

1 **Mid-level clouds over the Sahara in a convection-permitting**
2 **regional model**

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1 *Abstract*

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3 The simulation of Saharan mid tropospheric clouds is investigated with the
4 Weather Research and Forecasting (WRF) atmospheric model at convection
5 permitting (4 km) horizontal grid-spacing in a regional configuration. We identify
6 two potential problems in the simulations: one that affects cloud cover, and another
7 that affects both the mean and geographic patterns of both cloud and precipitation.
8 Our simulations show that using a vertical grid typical of GCMs (38 levels) limits the
9 model's ability to simulate the Sahara mid-level clouds. In particular, it
10 underestimates the supercooled liquid water (SLW) content that often resides at cloud
11 top in mid-level clouds in favour of ice, which falls out of the cloud very quickly. It is
12 only when the vertical resolution becomes high enough, allowing layers of SLW and
13 ice to exist separately, that the simulation of the Saharan mid-level clouds becomes
14 realistic. Additional improvement in the simulated clouds over the Sahel/Sahara is
15 achieved by using a high resolution surface albedo forcing dataset derived from
16 MODIS satellite, which shows that mid-level Saharan clouds prefer to form over
17 areas of low albedo. Furthermore, realistic patterns of albedo are crucial to simulating
18 the precipitation on the northern edge of the monsoon and the Sahel.

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1 *1. Introduction*

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3 Despite the West-African monsoon circulation having a zonally uniform nature,
4 simulating it poses a number of challenges, including the potential importance of
5 microphysical processes, boundary layer physics, and deep convection. Moreover, the
6 region is bounded to the south and west by ocean and to the north by a vast desert.
7 The zonal-mean cloud distribution is affected by all of these processes, and can be
8 roughly divided into three distinct features. To the south, over the Gulf of Guinea,
9 there are commonly shallow, non-precipitating stratiform clouds only a few hundred
10 meters above the surface that penetrate inland as far as 10-15°N (Knippertz et al.
11 2011). Deep monsoonal convection that stretches throughout the atmospheric column
12 occurs from 5-15°N with maximum cloud fraction in the upper troposphere (Stein et
13 al. 2011). To the north of 15°N, over the warm and dry Sahel/Sahara region,
14 convection becomes more sporadic and the cloud fraction is dominated by relatively
15 thin mid-level cloud layers (Saharan mid-level clouds, SMLC), consisting mostly of
16 altocumulus atop the very deep Saharan atmospheric boundary layer (SABL) (Parker
17 et al. 2005; Stein et al. 2011; Bouniol et al. 2011; Roehring et al. 2013). The SMLC is
18 the focus of this study.

19 The SMLC mostly consists of mixed-phase clouds that are non-precipitating but
20 can affect the radiation budget, and hence can indirectly impact local precipitation by
21 altering the environment for local small-scale convection or mesoscale convective
22 systems entering the region. To understand how these clouds form, we need to
23 understand the structure of the SABL. The SABL commonly reaches 5-6 km in height
24 during summertime afternoon, and encompasses the Saharan convective boundary
25 layer (SCBL) and the near-neutral Saharan residual layer (SRL) that caps it (Cuesta et
26 al. 2009). From morning until early afternoon these two layers are separated by a
27 weak temperature inversion (often 1K over 10-20 mb in height) caused by the
28 previous day's fully developed SCBL (Messenger et al. 2010; Garcia-Carreras et al.
29 2015). Furthermore, the strength and persistence of this inversion determines how
30 well mixed the SCBL will be throughout the SABL, and ultimately the entrainment
31 rate of free tropospheric air into the SABL. As the SCBL grows at the expense of the
32 SRL, it reaches its full depth in late afternoon. The presence of such a weak capping
33 inversion likely makes the representation of the evolution of the SABL by today's

1 climate models challenging, given that typical vertical grid-spacing are far greater
2 than the thickness of the inversion.

3 Global atmospheric models fail to simulate accurately this mosaic of clouds
4 associated with the African Monsoon and the Sahara desert. In particular, climate
5 models severely underestimate the SMLC cover (Roehrig et al. 2013; Bourgeois et al.
6 2016). Underestimation of mid-level clouds in GCMs is not a problem only over the
7 Sahara, but occurs globally (e.g., Zhang et al. 2005). The problem also exist in high
8 resolution mesoscale research models such as the Weather Research and Forecast
9 (WRF) atmospheric model (Cintineo et al. 2014; Thompson et al. 2016) and the
10 German COSMO model (Eikenberg et al. 2016). This might be associated with the
11 mixed-phase nature of these clouds (consisting of SLW and ice), and particularly with
12 the underestimation of the SLW taking place in a thin layer in the upper part of the
13 clouds (Barrett et al. 2016a; Barrett et al. 2016b). This thin layer of liquid water at
14 cloud top has also been shown to dominate the radiative impact of these clouds
15 (Hogan et al. 2003), by reflecting the shortwave radiation and consequently having a
16 net cooling effect on the planet. Cloud feedbacks represent the largest source of
17 uncertainty in future climate model predictions (Bony et al. 2006; Dufrense and Bony
18 2008; Andrews et al. 2012), and the generally poor simulation of mixed-phase clouds
19 contributes to this uncertainty. It is also fair to assume that mesoscale numerical
20 weather prediction (NWP) models as well as global models suffer from inadequate
21 coverage of SLW and mixed-phase clouds partly due to model resolution, simply
22 because model grid box average updrafts might be underestimating the sub-grid scale
23 eddies and their vertical velocity that is required to produce the supersaturation to
24 make clouds.

25 Another possible problem with GCMs or global NWP models is the
26 representation of the surface characteristics, and for our case, the surface albedo over
27 the Sahara desert. Modelling and theoretical studies show that horizontal
28 heterogeneity of latent and sensible heating anomalies over the surface can induce
29 local circulations that lead to convection (Froidevaux et al. 2018; Hohenegger and
30 Stevens 2018). A similar mechanism may operate over the deserts having surface
31 albedo variations.

32 The goal of this study is to simulate the Saharan mid-level clouds by running a
33 regional atmospheric model over the study region at convection-permitting horizontal
34 and vertical grid-spacing, which may allow a better simulation of convective and

1 cloud processes. Such an improvement will likely benefit the simulation of mid-level
2 clouds in general in numerical weather prediction applications at operational centres
3 that use more and more cloud-resolving and convection-permitting grid-spacing on
4 global scales. The implications of our results for past climate, like the Green Sahara
5 problem, are also discussed in section 4.

6 7 8 *2. Data and methods*

9 10 *2.1 Observations*

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12 We use three sets of satellite observations for this study. First, we use 2006-
13 2011 3-hourly precipitation rate derived from the Tropical Rainfall Measuring
14 Mission (TRMM, product 3B42, Huffman et al. 2007). Second, we use 2006-2010
15 monthly mean 3-D cloud fraction from collocated CloudSat spaceborne radar (2B-
16 GEOPROF version R04) CloudSat and Cloud-Aerosol Lidar (2B-GEOPROF-Lidar
17 version R04) with Orthogonal Polarization (CALIOP; Kay and Gettelman 2009).
18 These are sun-synchronous orbit satellites that are part of the A-train, and make
19 roughly 32 equatorial overpasses at approximately 01:30 and 13:30 local time, which
20 means that the observations over the Sahara are limited to this specific time of day.
21 Third, we use 2005-2015 Top of the Atmosphere (TOA) Cloud Radiative Effect
22 (CRE) for short wave, long wave and the net flux derived from Clouds and the
23 Earth's Radiant Energy System (CERES) mission, edition 4.0. The CRE represent the
24 difference between the observed radiative fluxes from broadband scanning
25 radiometers on board Terra, Aqua and S-NPP satellites and the estimated clear-sky
26 components.

27 28 29 *2.2 Experimental design*

30
31 The Weather Research and Forecast (WRF; Skamarok et al. 2008) atmospheric
32 model is used to simulate the West African monsoon and conditions over the western
33 Sahara. The experimental design is comprised of an outer domain D01 with 60 km
34 horizontal grid-spacing, a nested intermediate domain D02 with 20 km grid-spacing,

1 and an inner nested domain D03 with 4 km grid-spacing (Figure 1a). The inner
2 domain D03 covers the region of interest (20°W-14°E and 0°-32°N), i.e. the Sahel
3 region, the western Sahara, and the surrounding ocean. Implementing a horizontal
4 grid-spacing of 4 km enables us to deactivate the convective parameterization and
5 explicitly represent deep convection. This does not mean that all convective
6 processes, or even those that have a horizontal scale larger than 4 km, will be properly
7 resolved; Skamarock (2004) showed the effective resolution of WRF in a
8 configuration similar to our study is about seven times the grid spacing. Previous
9 studies using models with similar numerics have shown that horizontal grid spacing
10 of order 100m is needed to resolve individual deep convective drafts, while 4 km can
11 adequately represent the overall storm structure and organizational mode (e.g., Bryan
12 et al. 2003). The model uses ERA-*interim* reanalysis (Dee et al. 2011) as initial and
13 lateral boundary conditions. All runs presented in the study cover the period July-
14 September 2006. The choice of the year was made given that it is the first year where
15 3-D cloud fraction is available from the satellite data.

16 All simulations are run with 1-way nesting. Our simulations use the Betts-
17 Miller-Janjic convective scheme for the outer domains, the Mellor-Yamada-Janjic
18 planetary boundary layer scheme for all domains, and the two-moment Morrison
19 scheme (Morrison et al. 2009) for the microphysics.

20 Also, given observations of tropical *altocumulus* with a variety of instruments
21 by Ansmann et al. (2009), who found that almost all of the cloud layers had SLW at
22 the top down to -35°C, the nucleation of ice by deposition and condensation freezing
23 in the scheme was modified to only occur at temperatures below this value (compared
24 to the default value of -8°C). This has the effect of increasing the amount and lifetime
25 of SLW in mid-level cloud layers, since this limits the depletion of supercooled
26 droplets by ice crystals. Note that ice can still form at temperatures above -35°C from
27 heterogeneous freezing of pre-existing supercooled cloud droplets and rain.
28 Additionally, we use a cloud-fraction scheme (option *icloud=3*) that uses a critical
29 relative-humidity threshold (that is grid-spacing dependent) for the onset of non-zero
30 cloud amount, along with a cloud fraction that increases with RH following Sundqvist
31 et al. (1974). This option was created to improve a generally known deficiency of low
32 and mid-level clouds, consistent with previous studies (e.g., Cintineo et al. 2014;
33 Eikenberg et al. 2015; Thompson et al. 2016) and initially appears to create better

1 total cloud forecasts through comparisons with solar radiation observations in North
2 America (Thompson et al. 2016).

3 Initially, the model is run with a vertical grid (38 levels, Fig 1, Supplementary
4 material) that is close to what GCMs typically use, but later we present results using
5 higher vertical resolution (see below). Our simulations also test the sensitivity of
6 atmospheric conditions over the Sahara to the surface albedo. For this, first we use a
7 simple surface albedo scheme, which is constant with time and is based on vegetation
8 types (Figure 1c), before using a more realistic time-varying surface albedo (Figure
9 1d) that is derived from the MODIS satellite dataset (Schaaf and Wang, 2015). This
10 albedo has a resolution of 1 km, but is interpolated to the 4 km grid spacing of the
11 WRF inner domain.

12 13 14 3. *Results*

15
16 All simulations produce strong rainfall in the tropical regions and scattered mid-
17 level cloud systems over the Sahara. Many of the mid-level clouds over the Western
18 Sahara (10°W-10°E) are advected into the region by a clockwise circulation
19 associated with the mid tropospheric Saharan high (centred at 25°N) located above
20 the lower tropospheric Saharan low, as reported by Chen (2005). On occasions,
21 clouds also appear to result from detrainment from cumulus clouds from the south,
22 seen as northward bursts of tropical convection from the monsoon region. For an
23 animated view of these and other qualitative features, the reader is referred to a video
24 available in the Supplementary Information.

25 Compared with observations (Figure 2a), our baseline simulation captures, at
26 least in the zonal mean sense, the July-September (JAS) cloud amount distribution
27 reasonably well in the monsoon region (Figure 2b). It captures the position of the low
28 stratocumulus clouds over the Gulf of Guinea, as well as the deep convective clouds
29 associated with the African monsoon (5-17°N) except that the upper troposphere
30 cloud fraction is overestimated by roughly 50%. The last is associated with a well-
31 known bias of the Morrison 2-moment microphysical scheme that produces excessive
32 upper level low temperature clouds (Cintineo et al. 2014).

1 Our simulation also captures the position of the Saharan mid-level cloud layer,
2 but severely underestimates the cloud amount in that layer with maximum values
3 from 2 to 4% between 20-30°N, which is small compared to the observed ~24%
4 (Figure 2a). Given the limited daily sampling of the satellite data, we also show the
5 zonal mean JAS cloud fraction averaged from 2006 to 2010 (Figure 2, supplementary
6 material), where the mid-level Saharan cloud fraction appears slightly reduced, with a
7 maximum ~20%.

10 *3.1 Role of vertical resolution*

11
12 One possible explanation for the shortfall of simulated clouds is that the limited
13 vertical resolution (38 levels), with a maximum of 4-5 levels at heights typical of mid-
14 tropospheric cloud layers over the Sahara, is unable to capture the structure of these
15 clouds. To test this idea we conduct a similar run but with increased vertical
16 resolution, 87 levels (hereafter 87Lev), with roughly 18 levels within the Saharan
17 mid-level cloud layer. The resulting zonal mean cloud fraction is significantly
18 improved over the Sahara between 20-30°N, with maximum daily mean cloud
19 fraction from 5 to 8% (Figure 2c), still smaller compared to the observed 24% (Figure
20 2a). This difference between the simulated and the observed cloud fraction may be
21 partly explained by the fact that the cloud profiling radar on board CloudSat is unable
22 to distinguish clouds from elevated precipitation and snow, leading in some cases to
23 observed precipitation being interpreted as clouds (Mace et al. 2009). The same
24 argument can be used to explain the occasional presence of observed clouds within
25 the first 4000 meters of the atmosphere, as opposed to the simulated lower
26 atmosphere that appears to be cloud free. Roehrig et al. (2013), after using the same
27 satellite dataset, found a smaller observed zonal mean cloud fraction and no clouds
28 between 0-4000 meters after discarding the precipitating water phase from the
29 satellite observations.

30 A third simulation with even higher vertical resolution (109 levels, hereafter
31 109Lev), with 27 levels within the Saharan mid-level cloud layer, did produce slightly
32 more Saharan mid-level clouds in the zonal mean between 20-30°N, with maximum
33 values from 6 to 9% (not shown). It should be noted that the grid spacing for the

1 109Lev is only slightly denser compared to 87Lev, which also probably explains why
2 the increase in clouds is not that impressive. Despite this, and despite that the mid-
3 level Saharan clouds are still underrepresented, our experiments show that vertical
4 grid-spacing plays a crucial role, with more levels increasing the model's ability to
5 simulate these clouds. The question is why?

6 First of all, there is the physical aspect. These clouds are relatively thin;
7 thickness varies from 100-200 meters to 3-4 km, much thinner than the deep
8 convective clouds farther south. A model with a coarse vertical grid-spacing within
9 the mid-level cloud zone (between 600 and 400 hPa) will struggle to simulate thinner
10 layers of high relative humidity, and consequently the resulting clouds or their effects
11 on the surface energy budget. Furthermore, mid-level clouds exhibit constant rising
12 and sinking motion throughout the cloud layer, which is driven by long-wave
13 radiation cooling at cloud-top. This means that coarse vertical resolution simulations
14 won't be able to resolve properly the overturning dynamics that help maintained these
15 clouds.

16 Second there are also microphysical reasons that have to do with the interaction
17 of liquid water and ice within the clouds. To explain this, we compute the ratio:

$$\left\langle \frac{q_{liq}}{q_{ice} + q_{liq}} \right\rangle$$

18 where, q_{liq} and q_{ice} represent the mixing ratios of liquid water and ice, and the
19 brackets represent the zonal, meridional, daily and seasonal average (Figure 3). The
20 liquid plus ice mixing ratio was chosen for the denominator as opposed to ice mixing
21 ratio in order to avoid giving increased weight to clouds with very small ice
22 concentration. The ratio varies from 0 to 1, and profiles show the lack of ice in the
23 lower levels, and the lack of liquid water in the upper levels of the troposphere,
24 respectively. The most important finding here is that the more vertical levels we use
25 the more we increase the ratio in the upper part of the clouds, which means that the
26 amount of SLW relative to the amount of ice increases. The presence of SLW at the
27 top of mid-level clouds has been observed previously all over the globe, i.e. the
28 Arctic, the mid-latitudes, the Southern Ocean, the tropics and the Sahara during the
29 summer season (Zhang et al. 2010), but climate models often severely underestimate
30 the amount observed (Barrett et al. 2017a). This is partly because coarse vertical
31 resolution, by definition, is unable to represent thin mid-level supercooled liquid
32 layers. In our case, the increased fraction of the total condensate that is taken by ice in

1 a configuration with a limited number of vertical levels (Lev38) means that, once
2 liquid water and ice are mixed at a certain model level, all the liquid water goes to ice.
3 This is because the vapour saturation pressure over ice is always smaller than that
4 over liquid water at a given temperature (Bergeron-Wegener-Findeisen process).
5 Eventually the ice will fall out of the cloud, resulting in clouds with a short lifetime.
6 In contrast, more vertical levels allow layers of ice and liquid water to exist
7 separately; clouds are not depleted of liquid water so rapidly, allowing the clouds a
8 longer lifetime. This is consistent with the findings of Barrett et al. (2017b) who has
9 shown that coarse vertical grid spacing (500 m) models are unable to simulate the thin
10 and long-lived supercooled liquid layer at the top of mid-level clouds, and only when
11 a much finer grid spacing (50-100 m) is implemented the amount and lifetime of the
12 supercooled liquid layer is properly simulated.

13 Third, a heating feedback may amplify changes in cloud amount due to the
14 above factors. Table 1 outlines the mean surface energy budget terms (averaged from
15 10°W to 10°E, and 23 and 27°N) for the time of day when the clouds reach maximum
16 (19:00-20:00 UTC) and minimum (11:00-12:00 UTC) amounts (see bellow). During
17 the day, these mid-level clouds have on average a net cooling effect (with the
18 exception of the very thin ones that have a warming effect) of up to a few degrees.
19 This can also be seen by the decrease in the positive net surface heat flux (by 3.8
20 $\text{W}\cdot\text{m}^{-2}$) as cloudiness increases with higher vertical resolution, signifying less surface
21 warming. This is because the reduction in the net surface SW radiation cannot be
22 balanced by the increase in the net LW radiation or the reduction in the heat flux
23 leaving the ground through sensible and latent heating.

24 On the other hand, during the evening and night hours these clouds have a
25 warming effect, which can be seen by the increase in the negative net surface heat
26 flux by 2 $\text{W}\cdot\text{m}^{-2}$ (Table 2) as cloudiness increases with higher vertical resolution,
27 signifying less surface cooling. This is the result of the greenhouse effect of the
28 clouds by increasing the net surface LW radiation. The result is that, during the
29 evening and night hours, areas covered by clouds appear several degrees warmer on
30 average compared to the cloud free surrounding environment, with the warming effect
31 increasing as the clouds become deeper (not shown). The increased upwelling LW
32 flux associated with the warmer surface and subsequent cloud base warming could
33 help to sustain convective mixing in mid-level altocumulus layers during night time,

1 when the cloud layer and the surface become decoupled. This could play a role in
2 helping to maintain the cloud layer through a positive feedback on cloud formation.
3 This idea is supported by a PDF of the vertical velocity over the Sahara (Figure 4)
4 confirming that when the model vertical resolution increases, the upward and
5 downward motions in the mid-troposphere intensify, indicating a more vigorous mid-
6 level cloud overturning. Such evidence suggests that once these clouds are formed
7 they may become self-sustained during the evening and night hours. Note that
8 analysis of the zonal-mean vertical velocity does not show any systemic change in the
9 large scale overturning circulation over the Sahara with higher vertical resolution (not
10 shown).

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13 *3.2 Role of surface albedo heterogeneity*

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15 Another possible influence on clouds is the specification of the surface albedo.
16 Surface albedo is an important geophysical property of land surfaces that represents
17 the fraction of incoming solar radiation reflected back to the atmosphere. Also, over
18 the desert, where there is little vegetation and soil moisture, it is the only geophysical
19 property that affects the surface energy budget. So far, our simulations use surface
20 albedo that is derived from globally defined vegetation categories and is spatially
21 uniform over the Sahara (0.38). However, this is not very realistic (Cuesta et al. 2009;
22 Kealy et al. 2017), since the Saharan desert albedo varies spatially throughout from
23 0.14 to 0.51, with sharp horizontal gradients (Figure 1d).

24 Therefore, we conduct an additional simulation, which implements the MODIS
25 albedo (87LevM), but otherwise is similar to 87Lev. This configuration was chosen
26 over the 109Lev due to the high computational cost of the latter. Although the mean
27 surface albedo over the Sahara (averaged from 10°E-10°W, 20-30°N) is not very
28 different between the 87Lev and 87LevM runs (0.378 and 0.340, respectively), the
29 latter exhibits a zonal-mean cloud fraction that is considerably increased between 20-
30 30°N, with maximum values from 7 to 11% (Figure 2d) compared to 5-8% in 87Lev.
31 Thus we conclude that both vertical resolution and surface albedo matter for the
32 simulation of the Saharan mid-level clouds and therefore should be represented
33 adequately in models.

1 Regarding the mechanism of the increase in cloud fraction for 87LevM, the
2 vertical profile of the water-to-ice mixing ratio in the middle part of the Saharan cloud
3 layer (5.5-7 km) is not increased compared to 87Lev, which indicates that the increase
4 in cloud fraction is not achieved through microphysics. The difference in cloud
5 fraction is in this case associated with a change in the spatial distribution of the mid-
6 level clouds over the Sahara (Figure 5). 87LevM exhibits a cloud distribution that
7 resembles that of the surface albedo, with increased cloudiness over areas with lower
8 albedo. A histogram (Figure 6) reveals that over the desert (20-30°N) the vertically
9 averaged cloud fraction is a quasi-linear function of the surface albedo during
10 evening hours, when mid-level clouds are most abundant (shown below). In contrast,
11 during midday, when mid-level clouds are at their weakest, surface albedo has almost
12 no effect on cloud formation. This relationship also reveals that areas with albedo
13 larger than 0.5 experience throughout the day cloudiness that approaches zero.

14 This is consistent with the idea that areas of lower albedo experience a larger
15 warming, affecting the horizontal temperature and pressure gradients between areas of
16 high and low albedo, thus leading to more convection over the latter. Such local
17 maxima in mid-level cloud formation, which have been attributed to the surface
18 albedo contrast, have been previously reported in observations (Cuesta et al. 2009;
19 Kealy et al. 2017). In contrast, in 87Lev clouds are distributed rather spatially
20 uniformly. This simulation does however show that in some cases, elevated terrain
21 slightly favours mid-level cloud formation, even if surface albedo is spatially
22 homogenous. This can be seen west of the Hoggar mountains (2900 meters high, 6°E-
23 24°N), as well as elevated terrain to the south-west (3°E-20°N).

24 Our simulations also capture the diurnal cycle of the SMLCs. Previously, the
25 diurnal cycle of the SMLC has been investigated using satellite data provided by
26 CloudSat and CALIPSO, launched in 2006 (Stein et al. 2011). Figure 7 shows that,
27 regardless of vertical resolution, the mid-level clouds over the Sahara exhibit a diurnal
28 behaviour that resembles a simple sinusoidal wave. They are more frequent during
29 nighttime (maximum frequency at 20-21:00 UTC) and less during daytime, which we
30 know from observations is quite common for mid-level clouds in general (Bouniol et
31 al. 2011, Stein et al. 2011; Riihimaki et al. 2012).

32 However, comparing cloud fraction derived from satellite data with cloud
33 fraction from model output could raise some concern, since a “cloud” in the mode is

1 not the same as a cloud detected by satellite retrievals. We therefore compare the
2 simulated Cloud Radiative Effect (CRE) with CERES observations (Table 3)
3 averaging between (10°W-10°E and 25-29°N) to include only the effect of the mid-
4 level clouds and avoid high and convective clouds to the south, which our simulations
5 tend to overestimate. In the observations the LW component of the CRE dominates
6 over the SW component, resulting in a net warming effect of 7-8 W/m². Comparing
7 the CRE from 2006 with that of 2005-2015 climatology reveals that year 2006 was a
8 normal year in terms of cloud amount. In our model simulations, CRE_{SW} and CRE_{LW}
9 both increase with cloud amount as resolution increases, with the 87LevM run the
10 most accurate. It captures very well the SW cooling effect (-8 Wm⁻²), but
11 underestimates the LW warming effect by roughly 5 Wm⁻².

12 The CRE_{LW} disagreement can be attributed to a number of factors. First,
13 satellite derived CRE_{LW} tend to overestimate the actual value, because the atmosphere
14 has more water vapour when it is cloudy, and the clear-sky CRE_{LW} monthly value is
15 obtained only from days with no clouds and a dryer atmosphere (Sohn and Bennartz
16 2008). In contrast, model derived clear-sky OLR is obtained at all times but with the
17 clouds left out of the radiation calculation, resulting in smaller clear-sky OLR, and
18 consequently smaller CRE_{LW} compared to that from satellites. Sohn et al. (2006)
19 found that over the Sahara, satellite derived CRE_{LW} is overestimated due to upper
20 tropospheric humidity associated with the presence of clouds by 4-7 Wm⁻², which is
21 already enough to explain our 5 Wm⁻² discrepancy. Another possible explanation
22 would be if the model underestimates the cloud fraction, but at the same time
23 overestimates cloud opacity. In this case the CRE_{SW} could by accident come out
24 correct while the CRE_{LW}, which is insensitive to cloud opacity, would come out too
25 small. Overall, the CRE from 87LevM and CERES data agree with each other
26 suggesting that our model captures a good portion of the observed cloud amount or at
27 least its radiative effect.

28 Regarding the zonal-mean precipitation, despite the model's dry bias south of
29 10°S in all simulations (possibly the result of biases in the SSTs used to force the
30 model), north of 10°N it is simulated reasonably well compared to the TRMM
31 satellite data (Figure 8). When the simple albedo is used, the simulated precipitation
32 falls to zero much too abruptly around 15°N and over the desert, north of 17°N, rain is
33 significantly underestimated. These characteristics are shared among all three

1 simulations that use the simple surface albedo. However, when the MODIS albedo is
2 used instead in Lev87M, the simulated zonal precipitation profile well matches that of
3 TRMM on the northern portion of the monsoon, and the dry bias between 17-25°N is
4 significantly reduced, which shows the importance of representing the surface
5 characteristics accurately. Additionally, horizontal surface albedo heterogeneities also
6 seem to impact the horizontal distribution of precipitation on the northern edge of the
7 monsoon (16-21°N), where the climate transitions from a wet to a desiccated one.
8 Figure 9 shows that seasonal precipitation is a quasi linear function of surface albedo,
9 with low albedo anomalies favouring 2-4 times more precipitation than the high
10 albedo ones. It also shows that this linear relation becomes weaker (slope gets
11 smaller) as we move north, and north of 22°N the albedo seems to have no effect on
12 seasonal mean precipitation. A similar relationship can be found south of 16°N with
13 greater precipitation rates (not shown), but the surface albedo range is much smaller
14 given the extensive vegetation cover in the monsoon region.

15 The above results are in agreement with recent studies showing that surface
16 heterogeneities caused by tropical deforestation (Souza et al. 2000) or idealized
17 bipolar sensible and latent heating anomalies (Froidevaux et al. 2018; Hohenegger
18 and Stevens 2018) play a crucial role in organizing local convection. In analogy, our
19 result show that heating anomalies caused by anomalies of surface albedo are equally
20 important, for the creation of clouds and precipitation, even in a desiccated
21 environment like the Sahara desert.

22

23

24 *4. Implications for Mid-Holocene Sahara Greening*

25

26 The accurate simulation of the SMLCs is important for past climate as well. A
27 variety of paleo-proxy data suggest that during the Mid-Holocene (6000 years ago),
28 the southern Sahara desert was considerably smaller compared to present day, with
29 step vegetation and large lakes penetrating further north (Kusnir and Moutaye, 1997;
30 Jolly et al. 1998; Ghienne et al., 2002; Schuster et al., 2003, 2005, 2009; Drake and
31 Bristow, 2006; Leblanc et al., 2006; Wu et al. 2007; Bouchette et al., 2010; Lezine et
32 al. 2011). Such evidence suggests that during the Mid-Holocene the Sahara desert
33 experienced considerably more precipitation compared to present day conditions due

1 to a periodic change in Earth's orbit. In general the Mid-Holocene was associated
2 with stronger monsoons due to an orbitally induced strengthening of the insolation
3 contrast between summer and winter season (Joussaume et al. 1999; Mantsis et al.
4 2013).

5 Modelling studies have shown that a number of local and remote feedbacks may
6 have contributed to the greener Mid-Holocene Sahara: a) vegetation-albedo feedback
7 (Kutzbach et al. 1998), dust feedback (Pausata et al. 2016), c) "Mega Lakes"
8 feedback, d) SST feedback (Su and Neelin 2005), and Eurasian vegetation feedback
9 (Swann et al. 2014). The above feedbacks are all positive, but taking them into
10 account still fails to produce simulations of Mid-Holocene precipitation anomalies
11 that are large enough to support the vegetation suggested by the proxies or the
12 existence of a Mega-Chad lake (Harrison et al. 2015).

13 There are two possible reasons for this. First, the Mid-Holocene Sahara
14 Greening has been studied using low resolution GCMs that represent convection with
15 uncertain parameterizations that severely underestimate the Saharan Mid-Holocene
16 clouds and their radiative impact for today's climate. A high-resolution model that
17 captures the correct mid-level cloud amount over the Sahel/Sahara as well as its
18 radiative impact is likely to capture the climate response to a change in the TOA
19 insolation more accurately.

20 Second, GCMs predict that all known feedbacks associated with the Mid-
21 Holocene are positive. However, the opposite cannot be ruled out. For example,
22 Hohenegger et al. (2009) has shown that positive soil moisture anomalies have a
23 negative feedback on the summer precipitation in Central Europe when using 2 km
24 horizontal resolutions (convection permitting), but a positive feedback when using 25
25 km horizontal resolutions (convection is parameterized). A similar case should not be
26 ruled out in the Green Sahara problem, since a greener Sahara is associated with more
27 vegetation and more soil moisture. Of course, a greener Sahara would also be
28 associated with a different albedo that would further change the surface energy
29 budget. We suggest that a regional model operating at convection permitting
30 horizontal and vertical grid-spacing that captures both clouds and feedbacks might be
31 able to address a problem like the Mid-Holocene Sahara Greening that has challenged
32 low-resolution GCMs. Future plans include simulations that address this topic with a
33 high resolution regional model, that will also include the feedbacks associated with
34 the Mid-Holocene.

1 5. *Discussion*

2

3 GCMs have failed to simulate accurately Saharan mid-level clouds (Roehrig et
4 al. 2013). Our study shows that the use of cloud- and convection-permitting grid
5 spacing (4 km) produces a good diurnal cycle of clouds, but is not enough to simulate
6 properly the amount of Saharan clouds. It is only when the vertical resolution
7 becomes high enough to allow layers of liquid water and layers of ice to exist
8 separately that simulated clouds start to approach realistic amounts. Today's GCMs
9 used for climate studies have only a limited number of vertical levels (roughly 30),
10 with a maximum of 4-5 levels at heights typical of mid-tropospheric cloud layers over
11 the Sahara, which can stretch 3-4 km in the vertical. Our results suggest that such a
12 configuration will limit these models' ability to simulate the full spectrum of clouds
13 over the Sahara. We find that the use of grid spacing on the order of 100-200 meters
14 allows the simulation of a Saharan mid-level cloud layer, but still it underrepresents
15 the observed cloud amount, suggesting that an even higher vertical grid-spacing (50
16 m) should be used. One possible configuration, that future studies of Sahara mid-level
17 clouds could implement, in order to maintain computational efficiency, is to use a
18 dense vertical resolution between 4-8 km, but keep a coarser grid-spacing above and
19 below this layer. The same arguments could also be used for improving the simulation
20 of mid-level clouds in general in numerical weather prediction applications, which
21 use more and more often cloud-resolving or convection permitting grid-spacing.

22 Increasing the vertical resolution may seem a straightforward way to fix the
23 problem, but it does have limitations. First of all, implementing a very dense vertical
24 grid-spacing will result in high computational cost and computational efficiency.
25 Besides this, it is also likely that at some point the effect will saturate, where adding
26 more vertical levels will not result in better cloud simulation. We were not able to
27 obtain a full satisfactory simulation of mid-level clouds by high resolution alone.
28 While our study tested only the Morrison 2-moment microphysical scheme, it is
29 reasonable to expect that models with other microphysical schemes might also
30 improve as vertical resolution increases.

31 An additional simulation using high-resolution, satellite-derived surface albedo
32 shows that it is also necessary to represent accurately surface conditions to simulate
33 Saharan clouds correctly. Using the MODIS albedo resulted roughly in a 30%

1 increase in the zonal mean cloud fraction compared to a similar simulation that used a
2 surface albedo that was uniform over the desert but with nearly the same zonal mean.

3 Some limitations do apply to our study. Given the high computational cost of
4 running the WRF model at this horizontal and vertical grid-spacing, our simulations
5 cover only one season (July-September 2006), which poses some challenges. Also,
6 satellite data are much coarser in space and time compared to the model output, with
7 sampling taking place only twice a day. Additionally, the effective resolution of any
8 Eulerian numerical simulation is several times the grid spacing, which means that
9 processes spanning only a few model grids are only marginally represented. In an
10 aircraft-based study, Kealy et al. (2017) reported that 67% of the clouds encountered
11 have a horizontal scale smaller than 3 km, and that the most frequently observed
12 (25%) were also the smallest cloud size identifiable by the aircraft instrumentation
13 (300m). A higher horizontal resolution might allow the model to simulate the thinner
14 and smaller altocumulus clouds that are absent from our simulations.

15 These limitations are crucial because it may limit the model ability to accurately
16 simulate the precipitation over the Sahara during past climate. Also, it could
17 compromise the models ability to estimate the net mid-tropospheric heating of the
18 Saharan clouds and any remote effect this might have on the global circulation. Given
19 that the CRE_{NET} of these clouds is at least twice as that of the green-house gas
20 radiative forcing, such a bias might prove crucial for future climate projections.
21 Therefore, future studies addressing these topics, would have to implement a finer
22 convection permitting horizontal and vertical grid-spacing along with covering
23 multiple seasons to address the role of the mid-level Saharan cloud layer more
24 completely for regional or global climate.

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32 archived at NCI and can be provided upon request. We would also like to thank
33 Kartin Meissner for her useful comments.

34

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1 **Tables**

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Table 1. Partitioning of the surface energy budget (W/m²) for August 2006, averaged for 11-13:00 UTC. Positive (negative) sensible or latent heat flux means heat going out of (into) the ground.

	SW↓	SW↑	LW↓	LW↑	SH	LH	Q _{NET}
38 lev	921.8	301.4	399.0	556.6	288.9	79.8	94.1
87 lev	887.6	292.4	402.3	555.5	276.1	75.7	90.3
109 lev	880.9	290.6	403.6	555.3	272.9	75.9	89.8

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Table 2. Same as Table 1, but for 20-22:00 UTC.

	SW↓	SW↑	LW↓	LW↑	SH	LH	Q _{NET}
38 lev	-	-	388.9	456.7	-16.2	7.1	-58.7
87 lev	-	-	395.3	460.6	-15.8	7.0	-56.5
109 lev	-	-	396.7	460.4	-15.0	7.3	-56.8

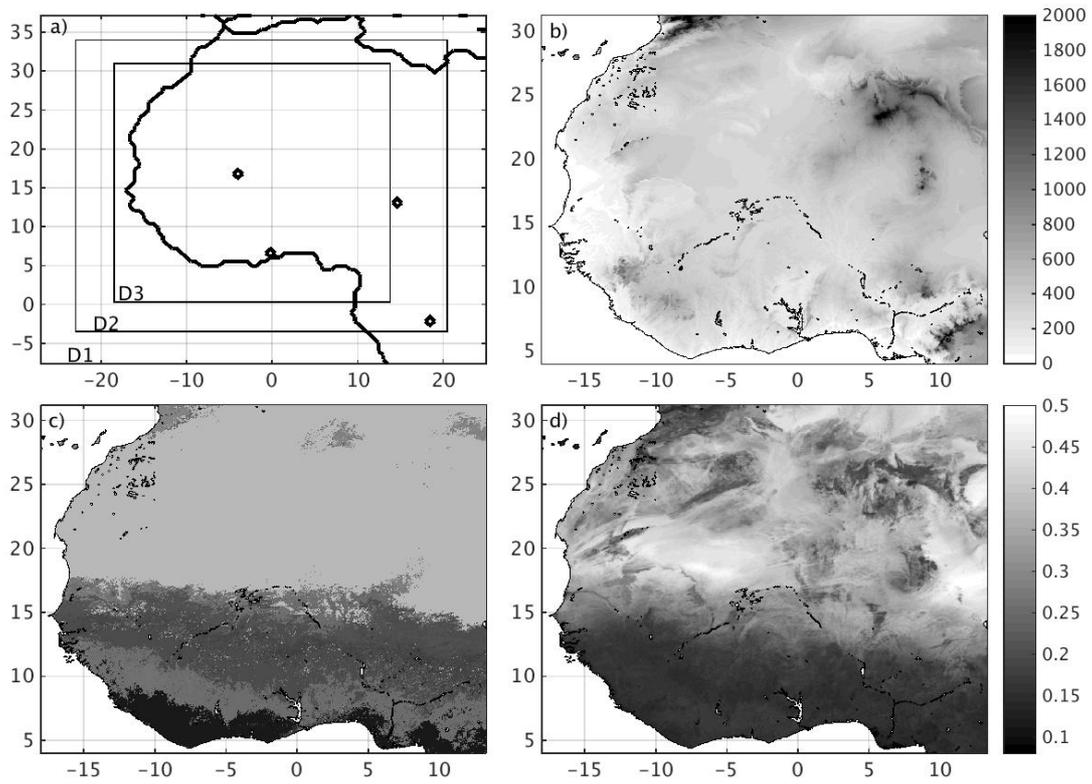
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Table 3. Average Cloud Radiative Forcing (CRF), defined as the difference between the TOA clear-sky radiation terms and the real counterparts for the WRF simulation and CERES satellite retrievals. The first are hypothetical quantities and are computed by the radiation scheme assuming zero cloudiness. CRE has been averaged between (10°W-10°E and 25-29°N), and covers the July-September period.

	38Lev (2006)	87Lev (2006)	87LevM (2006)	109Lev (2006)	CERES (2006)	CERES (2005-2015 clim.)
LW	6.5	10.1	11.1	9.8	16.5	15.7
SW	-3.4	-6.0	-8.0	-6.0	-8.7	-8.5
NET	3.1	4.2	3.1	3.8	7.8	7.2

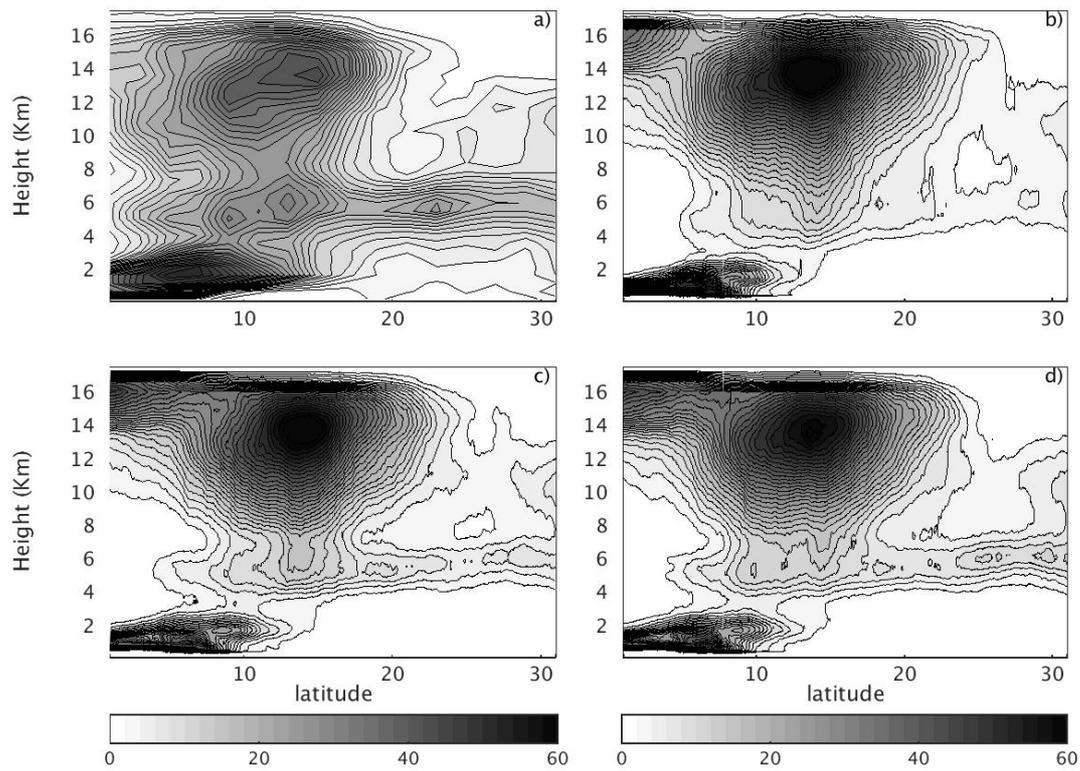
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1 **Figures**
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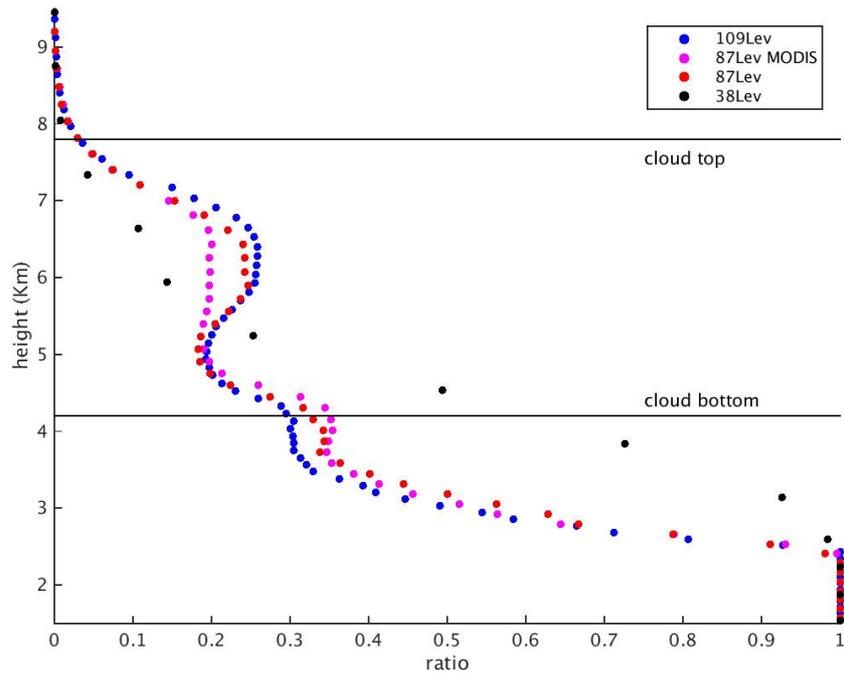
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6 *Figure 1. a) Model domain configuration, b) topography (meters) of inner domain (4*
7 *km grid-spacing), c) surface albedo as a function of vegetation, d) surface albedo*
8 *from MODIS satellite data. MODIS albedo corresponds to July 2006 monthly mean.*
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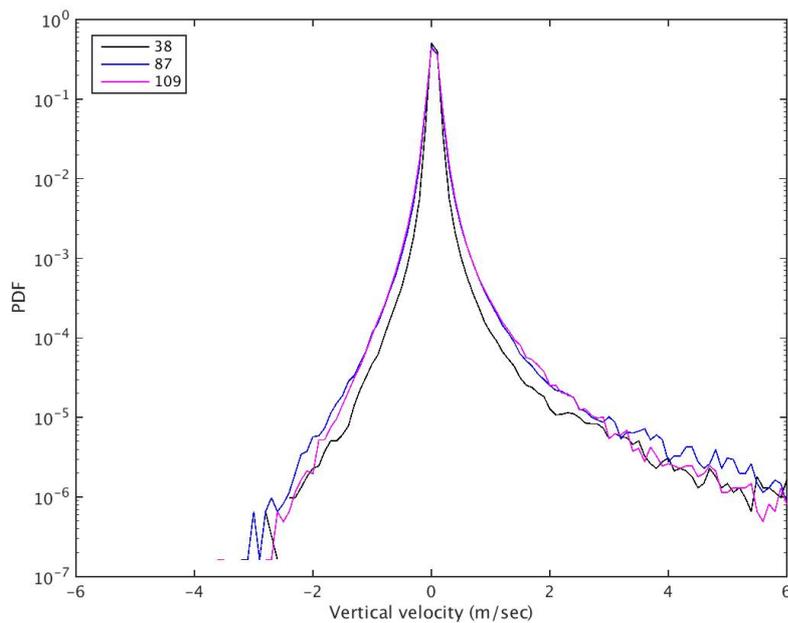


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 2 *Figure 2. Zonal mean (averaged between 10°W-10°E) cloud fraction for July-*
 3 *September 2006 for a) CloudSat and Calipso satellite observations, b) 38Lev case, c)*
 4 *87Lev case, d) 87Lev_MODIS case. All plots represent daily means and the contour*
 5 *interval is 2%.*

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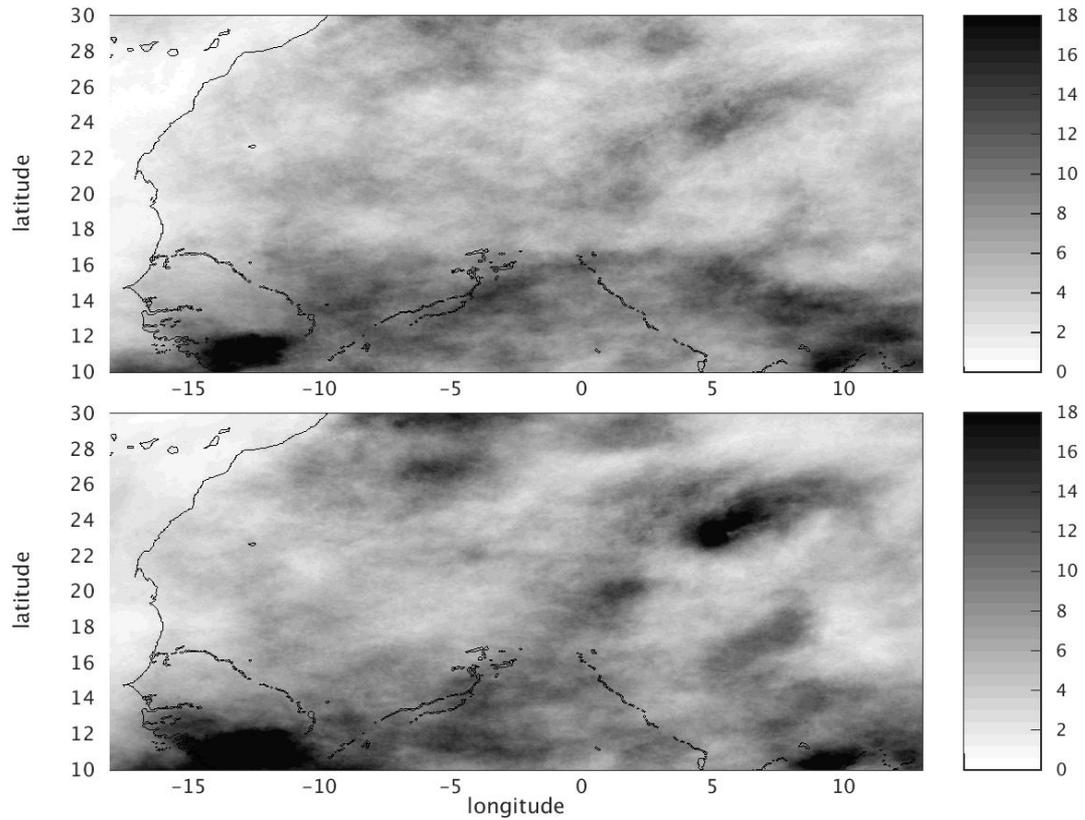


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 2 *Figure 3. Vertical profile of ratio of liquid to liquid plus ice mixing ratio. The ratio*
 3 *has been averaged zonally (10°W-10°E), meridionally (24-29°N), daily and*
 4 *seasonally (JAS). Thin black lines roughly represent the average level of the top and*
 5 *bottom of the Saharan mid-level clouds.*
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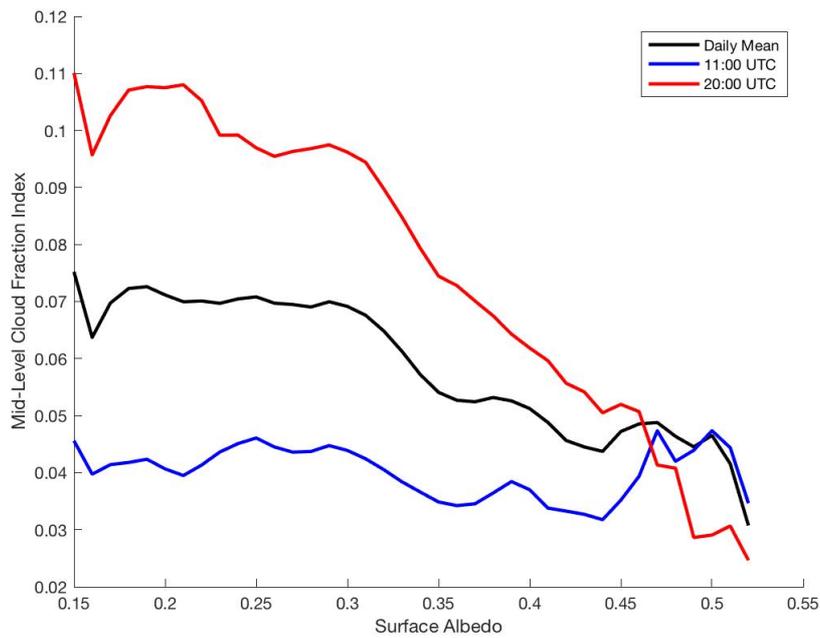
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 11 *Figure 4. PDF of vertical velocity (m/sec) at 500hPa for 38 (black), 87 (blue) and 109*
 12 *(magenta) vertical level simulation.*
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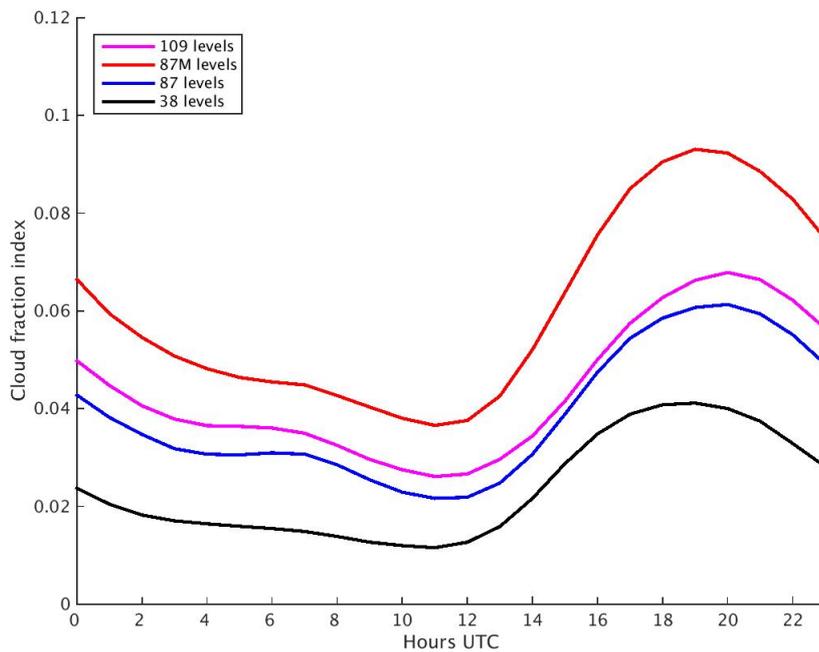


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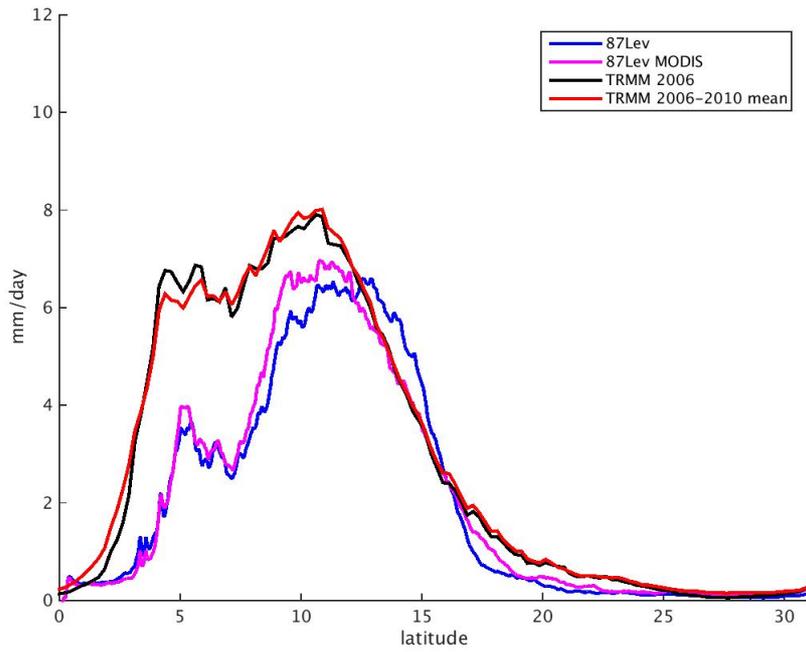
Figure 5. Simulated average cloud fraction from 600 to 400hPa for the month of July-September 2006 for 87Lev (top) and 87LevM (bottom) case. The cloud fraction has been averaged from 15:00 to 01:00 UTC, when the clouds have the largest extent.



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 2 *Figure 6. Histogram of vertically averaged cloud fraction as a function of surface*
 3 *albedo for 11:00 UTC, 20:00 UTC, and daily mean. The cloud fraction has been*
 4 *averaged within the mid-level cloud layer and for 10°W-10°E and 20°-30°N.*

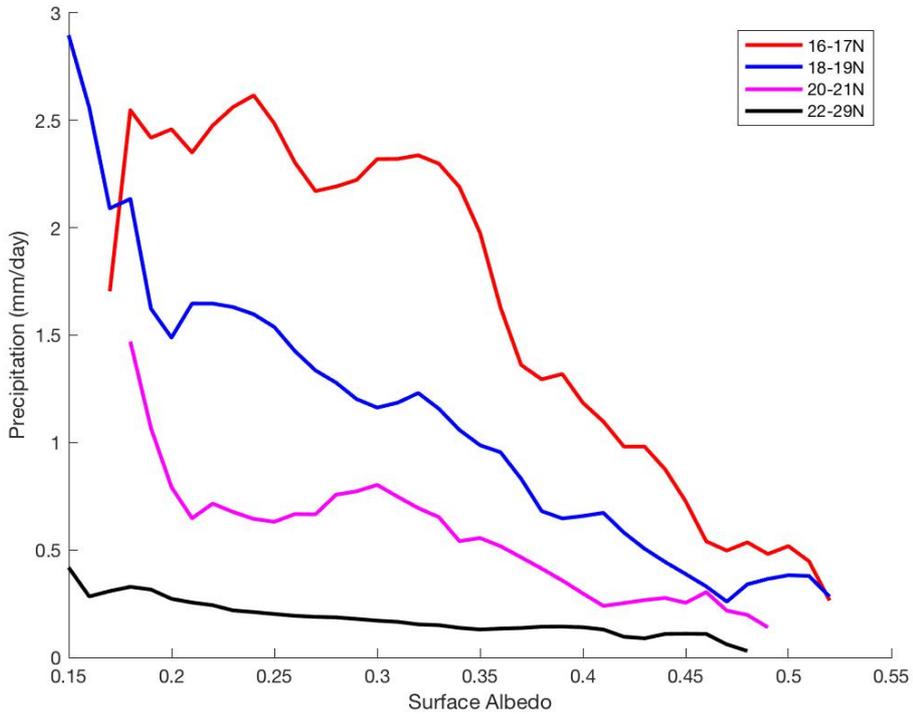


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 6 *Figure 7. Diurnal cycle of the zonal mean mid-level cloud fraction averaged between*
 7 *600-400hPa, 10°W-10°E, and 23°-27°N.*
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Figure 8. Zonal mean profile for precipitation during August 2006.



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Figure 9. Histogram of daily mean precipitation (seasonally averaged, JAS) versus surface albedo for different latitudinal bands.