especially  $U_{10}$ .

[27] Testing several wind and soil databases, we find that the major uncertainty in the mesoscale computation of dust emissions at Chicha and Faya is due to  $U_{10}$ . For the dusty period of March 10–12, the total simulated dust emissions range from 29 to 502  $\text{gm}^{-2}$  at Chicha, and from 24 to 489  $\text{gm}^{-2}$  at Faya. The emission difference due to the two soil databases is larger for the lowest simulated emissions and can reach 50% at Chicha and 30% at Faya. The difference due to the four wind databases reaches more than one order of magnitude, but just 65% when the most relevant winds (new LM and new RAMS  $U_{10}$ ) are considered. As the new LM  $U_{10}$ , the new RAMS  $U_{10}$  allow simulating several dust events on March 10–12 instead of permanent emissions using the RAMS  $U_{10}$  which do not satisfactorily reproduce

the wind diurnal variability for this period. These results illustrate the gains that can be obtained using a more accurate description of surfaces to compute  $U_{10}$  in the Bodélé and the large uncertainties still existing in the mesoscale modeling of mineral dust.

[28] **Acknowledgments.** We acknowledge Martin Todd and the BoDEX team for providing surface wind measurements at Chicha. We also would like to thank the reviewers for their helpful comments.

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- G. Cautenet and C. Bouet, Laboratoire de Météorologie Physique, UMR 6016 CNRS, Université Blaise Pascal, 24 avenue des landais, F-63170 Aubière Cedex, France.
- B. Heinold, B. Laurent, and I. Tegen, Leibniz-Institut für Troposphärenforschung, Permoserstrasse 15, Leipzig, D-94318, Germany. (laurent@tropos.de)