## Answer to reviewer 1

We would like to thank the anonymous referee for his/her positive and constructive remarks on the manuscript.

You will find enclosed a point to point answer to those remarks. The pdf showing the modifications of the paper itself is also available for control.

The referee was suggesting that our results may be a bit oversold in terms of improvement of dust lifting representation. And we acknowledge that : 1) pieces of evidence were missing concerning the representativity of the comparisons which were focused in the first manuscript on observation stations which are on the South margin of the emission zone. Comparisons between the two model versions are now shown for the whole Sahara and for 2 consecutive years in terms of both distribution in the day of dust emission and diurnal cycle of near surface wind (Fig 10 in the new manuscript). This figure confirms the conclusions of the first version of the manuscript. 2) we may have given the impression that the LMDZ winds were better than ERAI to predict the total emission of dust for instance. It was not our intention. We just say that the diurnal cycle itself is much better represented with the NP version of LMDZ than with both the SP version and ERAI. It is true that for one station, the morning wind is closer to observation in ERAI than in LMDZ-NP, but it is clearly linked to a strong overestimation of wind in ERAI during the rest of the day. It may occur that, because of compensation errors, direct use of ERAI may give better results for dust lifting. And anyway for LMDZ, the problem is that we have to rely partly on ERAI (through nudging) to get the correct large-scale circulation in the simulations. We acknowledge however that we made too strong a conclusion, when suggesting that ERAI winds may be too strong in general. We have the wind observations on Sahelian stations only. So the statements on this particular point were removed from the manuscript, as detailed bellow.

We have to add in introduction to this answer that we found a small error in the computation of the Weibull distribution. A normalizing factor was missing, which was systematically lowering the emissions. We thus updated all the figures with the new simulations. No conclusion is affected especially because we are focusing on the sensitivity to parameterizations more than on the realism of the simulated dust distribution. Comparison with observation is now better for the dust (surface concentration and AOT) but we insist (as in the first draft) on the fact that this good agreement may be more a question of chance, since a number of parameters which were not explored here may affect emission. In particular, taking into account an a priori subgrid scale variability through Weibull distribution strongly enhances dust emission, and may be seen as a trick to compensate our inability to account for sub-grid scale turbulent or mesoscale processes. To simplify a little bit the discussion on this subgrid scale distribution, the W* term in the emission was omitted in the new set of simulations. All the figures were redone with those new simulations that rely on a somewhat upgraded version of the LMDZ model, which also marginally affects the wind but without changing any of the conclusion or comment.

The Reviewer comments are reproduce in "script" font together with the answers.

Hoping you will find our answer appropriate,

with best regards,

Frdric Hourdin

```
Reviewer #1: Parametrization of convective
transport in the boundary layer and its impact on the representation of
diurnal cycle of wind and dust emissions

General:

parameterization NP for the mixing in the daytime boundary layer is
applied to analyse the effect on dust emission. The results for
near-surface wind are compared against simulations with the former
standard parameterization SP and observations, of which the latter is
limited to two stations away from dust sources. In addition the aerosol
optical thickness (AOT) and surface concentrations are compared at
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locations away from dust sources.

I welcome this study and see the value for dust modelling, but I
recommend to revise the strong conclusions and weak physical
explanations prior to publication. My first main concern is the weak
evidence for the conclusion that NP improves winds for dust emission.
The near-surface wind validation at Banizoumbou and Chinzana away from
dust sources indicate a worse and better performance relative to SP,
respectively. The LLJ at Banizoumbou is stronger with NP, but 10m- winds
in ERAI compare better with the observations at the morning. This
inconsistency is not discussed.
```

We hope to have shown evidences that the NP version improves the representation of the diurnal cycle of near surface wind. Since a salient feature of this diurnal cycle, corresponding to the morning peak, is probably responsible of a large fraction of dust emission in this region, we believe that it is step forward toward a more physical representation of dust lifting. As said above, it is not possible to go farther in the comparison since the LMDZ simulations are constrained through nudging by the ERAI wind. For the two stations we considered, ERAI winds are stronger than observation and LMDZ. Because the overestimation by ERAI is much larger at Cinzana than at Banizoumbou, it may give the impression that the LMDZ winds are closer to observations at Cinzana. But we do not consider this result as such is a conclusive evidence. On the other hand, the ratio of the maximum wind to the diurnal average, is very close to observation at both sites as illustrated in the lower panels of Figure 4, which we take as a quantification of the diurnal cycle representation.

```
 Conclusions on emission are than drawn by relating these wind changes
to a similar signal in one time series of winds of 11 days at one grid
cell at the southern margin of the West African dust maximum. More
evidence is needed to support the general conclusion that NP is better
for dust modeling. The effect of the new Weibull distribution relative
to the NP of plumes is not discussed.
```

Once again, we did not want to say that the dust was better represented but only that the emissions were increased in NP compared to SP, due to the better representation of the diurnal cycle. It is true that we did not discuss the effect of Weibull, since it was not the purpose of the paper to discuss the various elements of the dust emission computation. In the new version, we give more details concerning the description of this Weibull parameterization and insist on its impact on the computation of dust in the conclusion.

```
My second point addresses the physical explanation of boundary layer
dynamics. The downward momentum mixing due to mechanical turbulence
generation by the LLJ itself should be considered in the explanation of
the results.
```

Mechanical turbulence may play a role in early morning, but we do not think that the turbulence in between 9:00 and 12:00 is predominantly shear-driven. Since we represent both shear- and thermally-driven turbulent diffusion plus the thermal plume model which is only thermally-driven in our model, we can at least confirm that thermal boundary layer convection dominates the momentum transport from the LLJ in our case. This point is made explicitly in the conclusion.

```
2. This might be not be an important point but
could the reduction of the time-step for the higher resolution runs have
an effect on the sub-grid scale parameterizations?  Did you reduce the
radiation timestep or leave it unchanged?
```

All the simulations shown here are done with the same grid and thus with the same time steps. But, we ran a specific simulation reducing the time-step for radiation and physics by a factor of 2 to check this point. It leads to a very small systematic reduction of the emission, by a few percent, probably due to a reduction of the numerical noise in the simulation of the boundary layer, but without altering any of the result shown here.

Specific:

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- Lines 7 -9/3: The most uncertain dust-related process is emission
which depends non linearly upon the friction velocity. Experiments
indicate References to existing literature are missing here.
Observations based on which the models have been developed also show
these relationships. Please consider adding information.
```

References are added: *" One of the important and uncertain dust related processes is emission which depends non linearly upon the friction velocity U* (Gillette, 1977; Nickling and Gillies , 1989, 1993; Gomes et al., 2003; Rajot et al., 2003; Sow et al. , 2009; Shao et al., 2011)."*

```
- Lines 19 -20/3:  which corresponds to a quasi systematic maximum of
winds in the observations It is not clear what is meant with quasi
systematic. Consider removing this clause.
```

Changed to: *"which coincides with the daily maximum wind speed in the observations in the Sahel."*

```
- Lines 16-18/4:  i. e. upward the gradient of potential temperature
since the atmosphere is generally neutral or even somewhat stable above
the first few hundred meters which corresponds to the (unstable) surface
layer. You probably want to focus on the boundary layer not the
atmosphere as a whole. The unstable surface layer varies in height and
is only present during the day. Please revise this sentence.
```

This paragraph was concerning only the convective boundary layer, starting with : *"Various approaches have been proposed in the past decades to represent boundary layer convection."* We however rephrased the sentences above to avoid any possible confusion: *"[...] parameterizations of boundary layer turbulence that are based on eddy- or K-diffusion fail to represent the basics of boundary layer convection, which essentially transports heat upward from the surface. This transport is done upward the gradient of potential temperature since the atmosphere is generally neutral or even slightly stable in the so called "mixed layer" (typically several km thick in this region of the globe in the afternoon), above the unstable surface layer (typically a few-hundred-meter thick)."*

```
- Lines 8-9/5: in which the turbulent diffusion alone is at work
Vertical wind shear can be important for turbulence generation in the
nocturnal boundary layer, e.g. when a LLJ occurs.
```

We agree with the statement on the importance of wind shear-driven turbulence for the nocturnal boundary layer. The purpose here was more to insist on the the relative importance of the two parameterizations at work in our model for typical diurnal cycle over land (not specifically over Sahara) : turbulent diffusion and thermal plume model. However, we rephrased the sentence to account for this remark : *" This approach was shown to capture well also the typical diurnal cycle over land, contrasting a thin nocturnal boundary layer dominated by wind shear-driven turbulent diffusion, and daily conditions in which the role of the parameterized turbulent diffusion is confined to the unstable surface layer while the mass flux scheme accounts for most of the turbulent transport in the mixed layer."*

```
- Lines 9-10/5: "daily conditions in which the role of turbulent
diffusion is confined to the surface layer" You here use the term
surface layer for the lowest few cms above the ground whereas in line
Lines 16-17/4 you use it more generally for the entire lower unstable
part of the boundary layer. Please resolve this inconsistency.
```

We are referring in both cases to the unstable surface layer, typically a few hundred meter thick. We hope that the rephrasing done in reply to the two previous comments makes it clearer.

```
- Lines 2-7/6: primitive equations of meteorology and conservation
equations for trace species. LMDZ probably also has conservation of
other quantities than just tracers.
```

Yes, of course. Added : *"primitive equations of meteorology (approximate form of the conservation laws for air mass, momentum and potential temperature, under hydrostatic and "thin layer" approximation)"*

```
- Line 16/7: large scale Ambient air is probably more appropriate
here.
- Line 14/7: a classical approximation in parameterizations
Please provide reference(s). Why is the assumption valid?
- Line 17/7: which is equivalent to neglect the plume fraction th in
this part of the computation The equivalence is not clear from the
information that has been given. Does this imply that the fractional
coverage of the plume has no vertical dependency anymore? If so, why do
you introduce th than?
```

We tried to make all those details clearer in the revised manuscript. What we called "large-scale" variable was in fact the grid cell average $\overline{q}$, which is also the explicit state variable of the 3D model. In the approximation $\alpha \ll 1$ it is the same as the concentration of $q$ in the environment of the plumes $q_{\mathrm{env}}$. We now introduce those notations in the text to avoid ambiguities. This approximation is used in most mass flux parameterization. We added a reference to Tiedkte (1989) since he explicitely discusses the point when introducing the model ($q_{\mathrm{env}}$ being noted $\tilde{q}$). The approximation consists in replacing $e_{\mathrm{th}} q_{\mathrm{env}}$ by $e_{\mathrm{th}} \overline{q}$ in the plume equation (Eq 1 of the revised manuscript). Details are now given in a footnote.

```
- Lines 8-18/9: Please specify the particle size range from your model.
Also check singular/plural forms in this paragraph.
```

Done

```
- Lines 25-26/9: the zoom was chosen so as to get a quasi uniform 1  1
resolution over a (70 W 30 E; 10 S40 N) Does the regional nesting not
always have a resolution of one degree or what do you mean with quasi
uniform?
```

We do not use nesting but a stretched grid. We tried to state this point more clearly in the sentences that precedes the above sentence : *"The zoom consists of a refinement of the global grid discretization in both longitude and latitude, here over West Africa and the tropical Atlantic ocean."*

```
- Lines 12-15/11: 75 Mt for the NP version. The latter value is already
in the lower range of current estimates of the climatolgical total dust
emission by North Africa for March (see e.g. Figure 6 of Laurent et al.,
2008). Dust emissions have a large uncertainty. How do your simulated
values for March compare to other studies?
```

With the new simulations, the total emission is of 33 Mt for the SP version and 113 Mt for the NP version. It is still in the lower range of current estimates. We give more information on those estimates in a new footnote: *" Marticorena et al. (1997) report values of 163 and 101 Mt for 1990 and 1991 while considering only half of the Sahara. Laurent et al. (2008) compute mean emissions with ERA-40 winds for March (period 1996-2001) of the order of 80 Mt with a maximum value of 205 Mt while Schmechtig et al. (2011) compute emissions of the order of 300 Mt for March 2006 with ECMWF forecast winds."*

```
- Line 20/11: in the main emission area in Mauritania Why have you
chosen to present a grid cell at the southern margin of the emission
maximum and not in the centre of the West African dust maximum? A
selection of more than one grid cell over more time periods or a
statistical approach capturing extreme values would be better to support
the strong conclusions you draw later.
```

As stated above, we do recognize that the extension of the discussion to the full emission region was missing in the manuscript. This is now done in the conclusions. The idea of selecting this particular location is given in the new version : *"We choose this particular point for illustration because it is located in the south of the emission zone, not too far from the latitude at which we show comparisons with in situ wind measurements in the following section. However, as shown later, the behavior observed at this particular grid point is representative of the whole emission zone."*

- Lines 7-15/12: How does this result change when you analyse other grid points, e.g. in the centre of the West African dust maximum? A few days at one grid point is a too small sample for your conclusion, that NP is producing overall more variability and larger peak winds. I would expect that from the NP but more evidence from the region of dust emission is needed. In this context, how do you know that the winds change due to NP of convective plumes and not due to the introduction of a Weibull distribution for winds?

As just said, we now show that the contrasted behavior of the SP and NP versions is similar everywhere on the region (new Fig10). As for the Weibull parameterization, it is activated exactly in the same way in both the SP and NP versions. So it can not explain differences. It is stated more clearly in section 2.3.

- Line 19-27/13: It is interesting that NP shows an improvement at one station but not at the other one compared to observation. Why does NP overestimates the maximum winds at Chinzana? This needs to be discussed since you conclude that NP improves the model performance.

Sorry if the message was not clear. We mean that the NP version improves the representation of the diurnal cycle. We propose to characterize this cycle with the ratio of the maximum to mean diurnal value, since we are especially interested by the maximum value for dust emission. As for the representation of the wind itself, it is difficult to draw any firm conclusion since the large-scale wind is for a large part constrained by the nudging term. Local effects may explain difference with observations in addition to that. However, because we have an explanation for it, and because of the consistency with observations, we think that the improvement in the representation of the diurnal cycle is similar on both sites. Of course, directly for emissions, it is the maximum value that is important and it can be better in one simulation or reanalysis due to a compensation between a poorly represented diurnal cycle and erroneous mean value.

- Line 26-27/13: than the absolute mean value and mean field The meaning of this is not clear.

We do agree that the sentence was unclear. It was removed since the idea is much easier to get from the section on the mean diurnal cycle.

- Line 8-9/14: Note that there is also a significant and systematic increase of dust when weakening the nudging, going from  = 3 h to 48 h This indicates that the relaxation to ERAI winds suppresses the development of strong winds at M'Bour causing the underestimated emission and concentration. However, the observed morning winds at Banizoumbou compare better with ERAI than SP, NP3 and NP48, despite a stronger LLJ with NP.

The change in concentration at M'Bour does not come from modification of the wind at M'Bour since their is no emission at M'Bour in this configuration. Once again it is difficult to fully assess the interplay between nudging and model physics. However, we can state that changing from SP to NP or, to a lesser extent, weakening the nudging (going from $\tau$=3 to 48h) in both cases clearly enhances dust emission together with the amplitude of the wind diurnal cycle.

- Line 17-19/14: The fact that the improvement is slightly smaller for large values is consistent with the larger role played by large scale dynamics for those events. But even then, the representation of the diurnal cycle of winds plays a significant role. Please explicitly show that the large values are connected to large scale events and/or provide other evidence from the literature for supporting this statement.

We agree with the remark and do not think the sentence was adding much to the paper. It was thus removed in the new version.

- Lines 5-15/15: I note that you name possible reasons for the over-/underestimation at the two stations here. Please add a reference to this discussion on page 13 (see comment above) or consider to change the arrangement of the text.

We made explicitly a reference as suggested : *"It is shown later that this good agreement is linked more generally to a much better representation of the mean diurnal cycle than in the SP version."*

```
- Lines 12-15/15: In particular, tuning of emission algorithms with
overestimated winds from reanalyzes may lead to artificially
underestimate the emissions when better winds are given to the emission
module, as is the case here. This is based on a station away from
emission sources. Relating the finding to a similar signal in one grid
cell for 11 days does not allow to support this strong statement. Please
provide more evidence, since other studies (that you cite in the
introduction) have shown the contrary, namely a model underestimation of
wind speeds in the Bodele as important dust source in winter.
```

As stated in the introduction of this answer, we do agree with this remark and removed these sentences and the corresponding statements in the conclusions.

```
- Lines 10-18/16: The Richardson number is named already earlier in the
manuscript and would be helpful to explain mechanical production of
turbulence below the LLJ. Consider to describe it in the introduction.
```

It is true that the Richardson number is mentioned first in the description of the standard version of the model. It is clear also that the Richardson number could be used to characterize whether the turbulence is rather shear- or thermally-driven. We also agree that, during the night, turbulence below the jet is explained by mechanical production (shear-driven). However, at least in the model, the organized thermally-driven turbulence represented by the thermal plume model is clearly responsible for the downward transport of momentum that explains the wind maximum at surface in the morning. The turbulent diffusion, based on a prognostic equation for the turbulent kinetic energy that takes into account the shear-driven turbulence (as well as static stability) is acting the opposite way as visible in the lower panel of Fig9. The Richardson number used at this point in the paper is a different one. It is a so-called bulk Richardson number, the level 0.25 of which is used to identify the boundary layer height.

```
- Lines 25-26/16: The jet maximum intensity varies from about 8 to 25 m
s and the height of the jet core from 200 to 500 m depending on the
night considered. You could compare these values against observations
to support your argument that NP leads to a better model performance.
```

Yes. We are aware that observations exist; but there were not available to us when we did this work. We intend to make some finer assessment/tuning of the parameterization in the future with such observations. However, we mention some indirect and qualitative comparison to published results: *" Note that a similar underestimation of the ERAI low level jet intensity is shown in Fig. 4 of Fiedler et al. (2013), when compared to observations in the Bodele region."*

```
- Lines 13-14/17: The thermals still accelerates the surface layer as
long as the boundary deepens in the morning. As shown by the green curve
in the second panel of Fig. 9, this decrease is the consequence of
turbulent exchange with the surface. The acceleration by thermals is
then smaller because of the reduced vertical gradients in the mixed
layer. The wind speeds decrease in the afternoon despite the occurrence
of thermals. The mixed layer has by definition small vertical gradients
in potential temperature which does not explain the wind development.
Thermals contribute to the gustiness of the winds and the growth of the
daytime boundary layer. The latter helps to mix momentum from higher
layers where stronger winds prevail, e.g. a LLJ. The major source for
the near-surface momentum is the breakdown of the LLJ during the morning
in the cases here (see e.g. Knippertz and Todd, 2012). You could explain
the development by incorporating the Richardson number. Once this LLJ
momentum has been transported downwards, the near-surface winds
decrease.
```

The explanations we gave were probably a little bit confusing. We rewrote this paragraph as follows. *" It is this peak of downward transport from the nocturnal jet which explains the morning peak in near surface wind. The mixing by thermals also rapidly reduces the jet intensity, reducing in turn the acceleration of surface winds by thermals subsidences. The near surface wind then decelerates slowly in the afternoon, under the effect of turbulent exchange with surface. The negative diffusive term (green curve in the second panel of Fig. 9) is almost compensated by the thermals tendency which accounts for convective exchanges between the surface layer and the mixed layer above. Both terms almost fall to zero after sunset, resulting in a decoupling that allows for the creation of the low level jet of the following night."* As already discussed above, we do not discuss this phenomenon in terms of Richardson number but rather in term of boundary layer convection versus turbulent diffusion, since it is mainly through this partitioning that our model distinguishes between shear-driven and thermally-driven turbulence. Even if the turbulent diffusion itself depends on the competition between wind shear and static stability through the TKE equation, the thermal plume model accounts for most of the vertical transport in the mixed layer in convective conditions. We think that going in this discussion would add more confusion to the explanation.

```
- Lines 14-18/18, conclusion point 4: The results do not support this
general conclusion and ignores the worse comparison to observation with
NP compared to SP at one of the two stations shown. For instance morning
peaks do not agree better with observation at Banizoumbou and the mean
near- surface winds at nighttime are still overestimated with NP. Please
revise this conclusion.
```

We do not agree with this comment. Of course at a given time of day, ERAI can be closer to observations. But it is not to say that the diurnal cycle is better represented. Indeed, the diurnal cycle of surface wind speed is worse in ERAI during the dry season at both sites. A similarly poor behavior of ERAI during this season was also reported by Largeron et al. (2015) from the other sahelian more northern sites. We reformulate a little bit to specify what we mean by diurnal cycle : *"The mean diurnal cycle of the near surface wind is well captured in the NP version of the LMDZ model that includes these thermal plume processes, at the Sahelian stations considered here. It is much better represented in terms of mean value, phase and amplitude than in the reanalyzes used for nudging. "*

```
- Lines 19-20/18, conclusion point 5: At the three stations away from
dust sources, small differences are found with nudging of 3 and 48
hours. The implications stated are too general as the effect of nudging
may change for other models, seasons and geographical locations.
```

We absolutely agree with this comment. So we change a little bit this conclusion to insist that we comment here first on the stations for which we have observations. We then added a new paragraph and figure (Fig10) that confirms that there is a small but systematic effect in the whole emission zone.

```
- Lines 3-8/19: Even though the winds are better with NP at one station
during the morning, these lie away from the emission sources. In order
to support that NP is better compared to SP I suggest to extend the
discussion of morning winds directly in sources. The current
presentation of one grid point for 12 days is not sufficient to support
the large implications you assign to the NP for dust emission modeling.
The credibility of the conclusions would benefit from a comparison in
other seasons and years, which you say you have done but you do not
show.
```

We really did not want to say that the wind was better represented in the morning. Too strong a mean wind with a bad diurnal cycle, as is the case in ERAI, can produce a better wind and emission in the morning. We wanted to insist on the improvement of the diurnal cycle, that points to a much better representation of the boundary layer processes involved. Hoping that the modifications given to the text help avoid any confusion on this. Following the reviewer suggestion however, we added a new paragraph in the conclusion and the Fig10 that extends to other seasons and locations the findings of the paper.

```
- Figure 9: Pick another abbreviation for the turbulent diffusion as TKE
typically describes turbulent kinetic energy which is misleading here.
```

We use K-DIFF for K-diffusion instead of TKE in the new version of Fig 9.

```
Technical:

- Check singular/plural forms throughout the manuscript.

- Lines 5-7/3: Dust is a rather simple tracer of atmospheric motions
that sediments into the atmosphere more or less rapidly depending on the
size of the grains and can be washed out by rainfall.  Omit rather
simple and better one of: that can be deposited to the surface/from the
atmosphere rapidly

- Line 9/3:  dust emissions flux replace with: the vertical dust
emission to make the sentence clearer

- Line 26/3: on the depth replace with: over the depth

- Lines 8-9/4: of the boundary layer transport, contrast between ...
replace with: of the boundary layer. The contrast between ...

- Line 26/4: replace raise by rise

- Line 17/6:  introduced above it is actually introduced below

- Lines 8-9/10:  by nudging (relaxing) the model meteorology toward
observations You nudge to re-analysis not observation.

- Line 24/10: evalable available

- Line 4/11: interactif interactive

- Lines 5/16: omit  of the module

- Figure 9: The labels are too small at the two lower sub-figures and
the y-axis of the bottom figure is not sufficient for showing all values
of the 925hPa winds.
```

Done.

## Answer to reviewer 2

We would like to thank the anonymous referee # 2 for his/her positive and constructive remarks to the manuscript (in particular for all the corrections of colloquialism).

You will find enclosed a point to point answer to those remarks. The pdf showing the modifications of the paper itself is also available for control.

We have to add in introduction to this answer that we found a small error in the computation of the Weibull distribution. A normalizing factor was missing, which was systematically lowering the emissions. We thus updated all the figures with the new simulations. No conclusion is affected especially because we are focusing on the sensitivity to parameterizations more than on the realism of the simulated dust distribution. Comparison with observation is now better for the dust (surface concentration and AOT) but we insist (as in the first draft) on the fact that this good agreement may be more a question of chance, since a number of parameters which were not explored here may affect emission. In particular, taking into account an a priori subgrid scale variability through Weibull distribution strongly enhances dust emission, and may be seen as a trick to compensate our inability to account for sub-grid scale turbulent or mesoscale processes. To simplify a little bit the discussion on this subgrid scale distribution, the W* term in the emission was omitted in the new set of simulations. All the figures were redone with those new simulations that rely on a somewhat upgraded version of the LMDZ model, which also marginally affects the wind but without changing any of the conclusion or comment.

The Reviewer comments are reproduce in "script" font together with the answers.

Hoping you will find our answer appropriate,

with best regards,

Frdric Hourdin

```
Overall this is a very interesting article that makes a nice
contribution to our under- standing of both surface wind simulations, as
well as dust generation. I have a few minor comments on the paper, as
well as many edits on the English in the paper, which needs some more
work: because of the scientific quality of the work, and my interest in
this area, I was willing to do the extra work to edit the text.
```

Thanks a lot for the help. And sorry. We tried to do our best.

```
The most uncertain dust-related process is emission which depends non
linearly upon the friction velocity U_. I disagree. There are so many
uncertain dust related processes, including dry and wet deposition! I
would rephrase: One of the important and uncertain dust related
processes. . .
```

Done

```
Equation (1): I found this equation odd in the introduction. You could
make the same point without including such a complicated equation: just
cite the articles you cite al- ready to make the point the extremes in
the wind are really important.
```

The equation was moved to the section that describes Chimere emissions.

```
U*Th I find the nomenclature of the Th in superscript disconcerting,
and I kept mis- reading it as an exponent: I recommend a more standard
placement of the Th in the subscript.
```

Done

```
We use here the version of the scheme described by Rio et al. (2010) and
used in LMDZ5B (Hourdin et al., 2013b). You cant say its really
important and then just send us off to another paper! We are full of
suspense: give us a 1 sentence description of how to make this closure.
```

Added after the citation: *"In this version, air is entrained into (resp. detrained from) the plume as a function of the buoyancy of plume air parcels divided by the square of the vertical velocity when this buoyancy is positive (respectively negative). Entrainment is strong near the surface, where it feeds the plume. Then detrainment is strong at the top of the mixed layer, when the plume decelerates. Entrainment can be active again above cloud base, for cloud-topped boundary layers when cumulus clouds are buoyant. The plume air is then detrained close to the top of the cloud. Entrainment and detrainment rates also depends on $\alpha_{th}$. The vertical velocity is computed with the plume equation (Eq. 1) with additional buoyancy and drag terms on the right and side. The plume fraction is diagnosed as a the ratio of the $f$ and $w_{th}$. "*

```
Note that even the NP3 simulation underestimates the actual AOT as
illustrated later on. Please specify where instead of later on.
```

The sentence was removed since this point is discussed afterward.

```
Section 4: comparison with observations: I think the description of the
data should be in a methods section instead of in with the results.
Please change the Section 2 Model description and simulation setup to
be titled Methods and add a final section that describes the data you
are using. At least the first paragraph of the section 4 should be
instead in that section, plus probably some discussing how much we
should trust this data, etc. I would argue that a really important point
of this paper is value of the data, to compare to the model versions.
```

Done

```
Although the stations are not located in the emission area discussed
above, model results show very similar diurnal variations of wind at
these sites. Im not sure I under- stand this sentence, could you
clarify?
```

Removed. The introduction of this section (section 4) was rewritten after moving the description of observations to the section "Methods" (section 2.5).

```
The authors switch between using NP to NP3 or NP48. For consistency, I
think you should use the full case name in all cases (or tell us in the
into what it means if you leave off the number)
```

We went through all the occurrences and used SP3, NP3 and NP48 when referring to the simulations, and NP and SP, when referring to the model version.

```
Figure 5: missing the obs ___ legend.\afaire{Binta}
```

Done

```
Top of P. 27439: you say that the results are the same whatever time
period you look at, but presumably you only looked at a particular time
period, so please indicate which years you analyzed this behavior for,
even if this is in the methods.
```

Changed to: *"Note that this diurnal cycle is very similar whatever the period selected within the winter season for the years 2006 and 2007 considered here."* We also give this information which was missing at the end of section 2.4 *"Model configuration and simulations"*.

```
In particular, tuning of emission algorithms with overestimated winds
from reanalyzes may lead to artificially underestimate the emissions
when better winds are given to the emission module, as is the case
here. I think you are talking about certain groups which have done this
in the past, and that this might not work? Maybe you want to point to
these papers (e.g. Tegen et al., papers with the GISS model did this,
but perhaps you are thinking of others?
```

Yes. In fact this comment was too general. And it assumes that the ERAI winds may be overestimated everywhere over the region while we have observations over the Sahel only. So we removed the sentence in the revised manuscript.

```
Significant conclusions may be drawn that do not depend on the
particular model used for representation of dust I agree that your
conclusions are likely to be model independent, but you have not shown
this. I would rewrite asSignificant conclusions may be drawn that are
likely to be model independent
```

Done

```
It clearly attributes the observed morning peak of near surface wind to
the downward transport of momentum by the compensating subsidence of
thermal plumes, at there first stage, when they reach the height of the
low-level jet which develops during the night at a few hundred meters
above the surface, when the wind is decoupled from the surface This is
the result of analysis and model results, so I would write this less
strongly and remove clearly.
```

Rephrased: *" The morning peak of near surface wind observed quite systematically over Sahel is well captured by the NP version of the physical parameterizations. In the model, this peak is due to the rapid downward transport of momentum by the compensating subsidences when the thermal plumes reach the height of the low-level jet which develops during the night at a few hundred meters above the surface."*

```
Of course many points could be investigated to try to understand the
origin of this underestimation. Whatever those points, it does not alter
the main result of the paper which is that an 15 accurate representation
of the diurnal evolution of the boundary layer and transport of momentum
by boundary layer convective cells must be taken into account for a good
representation of winds, and that such a good representation is
accessible now to the modeling community. I found these sentences a bit
vague and redundant. I would just say Although there may be other
errors in the model, our results suggest that the thermal plume model
allows a more accurate representation of the diurnal evolution of the
boundary layer and transport of momentum by boundary layer convective
cells and it improves the representation of wind and dust in models..
```

Rephrased a little bit differently: *" This underestimation does not question however the main result of the paper which is that an accurate representation of the diurnal evolution of the boundary layer and transport of momentum by boundary layer convective cells must be taken into account for a good representation of winds, and that such a good representation can be obtained through a combination of turbulent diffusion and mass flux representation of the boundary layer convection."*

```
I would also like to know what happens in your free running GCM: does it
get similar diurnal cycle with and without the new scheme? Just a brief
comment about this would help provide context for other modeling groups.
```

To answer this question, we performed simulations in free climate mode inside the zoom area. The diurnal cycle is very close to that obtain with nudging. We added in the conclusions: *" Note that the mean diurnal cycle is almost identical when simulations are conducted in free climate mode, without nudging (results not shown)."*

```
Edits for English (please do reread carefully, as I probably missed a few).

Line 1:
boundary layer transport should be boundary layer?
```

Not sure to understand why but done.

```
It also reinforces dust emissions in better agreement with
observations, but the aerosol optical thickness is still significantly
underestimated. Replace reinforces with gen- erates.
```

Done

```
Desert dust is a secondary but significant contributor to the
atmospheric radiative transfer, with regional signature organized around
desert area like Sahara, which is estimated to contribute to 25 to 50%
of the global dust emissions suggest replace with Desert dust is
secondary but significant contributor to atmospheric radiative transfer,
with regional signatures dominated by desert areas like North Africa,
which is esti- mated to contribute 25-50% of the global dust emissions.
```

Done

```
that base the anticipation of future climate changes replace with on
which future climate change estimates are based.
```

Done

```
the importance of a good representation of the boundary layer
transport, contrast between nocturnal turbulence in a stable atmosphere
and convective transport during the.. replace with: the importance of
a good representation of the boundary layer transport, especially the
contrast between nocturnal turbulence in a stable atmosphere and
convective transport during the.. but this sentence is a bit long and
probably could be cut into two.
```

The statement was simplified *" Todd et al. (2008) and Knippertz and Todd (2012) underline the importance of a good representation of the contrast between nocturnal turbulence in a stable atmosphere and convective transport during the day for the representation of this nocturnal jet and its impact on surface wind."*

```
The counter-gradient term he proposed to reconcile the diffusive
formulations with convection conditions was later on given a more
explicit formulation based on the non local aspect of convective
transport by Troen and Mahrt (1986) and by Holtslag and Boville (1993).
Replace later on with later (colloquialism)
```

Done

```
The present study aims at exploring the impact of those new
parameterizations on the representation of dust emission and transport
and anticipate. Replace those with the above described, replace
anticipate with anticipates.
```

Done

```
Here air is assumed to enter the plume with the concentration of the
large scale , which is equivalent to neglect the plume fraction replace
large scale with large scale grid box, replace neglect with
neglecting.
```

Changed to: *"Here air is assumed to enter the plume with the mean grid cell concentration q, which is equivalent to neglecting ..."*

```
Coupling of LMDZ with the CHIMERE emission module follows the way
CHIMERE is currently forced by regional climate models replace with
The coupling of LMDZ with the CHIMERE emissions module is done
similarly to the standard method used to couple CHIMERE by regional
climate models.
```

Done

both computation giving very similar results. Replace computation with computations

The sentence was modified.

a Weibull parameterization is used to account for the effect of spatial inhomogeneities of wind speed within a grid mes A weibull distribution, not parameterization, right?

Yes. Modified.

with a distribution following a logarithmic increase replace with with a lognormal dis- tribution

Rephrased: *"In order to accurately describe this size distribution both in number of particles and in mass, it is common to use a discretization in size that follows a logarithmic law (Seinfeld and Pandis, 1998)."*

by a mean mass median diameter, Dp do you really want both mean and median in the same noun-phrase?

Rephrased: *"The boundaries for the 12 dust bins used here are 0.09, 0.19, 0.67,1.49,2.27, 3.46,4.81,5.58,6.79,12.99,26.64 ,41.60 and 63.0 m."* The notation Dp is not used anymore.

the model is run with its zooming capability the model simulations are conducted with the zooming capability. (run is a colloquialism)

Done

was described in details by Coindreau replace details with detail

Done

The zoom consists in a refinement of the longitude and latitude discretization. Here, the zoom covers West Africa and the tropical Atlantic ocean. Should be consists of, but these sentences are a little redundant, please combine to one sentence.

Changed to: *"The zoom consists of a refinement of the global grid discretization in both longitude and latitude over West Africa and the tropical Atlantic ocean."*

the zoom was chosen so as to get a replace to get with to obtain (colloquialism)

Done

A nearest neighbor method was retained instead that provides much better results. Replace retained with implemented.

Done

The LMDZ model is most commonly used in climate mode: integrated from an ini- tial 5 state just imposing some boundary conditions such as insolation, sea surface temperature replace just imposing with with imposition of .

Done

The longer the time constant the weakest the constraint by the analyzed wind fields. Replace weakest with weaker and by with of

Done

`interactif should be interactive`

Done

`In order to interpret at process level the: should be at a process level`

Done

`while the wind distribution for the NP version explores much larger values. explores should be includes At the opposite, when the emissions are related to the daily-mean wind speed (right panel of Fig. 2) it appears that the wind explored are on average weaker in the NP than in the SP version.. many issues: recommend: On the other hand, the relationship between daily mean wind speed and emissions (Figure 2b), suggest that the winds in the NP are smaller than SP, but emissions are larger for these lower wind speeds.`

Changed to: *"On the other hand, the relationship between daily mean wind speed and emissions (right panel of Fig. 2), suggests that the winds in the NP3 simulation are smaller than in SP3, but emissions are larger for these lower wind speeds."*

`p. 27436 line 14 reinforces should be increases`

Done

`Consistently with Fig. 3,: should be consistent with Fig. 3.`

Done

`it is for both stations the NP versions that give the best results should be it is the NP versions that give the better results for both stations.`

Done

`As for dust evaluation, should be In order to evaluate the dust`

Done

`This station is considered at first should be This station is considered first`

Done

`A more systematic and synthetic comparison should be A more systematic and com- plete comparison (synthetic means fake)`

Changed to: *"A more systematic comparison is shown"*

`We finally analyze should be Finally, we analyze`

Done

`bias in the reanalyzes winds used for nudging. . . should be or bias in the reanalyses winds used for nudging.`

Done

`p.27439 At the opposite, should be On the other hand`

Done

```
p.27440 first line: there should be their
```

Done

```
driven by the unbalance between the Coriolis unbalance should be imbalance
```

Done

```
The thermals still accelerates the surface layer accelerate
```

Reformulated

```
This conclusion goes beyond this particular model since many chemistry
transport models rely on reanalyzes for the computation of near surface
wind. Should be This conclusion is important for many chemical
transport models which rely on reanlyses for the computation of near
surface winds.
```

Done

```
as large as 48 h the synoptic situation is still rather well
constraint, constraint should be constrained
```

Done

```
the model seriously underestimates the observed dust loading of the
atmosphere, remove seriously (seriously is a colloquialism, and in
boring english science writing we rarely include adverbs)
```

Done

## Answer to reviewer 3

We would like to thank the anonymous referee #3 for his/her very positive comments on the manuscript. You will find enclosed a point to point answer the minor remarks. The pdf showing the modifications of the paper itself is also available for control.

We have to add in introduction to this answer that we found a small error in the computation of the Weibull distribution. A normalizing factor was missing, which was systematically lowering the emissions. We thus updated all the figures with the new simulations. No conclusion is affected especially because we are focusing on the sensitivity to parameterizations more than on the realism of the simulated dust distribution. Comparison with observation is now better for the dust (surface concentration and AOT) but we insist (as in the first draft) on the fact that this good agreement may be more a question of chance, since a number of parameters which were not explored here may affect emission. In particular, taking into account an a priori subgrid scale variability through Weibull distribution strongly enhances dust emission, and may be seen as a trick to compensate our inability to account for sub-grid scale turbulent or mesoscale processes. To simplify a little bit the discussion on this subgrid scale distribution, the W* term in the emission was omitted in the new set of simulations. All the figures were redone with those new simulations that rely on a somewhat upgraded version of the LMDZ model, which also marginally affects the wind but without changing any of the conclusion or comment.

The Reviewer comments are reproduce in "script" font together with the answers.

Hoping you will find our answer appropriate,

with best regards,

Frdric Hourdin

`27431, 18-19: define theta and theta_th here`

Added: *"where $\theta$ is the mean potential temperature in the grid box and $\theta_{th}$ the potential temperature within the thermal plume at the same model level."*

`27432, 1: define TKE`

Modified: *"is based on a steady-state solution of the evolution equation of the Turbulent Kinetic Energy (TKE) "*

`27433, 6-7: please give more details about the use of the Weibull parameterization`

Added to the text: *" In order to account for sub-grid scale variability of the mean wind speed, a Weibull distribution is used (Cakmur et al., 2004) with the following probability density function:"*

$$p(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left[-\left(\frac{u}{A}\right)^{k}\right] \tag{1}$$

*" where u is the sub-grid wind speed, the shape parameter $k$ is set to $k = 3$ and $A$ is calculated in order to fit the first moment of the Weibull distribution with the mean wind, i. e., $U = A\,\Gamma(1 + 1/k)$ with $\Gamma$ the Gamma function. "*

`27433, 14: what is the size range of the 12 bins?`

Added to the text: *" The boundaries for the 12 dust bins used here are 0.09, 0.19, 0.67,1.49,2.27, 3.46,4.81,5.58,6.79,12.99,26.64 ,41.60 and 63.0 µm."*

`27433, 16-17: settling and dry deposition  briefly report if e.g. a series of resistances model etc.`

Added to the text: *" Settling of dust particles and dry deposition are computed as in CHIMERE (Menut et. al., 2013)"*

`27435, 4: change to interactive`

Done

`27437, 11-12: I would say they are rather similar actually`

Yes, I agree. The comment on differences was removed.

`27437, 29-30: Have you considered comparing to the Tamanrasset station as well? It should be closer to the dust sources and have data for the study period. Also, please briefly describe how the AERONET data were treated to get the daily cycle.`

We intend to make direct comparison with Tamanraset observations in the future but did not have the observations when we did the work. We compared AOT at another station in the Sahel, showing a similar underestimation. We do not show daily cycle for the AERONET data but only the day-to-day variations.

`27442, 3: change to at their first stage`

The sentence was modified: *"In the model, this peak is due to the rapid downward transport of momentum by the compensating subsidences when the thermal plumes reach the height of the low-level jet"*

`27443, 5: here (and earlier in the text) you are implicitly assuming that AOD is repre- sentative of dust emissions, and that model AOD is indicating underestimation when compared to remote sensing retrievals maybe just put in somewhere what are the assumptions behind this, involving particle size and optical properties`

Added to the text: *" Despite a reasonable representation of the near surface winds (at least at the stations available, which unfortunately are not in the main emission zones), and despite the use of a Weibull distribution to account for the effect of spatial inhomogeneities of wind speed within a grid mesh, the model underestimates the observed dust, typically by 20-50% for the NP48 simulation that shows the strongest emissions. The underestimation is similar when considering either AOD or PM10 concentrations. AOD is sensitive to the atmospheric column with a stronger contribution of small particle while the PM10 concentration is a direct measurement of the mass concentration close to the surface. The fact that both indicate a similar underestimation suggest a general underestimation of emissions rather than a size distribution effect. "*

`27443, 10: change to the same observations are`

This section of the conclusion has been rewritten and extended.

`Figure 3: what is the black solid line in the upper panel?`

Added: *"The horizontal line in the upper panel corresponds to a wind of 7* $ms^{-1}$ *above which emissions start to be significant."*

`Figure 7: how does this compare to Figure 4?`

Added: *"As was already seen in Fig. 4, the mean value is somewhat overestimated at Cinzana and underestimated at Banizoumbou for the three LMDZ simulations."*

## Answer to interactive comment by Zhang Xuelei

Thank you for your interest and comments.

We understand that several options could be modified in the model, as for instance the threshold veolicty if wanting to account for possible weak dust emissions, or the possibility of using a stochastic parameterization.

We may of course consider those possibilities for future evolutions of our model. However, the scope of the present paper was to look specifically at the representation of the near surface wind, at the effect of the boundary layer paramaterizations on this near surface wind, and effect of this wind on emission. That is why we intentionally decided to use directly the emission module of Chimere without any modification.

We feel that adding sensitivity to some options of the dust emission module would bring more confusion to the paper.

However, thanks again for the comments and suggestions.

With best regards,

Frdric Hourdin

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# Parametrization of convective transport in the boundary layer and its impact on the representation of diurnal cycle of wind and dust emissions

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## Abstract

We investigate the impact of the representation of the boundary layer ~~transport~~ in a climate model on the representation of the near surface wind and dust emission, with a focus on the Sahel/Sahara region. We show that the combination of vertical turbulent diffusion with a representation of the thermal cells of the convective boundary layer by a mass flux scheme leads to a more realistic representation of the diurnal cycle of wind in spring, with a maximum near surface wind in the morning. This maximum occurs when the thermal plumes reach the low level jet that forms during the night at a few hundred meters above surface. The horizontal momentum in the jet is transported downward to the surface by compensating subsidences around thermal plumes in typically less than one hour. This leads to a rapid increase of wind speed at surface and therefore of dust emissions owing to the strong non linearity of emission laws. The numerical experiments are performed with a zoomed and nudged configuration of the LMDZ general circulation model, coupled to the emission module of the CHIMERE Chemistry Transport Model, in which winds are relaxed toward that of the ERAI reanalyzes. The new set of parameterizations leads to a strong improvement of the representation of the diurnal cycle of wind when compared to a previous version of LMDZ as well as to the reanalyzes used for nudging themselves. It also ~~reinforces~~ generates dust emissions in better agreement with ~~observations~~current estimates, but the aerosol optical thickness is still significantly underestimated.


## 1 Introduction

Desert dust is ~~a~~ secondary but significant contributor to ~~the~~ atmospheric radiative transfer, with regional ~~signature organized around desert area like Sahara~~signatures dominated by desert areas like North Africa, which is estimated to contribute ~~to 25 to 50~~25-50% of the global dust emissions (Engelstaedter et al., 2006). This change in radiation may affect the large scale circulation by inducing regional contrasts of several tenth of $\mathrm{W\,m^{-2}}$ (Yoshioka et al., 2007; Solmon et al., 2008; Spyrou et al., 2013), as well as the convective processes in the atmosphere through modulation of the atmospheric static stability. Dust is more and more often taken into account interactively in global climate simulations, such as those coordinated at an international level in the Coupled Model Intercomparison Projects (CMIP, Taylor et al., 2012) ~~that base the anticipation of future climate changes~~on which future climate change estimates are based. Dust is a ~~rather simple~~ tracer of atmospheric motions that sediments into the atmosphere ~~more or less rapidly depending on the size of the grains~~ and can be deposited to the surface rapidly and washed out by rainfall. ~~The most uncertain dust-related process~~ One of the important and uncertain dust related processes is emission which depends non linearly upon the friction velocity $U^*$ ~~. Experiments indicate that dust emissions flux can be considered as a fraction of the "saltation" flux, i. e. the amount of soil material in horizontal movement at the soil surface. The saltation flux can be expressed as a function of a threshold~~ $\cancel{U^{*\mathrm{Th}}}$ ~~and a cubic dependency of the wind friction velocity of the form~~

$$\cancel{F_h = \frac{K\rho_a}{g} U^{*3} \left(1 - \frac{U^{*\mathrm{Th}}}{U^*}\right)\left(1 + \frac{U^{*\mathrm{Th}}}{U^*}\right)^2}$$

~~according to the work of Marticorena and Bergametti (1995b) , where~~ $\cancel{K}$ ~~is the eddy diffusivity coefficient and~~ $\cancel{\rho}$ ~~the air density~~(Gillette, 1977; Nickling and Gillies , 1989, 1993; Gomes et al., 2003; Rajot et al., 2003; S

The emission thus depends more on the tail of the near surface wind distribution than on the wind mean value. During winter and spring, a large part of dust emissions occurs in the morning (see e.g., Schepanski et al., 2009), which ~~corresponds to a quasi systematic maximum of winds~~ coincides with the daily maximum wind speed in the observations in the Sahel (Parker et al., 2005; Lothon et al., 2008; Guichard et al., 2009; Schepanski et al., 2009). This maximum is associated with the low level jet which forms at a few hundred meters above the surface, after sunset, consecutively to a collapse of the near boundary layer turbulence (see e.g. Bain et al., 2010; Gounou et al., 2012; Fiedler et al., 2013). After sunrise, a convective boundary layer rapidly develops, which brings momentum from this low level jet down to the surface, and further mixes horizontal momentum ~~on~~ over the depth of the convective boundary layer, typically 2 to 6 km thick over Sahara and Sahel (see e.g. Cuesta et al., 2009). Todd et al. (2008) report problems in the representation of the diurnal cycle of near surface wind in a series of simulations with regional models over the Bodélé region during the Bodex 2005 experiment. They also conclude that the problem comes more from missing physics in the model than from the grid resolution. This diurnal cycle is neither well captured in the ERA-Interim reanalyzes (Fiedler et al., 2013) nor in other state-of-the-art reanalyzes datasets as recently shown by Largeron et al. (~~2014~~2015). Fiedler et al. (2013) report typical underestimation of 24–50 % for the jet maximum velocity in the Bodele region. Todd et al. (2008) and Knippertz and Todd (2012) underline the importance of a good representation of the ~~boundary layer transport,~~ contrast between nocturnal turbulence in a stable atmosphere and convective transport during the day ~~being a key~~ for the representation of this nocturnal jet and its impact on surface wind.

Various approaches have been proposed in the past decades to represent boundary layer convection. Deardorff (1970) first noticed that parameterizations of boundary layer turbulence that are based on eddy- or K-diffusion fail to represent the basics of boundary layer convection, which essentially transports heat upward from the surface~~, i. e.~~. This transport is done upward the gradient of potential temperature since the atmosphere is generally neutral or even ~~somewhat stable above the first few hundred meters which corresponds to the (unstable)surface layer~~slightly stable in the so-called "mixed layer" (typically several km thick in this region of the globe in the afternoon), above the unstable surface layer (typically a few-hundred-meter thick). The counter-gradient term he proposed to reconcile the diffusive formulations with convection conditions was later ~~on~~ given a more explicit formulation based on the non local aspect of convective transport by Troen and Mahrt (1986) and by Holtslag and Boville (1993). Stull (1984) underlined the importance of non local aspects and proposed the “transilience matrices” framework. Chatfield and Brost (1987) first proposed to combine a diffusive approach with a “mass flux” scheme dedicated to the representation of the boundary layer convection. In this approach, the convection is represented by splitting the atmospheric column in two compartments, one associated with the concentrated buoyant updrafts (or thermal plumes) that ~~raise~~ rise from the surface and the other one to compensating subsidence around those plumes. This approach was developed independently by two teams and since adopted in several groups (Hourdin et al., 2002; Soares et al., 2004; Siebesma et al., 2007; Pergaud et al., 2009; Angevine et al., 2010; Neggers et al., 2009; Neggers, 2009; Hourdin et al., 2013b). It has been shown in particular to open the way to quite accurate representation of cumulus clouds that form at the top of convective thermal plumes (Rio and Hourdin, 2008; Jam et al., 2013). The first application of these ideas to the simulation of the dry convective boundary layer (Hourdin et al., 2002) demonstrated the capability of the so-called "thermal plume model" to correctly represent the up-gradient transport of heat in a slightly stable convective mixed layer. This approach was shown to capture well also the ~~contrast between the very~~ typical diurnal cycle over land, contrasting a thin nocturnal boundary layer ~~, in which the turbulent diffusionalone is at work~~dominated by wind shear-driven turbulent diffusion, and daily conditions in which the role of the parameterized turbulent diffusion is confined to the unstable surface layer while the mass flux scheme accounts for most ~~part~~ of the turbulent transport in the mixed layer. This thermal plume model was developed for the LMDZ atmospheric general circulation model, in which it was activated in particular to perform a sub-set of climate simulations for the last CMIP5 exercise (Hourdin et al., 2013b).

The present study aims at exploring the impact of ~~those new~~ the above described parameterizations on the representation of dust emission and transport, and ~~anticipate~~ anticipates future versions of the climate simulations with interactive aerosols. For this, the emission module from the Chemistry Transport Model CHIMERE (Menut et al., 2013) was coupled to the climate model. We show here how the activation of the thermal plume model leads to a better representation of the diurnal cycle of near surface winds – even better than in current meteorological reanalyzes – and how this better representation reinforces surface emissions drastically. We focus here on emissions during the dry season while a companion paper will be devoted to the representation of dust emission by gusts associated with convection generated cold pools, for which a specific ~~parametrization~~ parameterization has been introduced also in LMDZ (Grandpeix and Lafore, 2010; Rio et al., 2009).

In Sect. 2, we present the ~~model setup~~numerical model and observations. We then illustrate the impact of the parameterization of the boundary layer on the near surface wind distribution and dust emission using online dust simulations with two versions of the LMDZ physical package (Sect. 3) and compare the results with site observations (Sect. 4), before analyzing in more detail the representation of the mean diurnal cycle of near surface wind over the Sahel when the thermal plume model is activated (Sect. 5) and drawing some conclusions.

## 2 ~~Model description and simulation setup~~Methods

### 2.1 LMDZ5 and IPSL-CM5

The LMDZ dynamical core is based on a mixed finite difference/finite volume discretization of the primitive equations of meteorology (approximate form of the conservation laws for air mass, momentum and potential temperature, under hydrostatic and "thin layer" approximation) and conservation equations for trace species. It is coupled to a set of physical parameterizations. Two versions of the model, LMDZ5A and LMDZ5B, are considered here that differ by the activation of a different set of parameterizations for turbulence, convection and clouds. In the “Standard Physics” package SP used in version LMDZ5A (Hourdin et al., 2013a), boundary layer turbulence is parameterized as a diffusion with an eddy diffusivity that depends on the local Richardson number. A counter-gradient term on potential temperature (Deardorff, 1972) as well as a dry convective adjustment are added to handle dry convection cases which often prevail in the boundary layer. In the “New Physics” package NP of version LMDZ5B (Hourdin et al., 2013b), the vertical transport in the boundary layer relies on the combination of a classical parameterization of turbulent diffusion with the thermal plume model ~~introduced above~~ described below (Hourdin et al., 2002; Rio and Hourdin, 2008). The SP and NP versions also differ by the representation of deep convection closure and triggering. However, we will concentrate the present study on the dry season over West Africa when deep convection does not activate. The two versions correspond to the IPSL-CM5A and -CM5B versions of the IPSL coupled model used for CMIP5 (Dufresne et al., 2013).

### 2.2 The "thermal plume model"

In the NP version, eddy diffusivity $K_z$ is computed based on a prognostic equation for the turbulent kinetic energy that follows Yamada (1983). It is mainly active in practice in the surface boundary layer, typically in the first few hundred meters above surface. It is combined with a mass flux scheme that represents an ensemble of coherent ascending thermal plumes as a mean plume. A model column is separated in two parts: the thermal plume and its environment. The vertical mass flux in the plume $f_{\text{th}} = \rho \alpha_{\text{th}} w_{\text{th}}$ – where $\rho$ is the air density, $w_{\text{th}}$ the vertical velocity in the plume and $\alpha_{\text{th}}$ its fractional coverage – varies vertically as a function of lateral entrainment $e_{\text{th}}$ (from environment to the plume) and detrainment $d_{\text{th}}$ (from the plume to the environment). For a scalar quantity $q$ (total water, potential temperatures, chemical species, aerosols), the vertical transport by the thermal plume reads

$$\frac{\partial f_{\text{th}} q_{\text{th}}}{\partial z} = e_{\text{th}} \cancel{q}\overline{q} - d_{\text{th}} q_{\text{th}} \tag{1}$$

$q_{\text{th}}$ being the concentration of $q$ inside the plume. Note that this formulation assumes stationarity of the plume properties when compared to the time scale of the change in ~~large scale model variables~~the explicit model state variables $\overline{q}$, a classical approximation in mass flux parameterizations of convective motions. Here air is assumed to enter the plume with the ~~concentration of the large scale~~mean grid cell concentration $\overline{q}$, which is equivalent to ~~neglect~~ neglecting the plume fraction $\alpha_{\text{th}}$ in this part of the computation. This approximation is generally considered as obvious for cumulus convection, which often covers a very small fraction of the horizontal surface (e. g. Tiedtke, 1989) . It is more questionable for the boundary layer convection where the fraction is often close to 5-10% but the approximation is generally maintained for numerical reasons [1]. The approximation is however probably less an issue than the specification of $e$ and $d$ and do not prevent accurate comparison with Large Eddy Simulations (Hourdin et al., 2002) .

The particular case of $q \equiv q_{\mathrm{th}} \equiv 1$ gives the continuity equation that relates $e_{\mathrm{th}}$, $d_{\mathrm{th}}$ and $f_{\mathrm{th}}$. The vertical velocity $w_{\mathrm{th}}$ in the plume is driven by the plume buoyancy $\cancel{g(\theta_{\mathrm{th}}-\theta)/\theta}$ $g(\theta_{\mathrm{th}}-\overline{\theta})/\overline{\theta}$, where $\overline{\theta}$ is the mean potential temperature in the grid box and $\theta_{\mathrm{th}}$ the potential temperature within the thermal plume at the same model level. The computation of $w_{\mathrm{th}}$, $\alpha_{\mathrm{th}}$, $e_{\mathrm{th}}$ and $d_{\mathrm{th}}$ is a critical part of the code. We use here the version of the scheme described by Rio et al. (2010) and used in LMDZ5B (Hourdin et al., 2013b). In this version, air is entrained into (resp. detrained from) the plume as a function of the buoyancy of plume air parcels divided by the square of the vertical velocity when this buoyancy is positive (respectively negative). Entrainment is strong near the surface, where it feeds the plume. Then detrainment is strong at the top of the mixed layer, when the plume decelerates. Entrainment can be active again above cloud base, for cloud-topped boundary layers when cumulus clouds are buoyant. The plume air is then detrained close to the top of the cloud. Entrainment and detrainment rates also depends on $\alpha_{\mathrm{th}}$. The vertical velocity is computed with the plume equation (Eq. 1) with additional buoyancy and drag terms on the right and side. The plume fraction is diagnosed as a the ratio of the $f$ and $\rho w_{\mathrm{th}}$.

Finally, for both the SP and NP versions, the time evolution of $q$ reads

$$\cancel{\frac{\partial q}{\partial t}} \frac{\partial \overline{q}}{\partial t} = -\frac{\partial \overline{\rho w' q'}}{\partial z} \tag{2}$$

[1] Abandoning the hypothesis of stationarity of the plume would imply adding a new state variable for each tracer (the tracer concentration inside the plume for instance). Abandoning the $\alpha \ll 1$ approximation would consist in replacing the term $e_{\mathrm{th}}\overline{q}$ in Eq. 1 by $e_{\mathrm{th}} q_{\mathrm{env}}$, where the tracer concentration in the plume environment $q_{\mathrm{env}}$ is given by $\overline{q} = \alpha_{\mathrm{th}} q_{\mathrm{th}} + (1-\alpha_{\mathrm{th}}) q_{\mathrm{env}}$. If at the beginning of a time step, there is tracer in the first model layer only ($\overline{q} = 0$ above), the concentration in the plume will be non zero above this first layer, which would lead (since $\overline{q} = 0$) to $q_{\mathrm{env}} = \alpha_{\mathrm{th}} q_{\mathrm{th}} / (\alpha_{\mathrm{th}} - 1) < 0$ which may at the end result in spurious negative tracer concentrations.

with

$$\overline{\rho w'q'} = f_{\text{th}}(\cancel{q - q}\overline{q} - q_{\text{th}}) - \rho K_z \left( \cancel{\frac{\partial q}{\partial z}} \frac{\partial \overline{q}}{\partial z} - \Gamma \right) \tag{3}$$

In the SP version, $f_{\text{th}} \equiv 0$, the computation of $K_z$ is based on ~~an equilibrium TKE equation~~ a steady-state solution of the evolution equation of the Turbulent Kinetic Energy (TKE) which leads to a Richardson dependent formulation, while the counter-gradient $\Gamma$ is introduced for transport of potential temperature. In the NP version, $\Gamma \equiv 0$, $K_z$ is computed from a TKE prognostic equation and $f_{\text{th}}$ accounts for the thermal plumes.

~~Note that the~~ The same equation is applied for the time evolution of the horizontal component of the specific momentum $u$ and $v$, but with an optional additional term in the plume equation, that accounts for the exchange of momentum by pressure torque following Hourdin et al. (2002). This optional term has a very minor impact on the results and is not activated in the present simulations for the sake of simplicity.

### 2.3 The CHIMERE dust emission module

Mineral dust injection in the atmosphere is computed using CHIMERE emission modules (Menut et al., 2013). The configuration is the one used in Menut et al. (2009) for the AMMA experiment. Dust emissions depend on the soil and surface properties and on the near-surface meteorology with the friction velocity. Soil and surface properties are issued from a $1° \times 1°$ database that covers North Africa including Sahara and Sahel available at http://www.lisa.u-pec.fr/mod/data/index.php. The saltation flux is estimated following the Marticorena and Bergametti (1995a) scheme (see also Marticorena et al., 1997; Callot et al., 2000)~~and the sandblasting~~. Experiments indicate that the vertical dust emissions flux can be considered as a fraction of the "saltation" flux, i. e. the amount of soil material in horizontal movement at the soil surface. The saltation flux can be expressed as a function of a threshold $U^*_{\text{Th}}$ and a cubic dependency of the wind friction velocity of the form

$$F_h = \frac{K\rho_a}{g} U^{*3} \left(1 - \frac{U^*_{\text{Th}}}{U^*}\right)\left(1 + \frac{U^*_{\text{Th}}}{U^*}\right)^2 \tag{4}$$

according to the work of Marticorena and Bergametti (1995b) , where $K$ is a constant of proportionality which is set to $K = 1$ in this work, as is recommended by Gomes et al. (2003) . The vertical flux associated with sandblasting is computed with the Alfaro and Gomes (2001) scheme, optimized following Menut et al. (2005). The threshold for the friction velocity is estimated using the Shao and Lu (2000) scheme~~and~~. In order to account for sub-grid scale variability of the mean wind speed, a Weibull distribution is used (Cakmur et al., 2004) with the following probability density function:

$$p(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left[-\left(\frac{u}{A}\right)^k\right] \tag{5}$$

where $u$ is the sub-grid wind speed, the shape parameter $k$ is set to $k = 3$ and $A$ is calculated in order to fit the first moment of the Weibull distribution with the mean wind, i. e., $U = A\Gamma(1 + 1/k)$ with $\Gamma$ the Gamma function. The sub-grid wind distribution has been discretized in 12 wind bins.

~~Coupling~~ The coupling of LMDZ with the CHIMERE emission module ~~follows the way CHIMERE is currently forced~~ is done similarly to the standard method used to force CHIMERE by regional climate models~~: an effective wind $U_{\text{eff}}$ is used instead of the large scale wind interpolated at the~~. The 10 m height wind, $U_{10\,\text{m}}$~~. Folowing~~ , computed by LMDZ is passed to the CHIMERE emission module. Optionally an effective wind $U_{\text{eff}}$ can be used instead. Following Beljaars and Viterbo (1994), this effective wind is computed by adding a convective vertical velocity $W^*$, ~~$U^2_{\text{eff}} = U^2_{10\,\text{m}} + 1.2W^{*2}$~~ $U^2_{\text{eff}} = U^2_{10\,\text{m}} + W^{*2}$ that aims at accounting for the wind gustiness in a statistically unstable atmosphere. ~~Both $U_{10\,\text{m}}$ and $W^*$ are computed by LMDZ. For the SP version, $W^*$ is estimated directly from the sensible heat flux $\overline{w'\theta'}_0$ at the surface as $W^* = \left(gh\overline{w'\theta'}_0/\theta\right)^{1/3}$ where $h$ is the boundary layer depth,~~

~~$g$ the gravity and $\theta$ the potential temperature in the first model layer. For the NP version, we use either the same computation of $W^*$ or directly the thermal plume velocity $w_{\mathrm{th}}$, both computation giving very similar results. The second option is retained for the simulations shown here. In addition, a Weibull parameterization is used to account for the effect of spatial inhomogeneities of wind speed within a grid mesh~~This option was not activated in the simulations presented here. Its activation only marginally enhances emissions during the dry season. The same Weibull distribution as in Chimere is used for both the SP and NP versions.

The diameter of emitted dust particles ranges typically from a few nanometers to micrometers. In order to accurately describe this size distribution both in number of particles and in mass, it is common to ~~describe the large range of aerosols sizes using bins and with a distribution following a logarithmic increase (Seinfeld and Pandis, 1998) . In the model, the aerosol distribution is represented by a mean mass median diameter, $D_p$, for each bin.~~ use a discretization in size that follows a logarithmic law (Seinfeld and Pandis, 1998) . For specific studies on emissions and transport of mineral dust, it has been shown that 12 bins corresponds to a good compromise between accuracy and computational cost for long-range transport model simulations (Forêt et al., 2006; Menut et al., 2007). The boundaries for the 12 dust bins used here are 0.09, 0.19, 0.67, 1.49, 2.27, 3.46, 4.81, 5.58, 6.79, 12.99, 26.64, 41.60 and 63.0 $\mu$m. Settling of dust particles and dry deposition are computed as in CHIMERE (Menut et al., 2013) . Scavenging is also activated in the model but it is not involved in the results presented here, before the monsoon onset.

### 2.4 Model configuration and simulations

In order to assess the representation of emission and turbulent processes, the model ~~is run with its~~ simulations are conducted with the zooming capability in a nudged mode. The use of the zoomed/nudged version for model evaluation was described in ~~details~~ detail by Coindreau et al. (2007).

The zoom consists ~~in a~~ of a refinement of the global grid discretization in both longitude and latitude~~discretization. Here, the zoom covers~~ , here over West Africa and the tropical

Atlantic ocean. In order to limit interpolation issues for soil properties, the zoom was chosen so as to ~~get~~ obtain a quasi uniform $1^\circ \times 1^\circ$ resolution over a (70° W–30° E; 10° S–40° N) longitude-latitude box, close to the CHIMERE data set resolution. Nevertheless, the points of the LMDZ grid do not exactly match those of the CHIMERE dust model. First tests have shown that a linear interpolation considerably degrades the results. A nearest neighbor method was ~~retained~~ implemented instead that provides much better results.

The LMDZ model is most commonly used in climate mode: integrated from an initial state ~~just imposing~~ with imposition of some boundary conditions such as insolation, sea surface temperature (in stand-alone atmospheric configurations), composition of dry air, etc. For validation of subcomponents of the model as is the case here, it can be desirable to force the model to follow the observed synoptic meteorological situation, by nudging (relaxing) the model meteorology toward ~~observations~~re-analysis. That way, errors coming from the deficiencies of the subcomponent can be distinguished from those that arise from the erroneous representation of the atmospheric circulation in the model. This also allows a direct day-by-day comparison with observations as illustrated by Coindreau et al. (2007). In practice here, winds are relaxed toward ERA-Interim re-analyzes of the European Centre for Medium-Range Weather Forecasts (ECMWF), by adding a non-physical relaxation term to the model equations:

$$\frac{\partial X}{\partial t} = F(X) + \frac{X^{\mathrm{a}} - X}{\tau} \tag{6}$$

where $X$ stands for $u$ and $v$ wind components, $X^{\mathrm{a}}$ their values in the reanalyzes, $F$ is the operator describing the dynamical and physical processes that determine the evolution of $X$, and $\tau$ is the time constant.

Before applying relaxation, ERAI data are interpolated on the horizontal stretched-grid of the LMDZ model as well as on the hybrid $\sigma$-$p$ vertical coordinates. At each model time step also, the ERAI data are interpolated linearly in time between two consecutive states, ~~evalable~~ available each 6 h in the dataset used here. Different time constants can be used inside and outside the zoomed region (with a smooth transition between the inner and outer region that follows the grid cell size). Here, the constant outside the zoom is 3 h. Inside the zoom tests were made with values ranging from 1 to 120 h. The longer the time constant the ~~weakest the constraint by~~ weaker the constraint of the analyzed wind fields. We focus here on simulations with $\tau = 3$ h, named SP3 and NP3 depending on the physical package used, as well as on a sensitivity test NP48 ran with the NP version and $\tau = 48$ h. The initial state of the simulations is taken from a multi-annual spin-up simulation with ~~interactif~~ interactive dust that corresponds to 1 ~~December~~November 2005. The three simulations cover the years 2006 and 2007 but only the months of the dry season, from November to April, are analyzed here.

### 2.5 In situ observation

In the framework of the AMMA (African Monsoon Multidisciplinary Analysis) international project (Redelsperger et al., 2006) , a set of three stations, the so-called "Sahelian Dust Transect", has been deployed in 2006 to monitor the mineral dust content over West Africa. As described in Marticorena et al. (2010) , the three stations M'Bour (Senegal, 14.39° N, 16.96° W), Cinzana (Mali, 13.28° N, 5.93° W) and Banizoumbou (Niger, 13.54° N, 2.66° E) are almost aligned around 13-14° north, on the main pathway of Saharan and Sahelian dust toward the Atlantic Ocean. They are located in the semi-arid Sahel, and the annual mean precipitation is, respectively, 496 mm in Banizoumbou, 715 mm in Cinzana and 511 mm in M'Bour for the period 2006-2010. In Senegal, instruments are located in the geophysical station of the Institut de Recherche pour le Développement (IRD), south of the city of M'Bour, about 85 km from Dakar. The instruments are installed at 10m height, on the roof of a building close to the seaside. In Mali, the instruments are located in an agronomical research station (Station de Recherche Agronomique de Cinzana, SRAC) of the Institut d'Economie Rurale (IER), 40 km east south-east of the town of Ségou. In Niger, the station is located in a fallow, 2.5 km from the village of Banizoumbou, about 60 km east of the capital Niamey. The instrumentation of the stations is described in detail in Marticorena et al. (2010) . In this study, two types of in-situ data are used: the dust surface concentration and local meteorological parameters. Atmospheric concentrations of Particulate Matter smaller than 10 $\mu$m (PM10) are measured using a Tapered Element

Oscillating Microbalance (TEOM 1400A from Thermo Scientific) equipped with a PM10 inlet. The inlet is located at 6.5 m height in Mali and Niger and 10 m in Senegal. The basic meteorological parameters (wind speed and direction, air temperature, relative humidity) are measured with Campbell Scientific Instruments. Wind speed and wind direction are measured at 1Hz with a 2DWindSonic, temperature and relative humidity using 50Y or HMP50 sensors and rainfall with an ARG100 tipping bucket raingauge. The data acquisition is made using data loggers CR200. Meteorological measurements are made at 10 m height in Senegal, 6,5 m height in Niger and 2.3 m height in Mali. The PM10 concentrations and the meteorological data are recorded as 5 min averages. The three stations are equipped with sunphotometers from the AERONET/PHOTONS network. The Aerosol Optical Depth (AOD) measured by the sunphotometer corresponds to the extinction due to aerosol integrated over the whole atmospheric column. This measurement is thus an indicator of the atmospheric content in optically active particles. Holben et. al. (2001) indicate that the uncertainty on the AOD retrieved from AERONET sunphotometers in the field was mainly due to calibration uncertainties and estimated the uncertainty to 0.01-0.02, depending on the wavelength.

## 3 Dependency of dust lifting to the representation of wind

We first present in Fig. 1 the average emission (colored shading) for March 2006 obtained in the SP3 (top) and NP3 (bottom) simulations. The zoomed grid is apparent on the right hand side of the lower panel from the distortion of the color rectangles, each corresponding to a grid cell. The contours corresponds to the ~~Aerosol Optical Thickness~~ AOD at 550 nm~~(noted AOT afterward in the paper)~~. The NP3 and SP3 emissions are essentially located in the same areas, but they are much stronger for the ~~NP version~~NP3 simulation. The total Saharan emission for March 2006 is of ~~18~~33 Mt for the ~~SP and 75~~SP3 and 113 Mt for the ~~NP version. The~~ NP3 simulation. Even the latter value is ~~already~~ in the lower range of current estimates of the ~~climatolgical~~ climatological total dust emission by North Africa for March~~(see e.g. Figure 6 of Laurent et al., 2008) .~~.[2] As a consequence of the stronger emissions, the ~~AOTs~~ AODs are also by a factor about 4 larger for the ~~NP~~ NP3 than for the ~~SP version. Note that even the NP3 simulationunderestimates the actual AOT as illustrated later on~~SP3 simulation.

In order to interpret at a process level the origin of the difference in emission between the two simulations, we show in Fig. 2 a scatter plot of the emission and wind intensity for a grid cell in the main emission area in Mauritania (location (7.5° W, 18.5° N) shown in red in Fig. 1). We choose this particular point for illustration because it is located in the south of the emission zone, not too far from the latitude at which we show comparisons with in situ wind measurements in the following section. However, as shown later, the behavior observed at this particular grid point is representative of the whole emission zone. The left panel of the figure corresponds to instantaneous values sampled hourly during the month. The cubic relationship used for emission computation is directly visible on this graph, and the same relationship is clearly exhibited for both simulations but the wind distributions markedly differ. Indeed, the maximum speeds explored by the ~~SP version~~ SP3 simulation never exceed $10\,\mathrm{m\,s^{-1}}$ while the wind distribution for the ~~NP version explores~~ NP3 simulation includes much larger values.

~~At the opposite, when the emissions are related to the daily-mean wind speed~~ On the other hand, the relationship between daily mean wind speed and emissions (right panel of Fig. 2) ~~it appears that the wind explored are on average weaker in the NP than in the SP version. However, even for rather moderate values of the wind of 4 to 6, the NP version exhibits significant emissions while the SP does not~~suggests that the winds in the NP3 simulation are smaller than in SP3, but emissions are larger for these lower wind speeds.

[2] Marticorena et al. (1997) report values of 163 and 101 Mt for 1990 and 1991 while considering only half of the Sahara. Laurent et al. (2008) compute mean emissions with ERA-40 winds for March (period 1996-2001) of the order of 80 Mt with a maximum value of 205 Mt while Schmechtig et al. (2011) compute emissions of the order of 300 Mt for March 2006 with ECMWF forecast winds.

It is thus the sub-diurnal distribution of the wind which explains the difference between the emissions of the two versions.

This is confirmed when focusing on time series of emissions and wind speed at the same grid point for 2 to 13 March (Fig. 3), a period which includes the strongest observed dust event of that particular month (Slingo et al., 2006). Thanks to nudging, both simulations follow a similar evolution of the wind at daily scale with a maximum between 6 and 8 March which correspond to this dust event. However, the NP3 simulation shows a marked peak each morning while the SP3 simulation does not. Because of the strong non linearity of the emission process, this morning peak ~~reinforces~~ increases emissions during the major dust event and also often produces emissions in the morning when the SP3 simulations does not predict any.

## 4 Comparison with site observations

~~For evaluation of the representation of the above mentioned processes, we compare the model results with observations recorded at surface stations installed in the framework of the AMMA project (Redelsperger et al., 2006) . A set of three stations dedicated to the monitoring of mineral dust were deployed in 2006 along a "Sahelian Dust Transect" (Marticorena et al., 2010) . The stations are aligned between 13 and 15N along the main pathway of the Saharan and Sahelian dust toward the Atlantic Ocean, namely Banizoumbou (Niger, 13.54N, 2.66E), Cinzana (Mali, 13.28N, 5.93W) and M'Bour (Senegal, 14.39N, 16.96W). The locations of the three stations are displayed in Fig. 1 as black rectangles. In addition to the local meteorology (wind speed and direction, air temperature, relative humidity), the atmospheric concentration of Particulate Matter smaller than 10(concentration) is continuously monitored with a 5time step. The AOT is measured by a sunphotometer from the AERONET/PHOTONS network.~~

~~Although the stations are not located in the emission area discussed above, model results show very similar diurnal variations of wind at these sites~~We compare the simulated wind with the available in-situ observations described above. We here consider the ~~full~~

~~2005–2006 winter, from December~~ dry season of 2006, from January to March. The comparison is done for the three simulations: SP3, NP3 and NP48. We show in the top panels of Fig. 4, for Cinzana and Banizoumbou, the evolution of the daily averaged wind. There is a reasonable agreement between models and observations as for the order of magnitude of this mean wind. All the simulations tend however to slightly overestimate the wind at Cinzana and underestimate it at Banizoumbou. Differences between the three simulations are generally small~~, with a tendency of SP3 to simulate slightly stronger winds, especially at Cinzana, similarly to what was seen in the right panel of Fig. 2~~. The day-to-day variations of the wind ~~closely~~ partly follow observations, which illustrates that relevant information at synoptic scales present in ERAI reanalyzis are passed to the numerical experiments through the nudging procedure.

The fact that the NP48 simulation does not depart that much from NP3 suggests that nudging with a 48 h time constant is in fact strong enough to constrain the model day-to-day variations.

The middle panels in the same figure show the maximum value for each day. ~~Consistently~~ Consistent with Fig. 3, the NP version of the model (both NP3 and NP48 simulations) produces much larger maximum winds than the SP version. Those winds are in fact larger than observations at Cinzana (where the SP3 version is closer to observations) and close to observations at Banizoumbou. However, when considering the ratio of the maximum to mean winds, ~~it is~~ the NP version gives better results for both stations~~the NP versions that give the best results~~. This ratio ranges from 2 to 2.5 for the NP3 and NP48 simulations and observations, against 1 to 1.2 for the SP3 simulation. It is ~~consistent with an idea that this relative variation of wind within a day is more controlled by physical processes and less subject to large scale biases (whatever they are) than the absolute mean value and mean field~~shown later that this good agreement is linked more generally to a much better representation of the mean diurnal cycle than in the SP version.

~~As for dustevaluation~~In order to evaluate the dust, we first show in Fig. 5 the comparison of the observed and modeled $PM_{10}$ surface concentration and ~~AOT~~ AOD at 550 nm (computed following Moulin et al., 2001) at M'Bour, close to Dakar/Senegal. This station is considered ~~at~~ first because it is downstream of the dust emissions discussed in the previous section. The synoptic behavior is captured reasonably well by the model, and in particular the occurrence of the main dust event of the winter in early March. This once again reflects that some information on the actual circulation is transmitted to the simulation thanks to nudging by reanalyzes. The concentrations and emissions are however typically underestimated by ~~a factor of 2 in the NP~~ 20-50% in the NP3 and NP48 simulations, the ~~SP version~~ SP3 simulation being even farther from observations. Note that there is also a significant and systematic increase of dust when weakening the nudging, going from $\tau = 3$ h to 48 h.

A more systematic ~~and synthetic~~ comparison is shown in Fig. 6 for the three stations in form of a scatter-plot of observed vs. simulated ~~AOT~~AOD. The underestimation of ~~AOTs~~ AODs is clearly present at the three stations, and it is even somewhat worse at Cinzana and Banizoumbou. The behavior is however similar in terms of comparison of the three simulations: ~~AOTs~~ AODs are always larger for the NP than for the SP physics, and increase when weakening the nudging (from NP3 to NP48). Note that the improvement is significant both for the weak (associated with small lifting events) and strong concentrations. ~~The fact that the improvement is slightly smaller for large values is consistent with the larger role played by large scale dynamics for those events. But even then, the representation of the diurnal cycle of winds plays a significant role.~~

Several factors can explain the overall underestimations of ~~AOTs~~ AODs and concentrations but this discussion is out of the scope of the present paper and will deserve further investigations.

## 5 Mean diurnal cycle of boundary layer wind

~~We finally~~ Finally, we analyze the representation of the diurnal cycle of wind. We show in Fig. 7 the mean diurnal cycle of the near surface wind at Cinzana and Banizoumbou for the full winter period (~~December 2005~~ January to March 2006). Note that this diurnal cycle is very similar whatever the period selected within the winter season ~~and whatever the~~

~~year considered~~ for the years 2006 and 2007 considered here.[3] ~~This~~ As was already seen in Fig. 4, the mean value is somewhat overestimated at Cinzana and underestimated at Banizoumbou for the three LMDZ simulations. The phase and amplitude of the diurnal cycle is ~~better represented in the NP than in~~ however much better represented when using the NP rather than the SP version of the model, and also better represented than in the reanalyzes used for nudging. The rather poor representation of the diurnal cycle of wind in ERAI as well as in other reanalyzes datasets was recently pointed out by Largeron et al. (~~2014~~2015).

The tendency of the ~~NP~~ NP3 and NP48 simulations to over-predict winds at Cizana and under-predict them at Banizoumbou, already visible in Fig. 4, may have several explanations: effect of local subgrid-sale topography, bad prediction of the local drag which is taken directly from the climate model boundary conditions and not from the more accurate database used to compute emissions ~~,~~ or bias in the reanalyzes winds used for nudging~~... More surprising is the fact that ERA reanalyzes~~. Note also that the reanalysis ERAI almost systematically over-estimate wind speed ~~, which may have practical implication for dust transport computations. In particular, tuning of emission algorithms with overestimated winds from reanalyzes may lead to artificially underestimate the emissions when better winds are given to the emission module, as is the case here~~for those stations.

The differences seen in Fig. 7 for the 10 m wind diurnal cycle between simulations and reanalyzes reflects strong differences in the vertical too. We show in Fig. 8 the vertical profiles at 6 a.m. (left) and noon (right) for Banizoumbou.[4] At the end of the night, the jet is much stronger in the ~~NP version~~ NP3 and NP48 simulations than in the reanalyzes, as well as its decoupling from the surface. Note that a similar underestimation of the ERAI low level jet intensity is shown in Fig. 4 of Fiedler et al. (2013), when compared to observations in the Bodele region. ~~At the opposite~~On the other hand, the wind is much better mixed within the boundary layer at noon in the ~~NP~~ NP3 and NP48 simulations while the reanalyzes keep the

[3]The diurnal cycle at M'bour (not shown) displays a similar cycle with maximum in the morning, but not as marked, probably because the land–sea contrasts maintain a significant amount of wind even during the night.

[4]The profiles are very similar for Cinzana and not that different for M'Bour (not shown).

signature of the low level jet. Note the similarity of the SP version with the reanalysis, which may be related to the fact that both the SP version of LMDZ and the ECMWF model used to produce the reanalysis, base ~~there~~ their boundary layer computation on eddy diffusion approaches, without accounting for the non local transport by thermal plumes.

The vertical mixing of horizontal momentum by thermal cells is key for the representation of the nocturnal jet and near surface wind~~in the NP simulation~~. We present in the upper panel of Fig. 9, for the NP48 simulation and for four consecutive days, the vertical profile of ~~the module~~ $\|V\| = \sqrt{u^2+v^2}$ ~~of the horizontal wind~~ in black contours, together with the tendency of this wind module due to the thermal plume model (color shadings)

$$\frac{\partial \|V\|}{\partial t}_{|\mathrm{th}} = \frac{1}{\|V\|}\left(u\frac{\partial u}{\partial t}_{|\mathrm{th}} + v\frac{\partial v}{\partial t}_{|\mathrm{th}}\right) \tag{7}$$

The top of the turbulent boundary layer is also identified on the graphs as a red curve. Following a classical approach (see e.g. Hourdin et al., 2002), the curve corresponds to $Ri_b = 0.25$, where

$$Ri_b = \frac{gz}{\theta}\frac{\theta-\theta_\mathrm{s}}{\|V\|^2} \tag{8}$$

is a so-called bulk Richardson number (similar to a gradient Richardson number but computed non locally by replacing gradient terms by finite differences between altitude $z$ with a potential temperature $\theta$ and surface with a temperature $\theta_\mathrm{s}$, where the wind is assumed to vanish). During the day, the momentum is well mixed within the full convective boundary layer which grows as high as 5 km, with vertical winds in the thermal plumes of the order of 2 m s$^{-1}$. The collapse of the boundary layer at sunset is very rapid. There is essentially no turbulence left after 18:00. The wind, decoupled from the surface, then starts to accelerate, driven by the ~~unbalance~~ imbalance between the Coriolis force and horizontal pressure gradient (which evolves itself in response to the diurnal cycle of the thermal forcing of the monsoon flow, Parker et al., 2005). The jet maximum intensity varies from about 8 to 25 m s$^{-1}$ and the height of the jet core from 200 to 500 m depending on the night considered. The strong wind shear created at the surface gradually produces turbulence in the surface layer, but it is only at sunrise that the boundary layer rapidly develops. The thermal convection starts at 08:30 LT and reaches 1 km before 10:00 LT. Because the shear in momentum is very strong at the beginning, the impact of vertical transport by the thermal plume model is also very large. The wind speed at surface can increase by up to 25 m s$^{-1}$ in only one hour in the first model layer (middle panel). The peak is very short in time (less than one hour). With a typical updraft velocity $w_{\text{th}} \simeq 1$ m s$^{-1}$ at the height of the nocturnal jet and an horizontal fraction of the surface covered by thermal plumes $\alpha_{\text{th}}$ of typically 0.1 to 0.2, the compensating subsidence (10–20 cm s$^{-1}$ typically) needs less than one hour to bring the air from the jet core (200–500 m) down to the surface.

It is this peak of downward transport from the nocturnal jet which explains the morning peak in near surface wind. The mixing by thermals also rapidly reduces the jet intensity~~. The thermals still accelerates the surface layer as long as the boundary deepens in the morning~~, reducing in turn the acceleration of surface winds by thermals subsidences. The near surface wind ~~slowly decreases afterward, until late afternoon. As shown by the~~ then decelerates slowly in the afternoon, under the effect of turbulent exchange with the surface. The negative diffusive term (green curve in the second panel of Fig. 9~~, this decrease is the consequence of turbulent exchange with the surface . The acceleration by thermals is then smaller because of the reduced vertical gradients in the mixed layer~~) is almost compensated by the thermals tendency which accounts for convective exchanges between the surface layer and the mixed layer above. Both terms almost cancel after sunset, resulting in a decoupling that allows for the creation of the low level jet of the following night.

## 6 Conclusions

This study focuses on the impact of the representation of boundary layer processes on near surface wind and on dust emissions. Significant conclusions may be drawn that ~~do not depend on~~ are likely to be independent of the particular model used for representation of dust (as soon as it accounts for the strong non linearity of emission to near surface wind).

1. This study underlines the importance of a correct representation of the vertical transport of horizontal momentum by boundary layer processes for a good representation of the diurnal cycle of wind at the surface.

2. ~~It clearly attributes the observed~~ The morning peak of near surface wind ~~to the~~ observed almost every day over Sahel is well captured by the NP version of the physical parameterizations. In the model, this peak is due to the rapid downward transport of momentum by the compensating ~~subsidence of thermal plumes , at there first stage, when they~~ subsidences when the thermal plumes reach the height of the low-level jet which develops during the night at a few hundred meters above the surface~~, when the wind is decoupled from the surface~~.

3. This study advocates for the representation of vertical boundary layer transport through the combination of eddy diffusion and mass flux representation of the coherent structures of the convective boundary layer, an approach first proposed by Chatfield and Brost (1987). It confirms in particular the ability of the the so-called thermal plume model to represent in a physical way the vertical transport of momentum, as already illustrated in Fig. 2 of Hourdin et al. (2002), based on comparison of single-column computations with Large Eddy Simulations results issued from an inter-comparison study coordinated by Ayotte et al. (1996).

4. The mean diurnal cycle of the near surface wind is well captured in the NP version of the LMDZ model that includes these thermal plume processes, ~~and~~ at the Sahelian stations considered here. It is much better represented in terms of mean value, phase and amplitude than in the reanalyzes used for nudging. This conclusion ~~goes beyond this particular model since many chemistry transport models~~ is important for many chemical transport models which rely on reanalyzes for the computation of near surface ~~wind~~winds.

5. An important practical consequence of this point is that it could be better to use much larger time constants for nudging than what was currently believed. The rationale for

using time constants of a few hours was to let the rapid processes represented in turbulent parameterizations to express themselves, without departing from the observed synoptic situation. The problem is that the time constants which prevail for the creation and control of the nocturnal jet are typically those of the diurnal cycle itself. So constants larger than one day should be used for this particular problem. It seems that with time constants as large as 48 h the synoptic situation is still rather well ~~constraint~~constrained, which probably points to a reasonable behavior of the physics of the LMDZ model which does not tend to depart too fast from the observed situation. Note also that the mean diurnal cycle is almost identical when simulations are conducted in free climate mode, without nudging (results not shown).

~~Despite a reasonable representation of the near surface winds (at least~~ Although the detailed analysis of the diurnal cycle of wind was conducted at the stations ~~available, which unfortunately are not~~ for which we have observations, located at the south of the emission zone, the same difference between the SP3, NP3 and NP48 simulations is obtained everywhere over the Sahel and Sahara and for all the winter period, as illustrated in Fig. 10. The left panels show, for March 2006, the monthly mean of the ratio of the daily maximum to the daily average of the 10 m wind. This mean ratio is maximum over Sahel for all simulations. At 12N, it is typically of 1.6 in SP3 and 2.3 for NP3 and NP48. Over the Sahara, in the main emission zones~~), the model seriously underestimates the observed dust loading of the atmosphere, typically by a factor of 2~~ , it is of the order of 1.3 for ~~the~~ SP3 and 1.8 to 2.2 for NP3 and NP48~~simulation that shows the strongest emissions~~ . The ratio is systematically a little bit larger for NP48 than for NP3. The mean wind itself is generally smaller in NP3 than in SP3, and a little bit stronger in NP48 than in NP3. ~~Such discrepancies are however not that exceptional for simulations of African desert dust (e.g., Todd et al., 2008)~~

As a consequence of the different representation of the wind diurnal cycle, a much larger fraction of the dust emissions occur in the morning between 06 and 12 UTC in NP3 than in SP3, as seen in the second column of Fig. 10. This fraction is larger than 90% in the northern part of Sahara, and is slightly larger as well in the NP48 than in the NP3 simulation.

~~The discussion was focused here on year~~ This behavior is not specific of this particular month as can be seen on the third column that shows, for all the dry season months of years 2006 ~~but the comparison was extended on the following years (for which the same observation are available) leading to very similar results. Note that the model already includes~~ and 2007, the total emission over Africa, split into slots of 6 hours UTC. The dominance of morning emissions concerns all the months. This figures can be compared with Fig 4 of Tegen et al. (2013) that shows that more than 95% of dust source activation computed from MSG satellite observations occur between 6 and 12 UTC.

By cumulating emission over the 12 months displayed, the total emission is 205 Mt for SP3, 757 for NP3 and 765 for NP48, and the fraction of this emission that occurs between 06 and 12 UTC: 32%, 55% and 61% respectively.

Despite a reasonable representation of the near surface winds (at least at the stations available, which unfortunately are not in the main emission zones), and despite the use of a Weibull ~~parameterization~~ distribution to account for the effect of spatial inhomogeneities of wind speed within a grid mesh~~. Of course many points could be investigated to try to understand the origin of this underestimation . Whatever those points, it does not alter~~ , the model underestimates the observed dust, typically by 20-50% for the NP48 simulation that shows the strongest emissions. The underestimation is similar when considering either AOD or PM10 concentrations. AOD is sensitive to the atmospheric column with a stronger contribution of small particles while the PM10 concentration is a direct measurement of the mass concentration close to the surface. The fact that both indicate a similar underestimation suggests a general underestimation of emissions rather than a size distribution effect.

Such discrepancies are however not that exceptional for simulations of African desert dust (e.g., Todd et al., 2008) .

This underestimation does not question the main result of the paper which is that an accurate representation of the diurnal evolution of the boundary layer and transport of momentum by boundary layer convective cells must be taken into account for a good representation of winds, and that such a ~~good representation is accessible now to~~

~~the modeling community~~good representation can be obtained through a combination of turbulent diffusion and mass flux representation of the boundary layer convection. This study also underlines the importance of in-situ long-term and high frequency meteorological and dust observations for evaluation and improvement of weather forecast and climate models.

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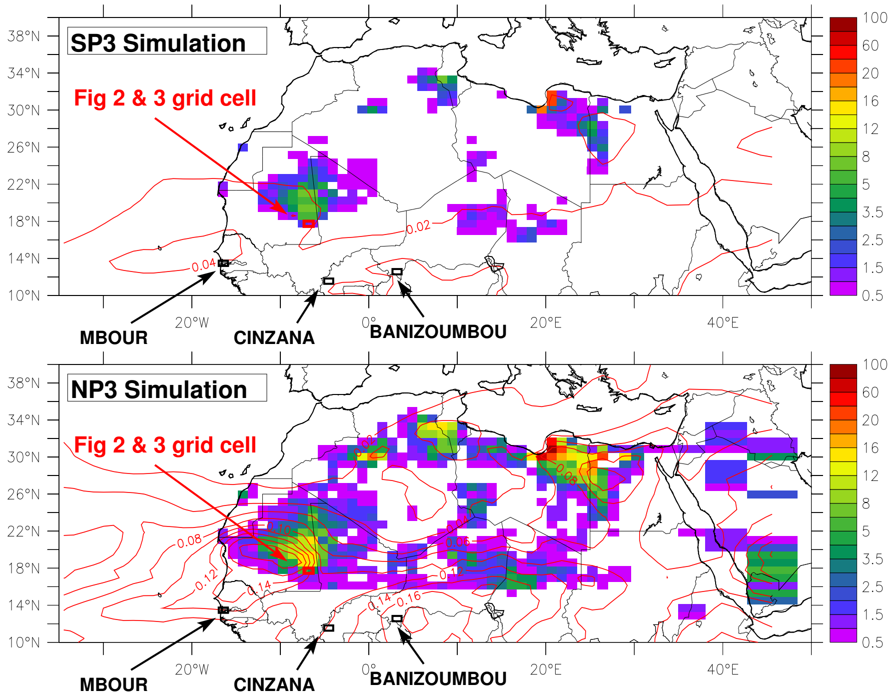


**Figure 1.** Comparison of the total emission ($\mu g\,m^{-2}\,s^{-1}$) for the SP3 (top) and NP3 (bottom) simulations (NP and SP versions of the physical package with $\tau = 3\,h$ for nudging) for March 2006. Contours correspond to the mean ~~AOT~~ AOD at 550 nm, with a 0.02 interval between contours.

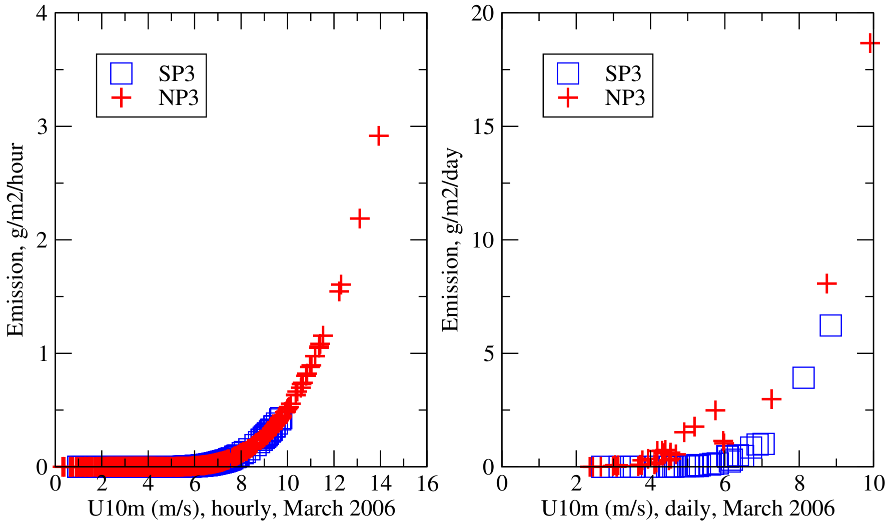


**Figure 2.** Scatter plot of the emission vs. 10 m wind speed ($m\,s^{-1}$) for simulations SP3 (blue) and NP3 (red) for March 2006, at (7.5° W, 18.5° N) (location shown in red in Fig. 1). The left panel corresponds to an hourly sampling of instantaneous values (with emission given in $g\,m^{-2}\,h^{-1}$) while the right panel is made from daily averages (with emissions given in $g\,m^{-2}\,day^{-1}$).

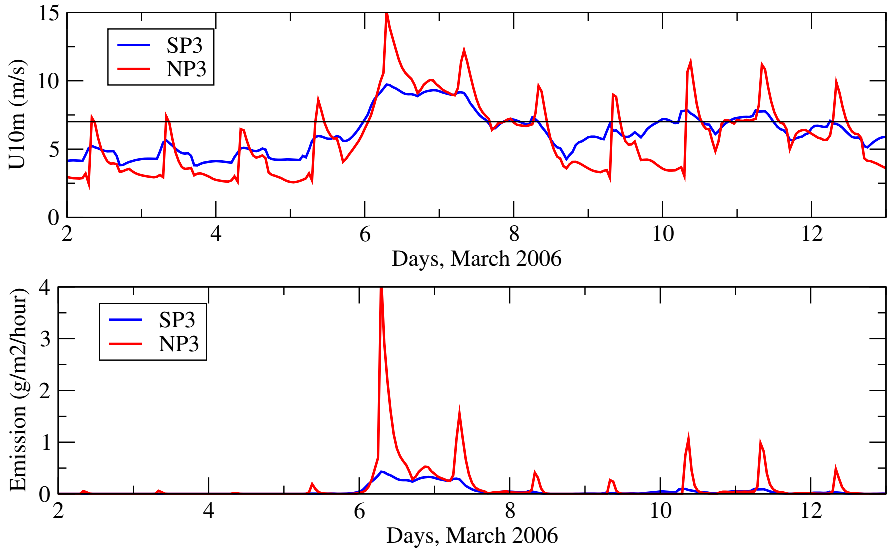


**Figure 3.** Comparison from 2 to 13 March 2006 of the 10 m wind (upper panel, $m\,s^{-1}$) and emission (lower panel, $g\,m^{-2}\,h^{-1}$) for simulations SP3 (blue) and NP3 (red) in the grid cell selected for emission analysis at (7.5° W, 18.5° N) (shown in red in Fig. 1). The horizontal line in the upper panel corresponds to a wind of 7 $m\,s^{-1}$ above which emissions start to be significant.

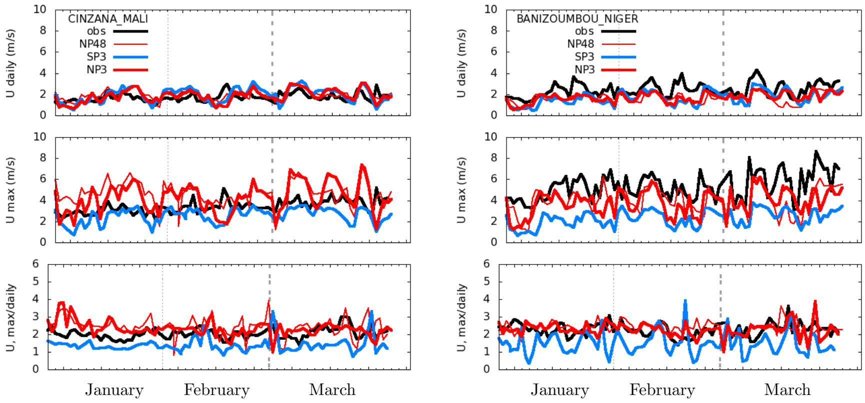


**Figure 4.** Time evolution over winter 2006 of the daily mean (upper panels) and maximum (mid panels) 10 m wind speed ($m\,s^{-1}$) as well as the ratio (lower panels) of the maximum value to the daily mean for Cinzana (left) and Banizoumbou (right). Results of the SP3 (blue), NP3 (red) and NP48 (red dashed) simulations are compared to site observations (black).

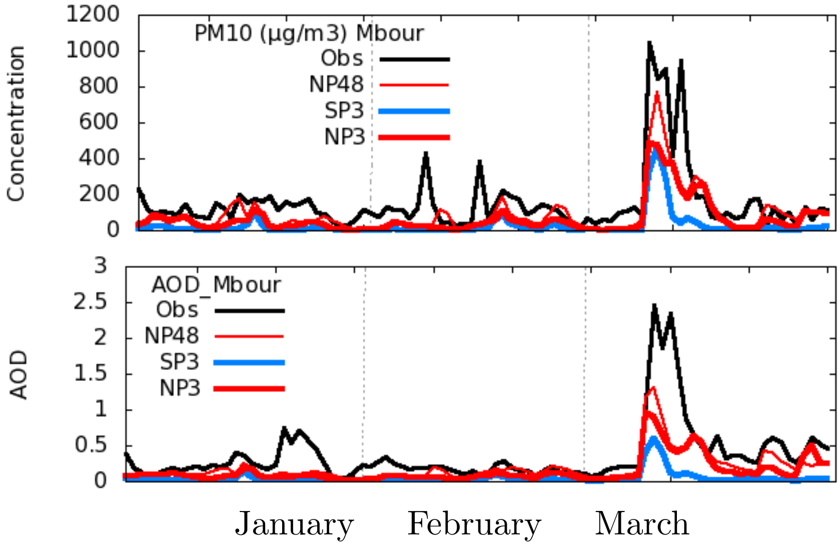


**Figure 5.** Time evolution over winter 2006, of the daily mean $PM_{10}$ concentration (top, in $\mu g\,kg^{-1}$) and ~~AOT~~ AOD for the M'bour station for simulations SP3 (blue), NP3 (red) and NP48 (red dashed) and for observations (black).

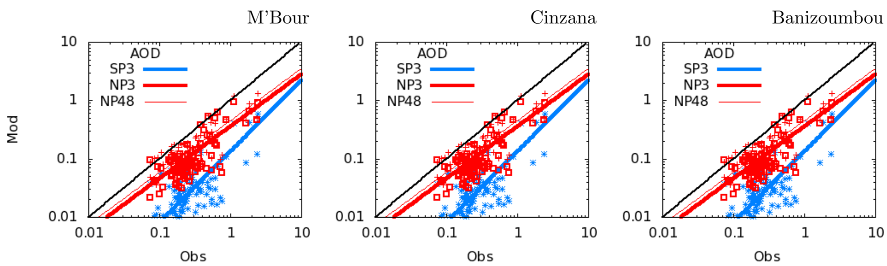


**Figure 6.** Scatter plots of the model vs. observed ~~AOT~~ AOD at M'bour, Cinzana and Banizoubmou for simulations SP3 (blue), NP3 (thick red line and ~~crosses~~squares) and NP48 (thin red ~~dashed~~ line and ~~squares~~crosses) computed at daily frequency.

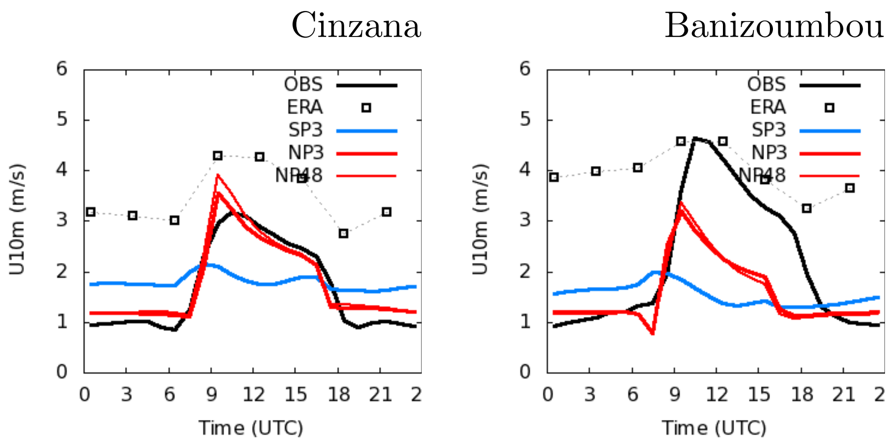


**Figure 7.** Wind mean diurnal cycle for ~~DJFM of winter 2005–2006~~ JFM 2006 ($\mathrm{m\,s^{-1}}$) for the Cinzana (left) and Banizoumbou (right) stations. Model results (colored curves) are compared to observations (black curve) and ERAI reanalyzes (squares) for the same time period. Note that the universal and local times do not depart by more than one hour for the region considered here.

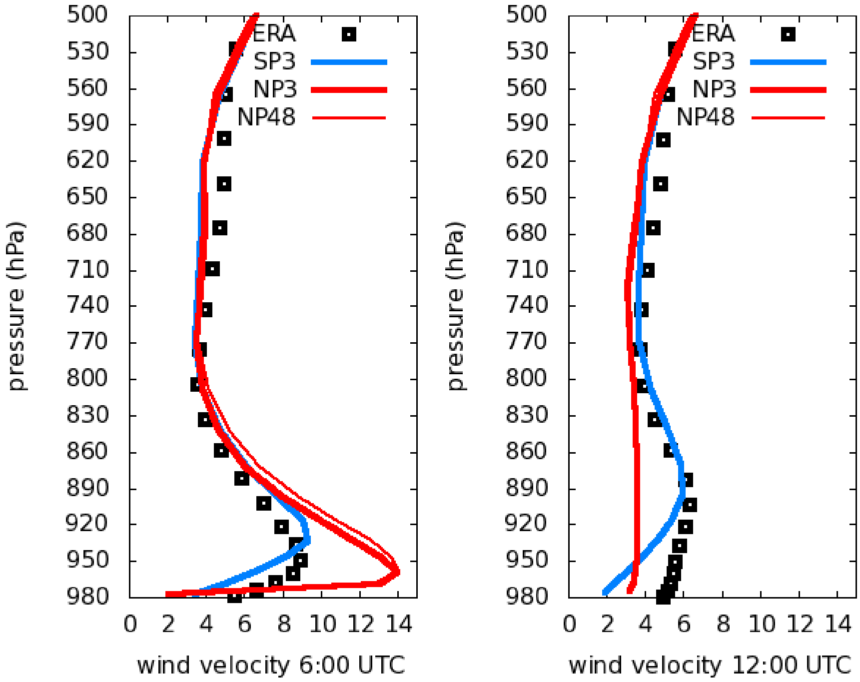


**Figure 8.** Wind mean vertical profiles ($m\,s^{-1}$) for ~~DJFM of winter 2005–2006~~ JFM 2006 at 06:00 and 12:00 UTC at Banizoumbou. Model results (colored curves) are compared to ERAI (black squares) for the same time period.

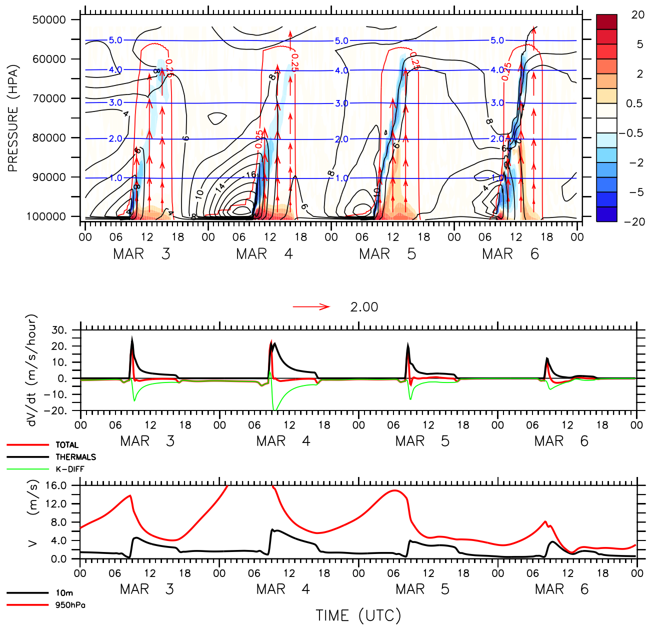


**Figure 9.** Four consecutive days showing the diurnal cycle of the boundary layer at Banizoumbou, in early March 2006. Are shown in the upper panel: the vertical distribution of the module of the horizontal wind (black contours, $\mathrm{m\,s^{-1}}$), the wind module tendency due to vertical transport by the thermal plume model, according to Eq. (7) (colored shades with absolute iso-values 0.5, 1, 2, 3, 5, 10 and 20 $\mathrm{m\,s^{-1}\,h^{-1}}$). The red contour delimits the depth of the boundary layer and corresponds to the 0.25 value of the bulk Richardson number (Eq. 8). The red arrows correspond to the thermal plume velocity in $\mathrm{m\,s^{-1}}$ (under-sampled with respect to the space–time discretization of the simulation). The vertical axis, in pressure (Pa), and the altitude (in km, blue contours) are also shown. In the middle panel, we show for the first model layer (located at about 30 m above surface) the decomposition of the total wind module tendency (TOTAL, red, $\mathrm{m\,s^{-1}\,h^{-1}}$) as the sum of the thermal plume contribution (THERMAS, black) and turbulent diffusion (TKE, green). The lower panel shows the wind speed at 10 m (black) and 950 hPa (red), close to the altitude where the nocturnal jet reaches its maximum.

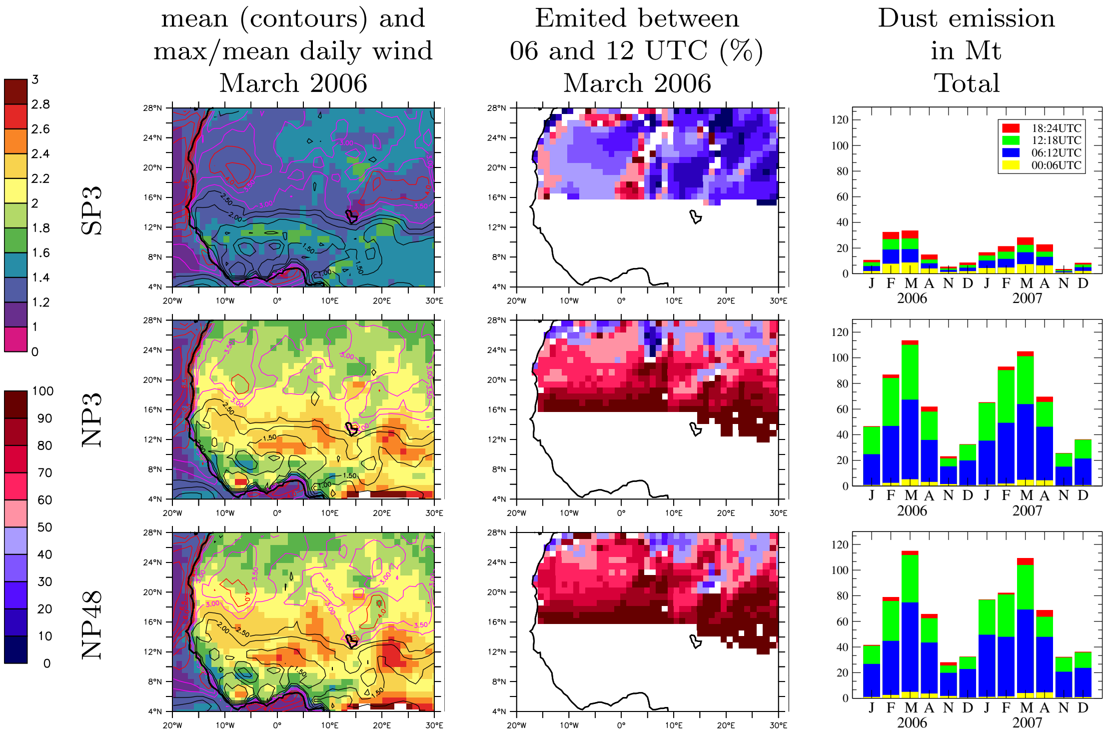


**Figure 10.** Diurnal cycle of winds and emission for the SP3 (top), NP3 (middle) and NP48 (bottom) simulations. The first two columns correspond to March 2006. The first one displays the mean wind (contours) as well as the monthly mean of the ratio of the daily maximum to averaged wind (color shading). The second column shows the fraction of emission that occurs between 06 and 12 UTC. The right column shows for the dry season months of years 2006 and 2005 the total African emission and its distribution between consecutive slots of 6 hours within the day.