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The importance of the representation of deep convection for modeled dust-generating winds over West Africa during summer

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[1] West Africa is the world's largest source of airborne mineral dust, which affects weather, climate, and biogeochemical processes. We use continental-scale ten-day simulations from the UK Met Office Unified Model to study the effects of the representation of deep convection on modeled dust-generating winds in summertime West Africa. To isolate the role of meteorology from the land surface we use a new diagnostic parameter "uplift potential", which represents the dependency of dust uplift on wind-speed for an idealized land surface. Runs permitting explicit convection suggest that cold pool outflows from moist convection (so called "haboob" dust storms) potentially generate on the order of half the dust uplift. Simulations with parameterized convection show substantially less haboob uplift, but compensating increased uplift from low-level jets associated with a stronger Saharan heat low (SHL). This leads to reduced dust emission on convectively active days, in the afternoon and evening hours, and in the Sahel. The common practice of tuning coarse-resolution dust models cannot resolve these problems. A realistic representation of the dust cycle, as well as of the SHL, requires targeted efforts to develop computationally inexpensive ways to incorporate the effects of cold-pool outflows from deep convection.

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1. Introduction

[2] West Africa generates approximately 25 to 50% of the global emissions of mineral dust [Luo *et al.*, 2003; Engelstaedter *et al.*, 2006]. The dust impacts air-quality and affects both weather [Rodwell and Jung, 2008] and climate [Carslaw *et al.*, 2010]. The growing recognition of the importance of dust has led to a recent increase in the use of dust modules for applications reaching from regional air-quality and weather forecasting through aerosol-chemistry transport models to Earth-system models. Some of the climate models used for the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change will account for effects of dust.

[3] Models usually parameterize dust uplift based on grid-scale friction velocity using a cubic dependence of dust flux with soil-dependent wind thresholds [Bagnold, 1941; Marticorena and Bergametti, 1995]. This leads to a high sensitivity to the representation of the upper tail of the wind-speed distribution [Timmreck and Schulz, 2004; Uno *et al.*, 2006]. Typically, tuning is applied to increase agreement between modeled dust loadings and satellite or ground-based estimates of optical thickness [Cakmur *et al.*, 2004].

[4] For the Sahara and Sahel, the world's strongest summertime dust source, a range of meteorological processes have been shown to generate dust uplift. These include: synoptic-scale systems [e.g., Johnson *et al.*, 2011], the downward mixing and dissipation of momentum from nocturnal low-level jets (LLJs) during the morning build-up of the planetary boundary layer [Parker *et al.*, 2005; Knippertz, 2008], cold pools (often referred to as *haboobs*) associated with evaporating precipitation from convective storms [Marsham *et al.*, 2008], and boundary-layer convection and dust-devils [Koch and Renno, 2005]. LLJs are most active in the regions of large horizontal pressure gradients around the intense summertime Saharan heat low (SHL), while haboobs are frequently observed during the afternoon and nighttime hours along the southern [Flamant *et al.*, 2007; Marsham *et al.*, 2008] and northern [Knippertz *et al.*, 2007] fringes of the desert. The relative importance of these processes for uplift is currently debated [Marsham *et al.*, 2008; Schepanski *et al.*, 2009; Williams, 2008]. The inability of satellites to detect dust under clouds and the use of convective parameterizations in models, which fail to represent the mesoscale organization intrinsically involved in haboob formation, have so far impeded a rigorous assessment of their role in the global dust cycle. This is a serious limitation in our understanding, given that sources in the Sahel, which are most affected by haboobs, contribute strongly to the interannual variability of dust export from West Africa [Moulin and Chiapello, 2004].

[5] Parameterizations of moist convection are used in all operational global weather and climate models. Assuming that all deep convective motion occurs within a single model column, these schemes produce warming aloft and cooling at low-levels, but are ineffective at generating cold pool outflows and propagating convective systems [e.g., Davis *et al.*, 2003, Figure 12]. It is now possible to run limited-area weather prediction models at sufficient resolution to explicitly resolve convection (typically 1 to 5-km grids), and it is now well documented that this has the capacity to

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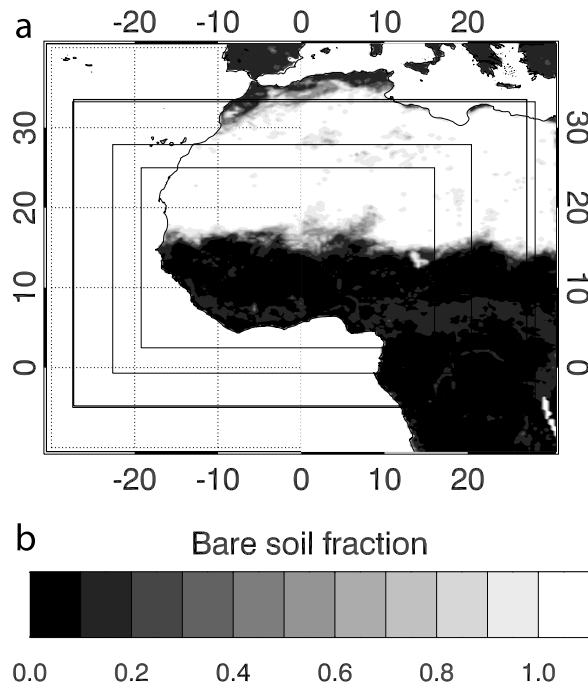


Figure 1. Bare soil fraction used in the calculation of dust uplift potential (grey-scaled) with domains of Unified Model simulations performed within the *Cascade* project. Nested 40-km (thicker line), 12-km (very similar to 40-km), 4-km, and 1.5-km domains are shown.

improve the representation of the location, timing, and growth cycles of deep convection including cold-pool outflows [e.g., *Lean et al.*, 2008; *Reinfried et al.*, 2009; *Pearson et al.*, 2010].

[6] In this paper we use multi-day, continental-scale, convection-permitting simulations for West Africa (Section 2) to quantify for the first time the relative importance of haboobs and LLJs in generating the near-surface wind events that can lead to dust uplift and to show how their representation in models depends critically on horizontal resolution and explicit deep convection (Section 3).

2. Method

[7] In the framework of the *Cascade* project simulations for the 10-day period 25 July to 03 August 2006 were carried out with the version 7.1 of the UK Met Office Unified Model (UM). These used a nesting approach (Figure 1) going from large domains at 40-km and 12-km grid-spacings to smaller nested domains at 4-km and 1.5-km grid-spacings (the latter is only available for 25 and 26 July). The model configuration is described by *Lean et al.* [2008] and used by *Pearson et al.* [2010]. The lowest model level is at 10 m in the 12-km and 40-km runs, and at 2.5 m in the 4-km and 1.5-km runs.

[8] As in operational UM runs, simulations with 40-km, 12-km, and 4-km grid-spacings used a bulk-plume parameterization of convection with a CAPE closure [*Gregory and Rowntree*, 1990]. However, at 4-km the closure time-scale is increased at high CAPE, leading to very little parameterized convection. This closure was also used for an addi-

tional 12-km simulation. We will refer to these runs and the 1.5-km run as having an explicit representation of deep convection. Two further global simulations with grid-spacings of 135 and 270-km were also analyzed in the auxiliary material.¹

[9] According to a widely used parameterization of dust uplift by *Marticorena and Bergametti* [1995] the vertical mass flux for a bare-soil surface is proportional to

$$(\rho_a/g)U^{*3}(1 + U_t^*/U^*)(1 - U_t^{*2}/U^{*2}),$$

where ρ_a is the density of air, g the gravitational acceleration, U^* the friction velocity (a reference velocity that defines surface shear stress), and U_t^* a threshold friction velocity depending on surface characteristics. As U^* was not output from *Cascade* simulations wind speed at 10 m (U) is used instead. For the 1.5-km and 4-km runs these were logarithmically interpolated to 10 m using the 2.5-m and 13-m model levels. Using U instead of U^* neglects 2nd order effects of stability and roughness on uplift [*Cakmur et al.*, 2004], but we do not expect these to substantially affect our analysis. In order to isolate the role of the meteorology from that of the land surface and to understand the effects of changing model resolution and the representation of convection on modeled low-level winds, we idealize the problem by assuming a constant threshold of $U_t = 7 \text{ m s}^{-1}$, typical of this region [*Chomette et al.*, 1999], and only retain wind-related terms. This way we can define a quantity “uplift potential” as $\nu U^3 (1 + U_t/U)(1 - U_t^2/U^2)$, where ν is the bare-soil fraction in a grid box, and calculate it over the entire domain north of 12°N (masking sea and coastal regions), using the vegetation fraction map applied throughout the year in the operational Met Office forecast models based on data from *Loveland and Belward* [1997] (Figure 1). Therefore, if the only variation in land-surface characteristics was from vegetation, the amount of dust emitted by *Marticorena and Bergametti*’s [1995] scheme would depend only on uplift potential (neglecting differences from using U rather than U^*). This is an idealization used to better quantify the effects of changing model meteorology. However, in this area, where almost all bare-soil regions have been observed to lead to some dust uplift [*Formenti et al.*, 2010, Figure 1], uplift potential is expected to be closely related to real-world dust uplift, despite important variations in soil properties over the area. Finally, we note that an “uplift potential” based on the emission scheme of *Cakmur et al.* [2004] gave very similar results (Figure S1).

3. Results

[10] Despite the differences in horizontal resolution and treatment of convection, all simulations show similar spatial patterns of ten-day averaged uplift potential (Figure 2), with four distinct maxima: (A) The most extensive one is located along the southern fringes of the SHL over Mauritania and Mali between 16 and 22°N . (B) A smaller maximum is found in northern Mauritania where the low-level trade winds are forced to flow around the southwestern end of the

¹Auxiliary materials are available in the HTML. doi:10.1029/2011GL048368.

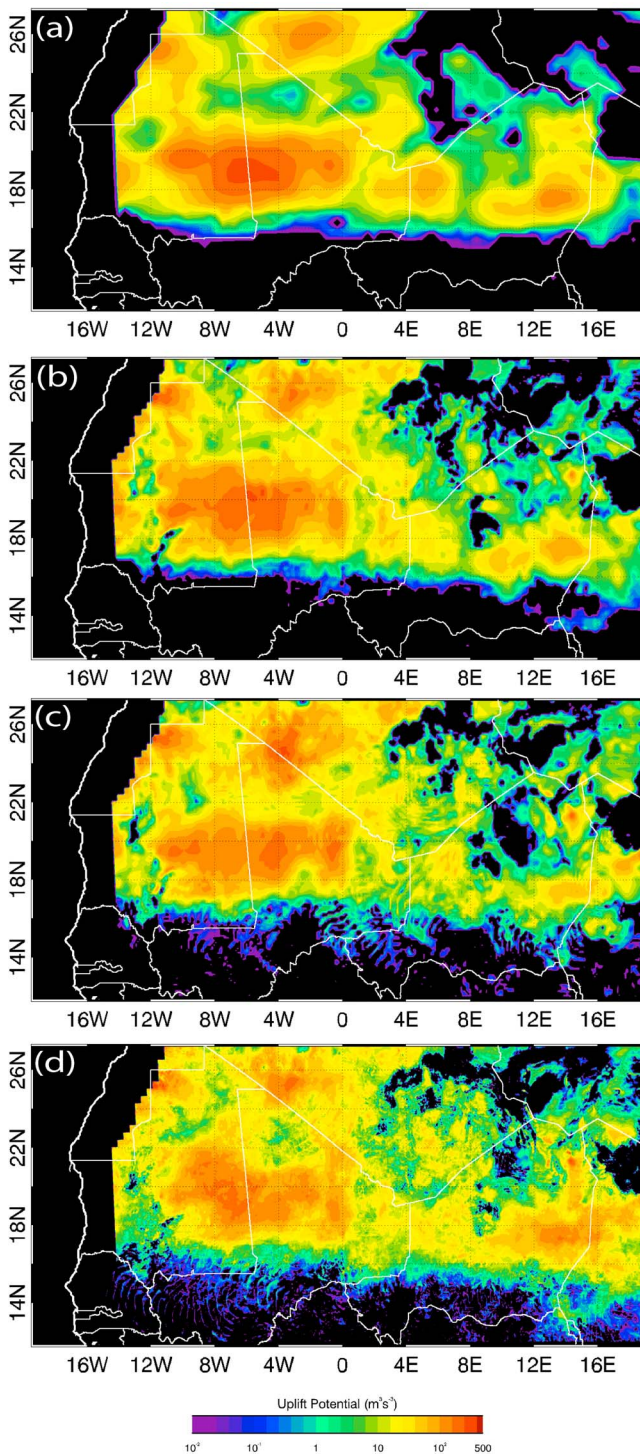


Figure 2. Mean uplift potential (defined in Section 2) over the 10-day period 25 July to 03 August 2006 for the (a) 40-km parameterized, (b) 12-km parameterized, (c) 12-km explicit, and (d) 4-km explicit model runs, shown over the 4-km domain north of 12°N. Note the logarithmic scale spanning five decades.

Atlas Mountains. (C) Orographic channeling might also play a role for the maximum over western Algeria around 25°N 3°W. (D) The only distinct maximum in the eastern part of the domain is located in the flat terrain to the east of

the Air Mountains in eastern Niger. Only the 40-km run has a corresponding maximum further west. Runs with explicit convection show arcs of increased uplift potential from the leading edges of cold pools, including in the Sahel south of 16°N, where there is very little uplift potential in the models with parameterized convection. These arcs reach 12°N, but values are much lower than those around 16°N due to vegetation (Figure 1). Significant dust uplift was observed around Niamey (13.5°N) during this period [Williams *et al.*, 2009] and it is possible that the fixed vegetation map used in this study overestimates the effects of vegetation. Integrating the uplift potential over the domain shown in Figure 2, shows that total uplift potential is almost independent of grid-spacing (first row in Table 1).

[11] The area-averaged mean diurnal cycle of uplift potential (Figure 3) allows an evaluation of the relative importance of LLJs and haboobs. Figure 3a shows results for the convectively active 2-day period 25–26 July 2006, which was characterized by a northward excursion of the West African rain belt to the Hoggar Mountains and widespread dust emissions in the Sahara [Cuesta *et al.*, 2010]. The downward mixing of momentum from nocturnal LLJs leads to a sharp peak at 07 to 10 UTC, which is similar in all simulations, but strongest at the 1.5-km grid-spacing. The development of convection during the afternoon and evening leads to a haboob-generated maximum between 16 and 01 UTC in runs with explicit convection, which is barely visible in the other runs. The last row in Table 1 shows that about half of the uplift potential occurs during the afternoon and evening hours in the explicit runs with only 13% and 23%, respectively, in the other two. For explicit runs, animations of the diurnal cycle of the spatial distribution of mean uplift potential (auxiliary material) show spreading arcs of high uplift potential growing in size as the convection and the associated cold pools develop. The delayed haboob-generated peak for coarser grid-spacings is consistent with idealized simulations of Weisman *et al.* [1997]. Together these results show an important role of haboobs for total uplift potential.

[12] The corresponding results for the whole ten-day period confirm the haboob-related peak in the afternoon and evening for explicit runs (Figure 3b and Table 1). However, runs with parameterized convection now show a much larger LLJ peak and greater uplift potential between 00 and 06 UTC (see also Table 1). The former is unlikely to be a result of higher vertical or horizontal resolution, since the two 12-km runs show a large impact of the representation of convection. Instead, understanding these differences requires an analysis of the pressure gradients that lead to the nocturnal acceleration of the LLJs.

[13] Ten-day averages of 925 hPa geopotential height are almost identical for all model runs over the subtropical Atlantic Ocean, but the SHL is shallower in runs with explicit convection (Figures 4a–4d) consistent with weaker LLJ uplift (Figure 2b). Evaluating the model fields in Figure 4 is difficult due to the scarcity of observations in the SHL region, which leads to a strong weight of the short-term model forecasts in analysis products. Operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF; Figure 4e), which were used to initialize and force the 40-km and 12-km runs, show a SHL similar to but deeper than those in the runs with parameterized convection, while the corresponding data

Table 1. Percentages and Absolute Values of Domain-Averaged Uplift Potential Defined in Section 2 and Integrated Over Different Times of Day for Different Model Runs^a

Period	Space/Time	40-km Param.	12-km Param.	12-km Explicit	4-km Explicit	1.5-km Explicit
25 July–3 August	All	(16.3)	(15.1)	(15.0)	(15.4)	
25 July–3 August	06–14 UTC	65% (10.7)	61% (9.2)	41% (6.2)	43% (6.6)	
25 July–3 August	14–01 UTC	18% (2.9)	23% (3.5)	40% (6.0)	47% (7.3)	-
25 July–3 August	01–06 UTC	17% (2.7)	15% (2.3)	19% (2.8)	10% (1.5)	-
25–26 July	14–01 UTC	13% (1.3)	23% (2.4)	47% (7.9)	50% (10.9)	47% (14.3)

^aAbsolute values, $\times 10^5 \text{ m}^3 \text{ s}^{-2}$, are in brackets. Averages for 25 July to 03 August are over the “unmasked” 4-km domain ($5.7 \times 10^6 \text{ km}^2$) and for 25 to 26 July over the “unmasked” 1.5 km domain ($4.2 \times 10^6 \text{ km}^2$).

from the National Centers for Environmental Prediction (NCEP; Figure 4f) show a SHL shallower than the runs with explicit convection. We hypothesize that the decrease in SHL intensity in runs with explicit convection is a result of the SHL ventilation by cold pools, but may also be affected indirectly by upper-level circulations induced by convection (see Figure S2 and its discussion). The details of these processes are beyond the scope of this paper and left for future study. The differences in SHL depth can also explain part of the differences in uplift potential between 00 and 06 UTC (Figure 3). Animations of the mean diurnal cycle of uplift potential (auxiliary material) show that most of this nocturnal activity occurs in a zonal band at the southern edge of the SHL. In this area, dust uplift has been observed in association with the leading edge of the nocturnal monsoonal southwesterlies [Bou Karam *et al.*, 2008]. The greater uplift potentials from 00 to 06 UTC in ten-day runs with parameterized convection are consistent with the deeper SHLs in these runs.

4. Conclusions

[14] Summertime West Africa is an important dust source with far-reaching impacts on weather and climate. Rather little is known about the physical mechanisms that control this source and their representation in numerical models. In order to isolate the role of meteorology from that of the land-surface in a series of model experiments with the UK Met Office Unified Model at different resolutions, we have defined a new diagnostic parameter termed “uplift potential”, a quantity that would determine parameterized dust uplift if land-surface characteristics were uniform in bare-soil areas.

[15] Over the first two days of the simulations (25–26 July 2006) haboobs dominate during the afternoon and nighttime and parameterized convection leads to an underestimation of uplift potential from haboobs (with approximately 18% rather than 48% occurring between 14 and 01 UTC) and a smaller total uplift potential. The lack of haboob uplift is retained over the 10-day period 25 July to 03 August, but is compensated by increased uplift between 00 and 12 UTC associated with a stronger SHL leading to stronger nocturnal LLJs. As a result, all simulations show similar spatial patterns and totals, but different timings. These conclusions are supported by additional global runs using grid-spacings greater than 100 km (auxiliary material). Unfortunately, the large disagreement between operational analyses does not allow a clear evaluation of the modeled SHLs, showing the need for improved observations. Only explicit runs show significant uplift potential south of approximately 16°N ,

where haboobs are regularly observed [Williams *et al.*, 2009; Marticorena *et al.*, 2010]. This probably contributes to the reported northwards bias in dust loadings in 20-km UM simulations [Johnson *et al.*, 2011]. The balance between LLJ uplift and haboobs is also expected to affect subsequent dust transport. The common practice of tuning coarse-resolution models by changing emission thresholds or source strength will not solve the lack of haboob uplift in models with parameterized convection.

[16] The results presented here show for the first time the potential role of haboobs for dust emission over northern Africa for a ten-day period. As haboobs occur in all major deserts [Knippertz *et al.*, 2007], more efforts are needed to parameterize their effects on dust generation and the SHL in coarse resolution models with potential positive impacts on

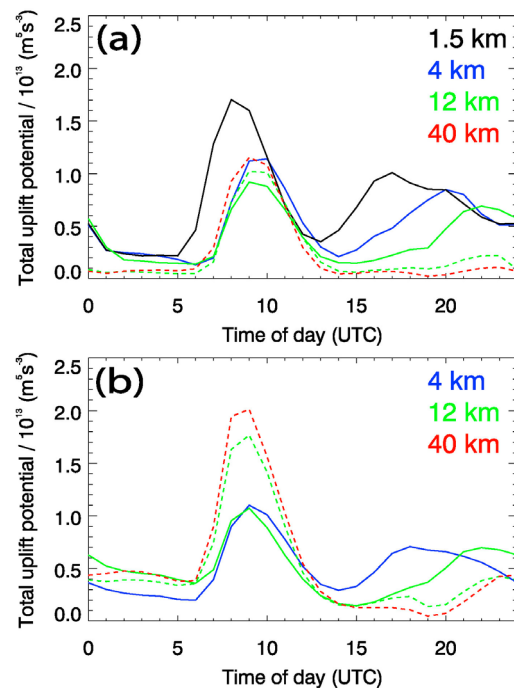


Figure 3. Mean instantaneous hourly uplift potential (defined in Section 2) for different grid-spacings, for (a) the convectively active 2-day period 25 to 26 July 2006, integrated over the 1.5-km domain (see Figure 1) and (b) the 10-day period 25 July to 03 August 2006, integrated over the 4-km domain. Dashed lines show results from models with fully parameterized moist convection.

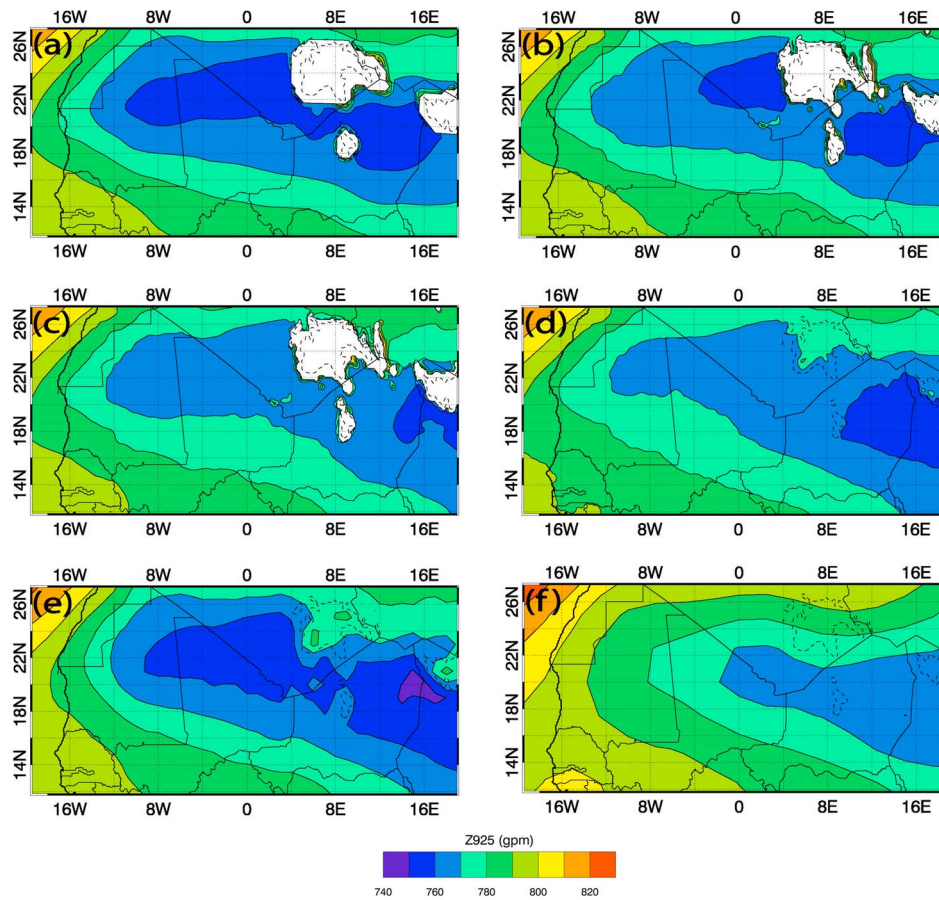


Figure 4. Geopotential height at 925 hPa averaged over the 10-day period 25 July to 03 August 2006. *Cascade* simulations using the (a) 40-km parameterized, (b) 12-km parameterized, (c) 12-km explicit, and (d) 4-km explicit model runs, as well as operational analyses from (e) ECMWF (1°) and (f) NCEP (2.5°). Dashed lines show the 1000-m contour of orography at 12-km (white areas have orography above the 925 hPa surface; geopotential is interpolated below the surface for the 4-km run and analyses).

the representation of the West African monsoon, the global dust cycle, and dust-related climate feedbacks.

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