

## Responses to reviewers

The reviewers make many helpful comments, which we use to improve the paper. We respond to each comment here and indicate what changes we propose to the text. The *reviewers' comments are in italics*, while our responses are in regular type.

### *Anonymous Referee #1*

#### *General comments:*

*In this paper Mahowald et al. study the variability of desert dust in the 20th century based on paleodata from around the world. By combining the data with different models representing the atmosphere, ocean and land the impact on biogeochemistry and climate is investigated. The impact of dust and the differences in radiative forcing between dusty and non-dusty periods is significant. This study is hence an important contribution to our understanding of the climate system. There are major uncertainties associated with this type of study, but a detailed discussion and estimates of these are given in the paper.*

*I recommend the paper for publication in ACP as the topic is highly relevant. The data handling, methods and associated assumptions seem sound and the applied models are, to my knowledge, current state-of-the-art. There is one assumption/method that to my opinion should be better described before publication, see below. Apart from that, I have only minor comments and corrections. The paper is well written and well founded in existing literature.*

#### *Specific comment:*

*Page 12587 Line 1-2: Desert dust ... interacting with incoming ..., thereby changing precipitation . . . As you write later in the paper dust can also change precipitation patterns by acting as cloud condensation nuclei – so could this first sentence be reformulated in order to be more precise?*

We change the first sentence to:

Desert dust perturbs climate by directly and indirectly interacting with incoming solar and outgoing long wave radiation, thereby changing precipitation and temperature, in addition to modifying ocean and land biogeochemistry.

*P 12594 L20: We then conducted simulations where we forced . . . . As I understand it, this is what you later call “the inversion”? Use this term here also to make it clear. It is still hard for me to understand that the variability in the atmospheric transport is not an important factor for the variability seen in the data. . . . Also is not clear to me how you by this method constrain the dust sources based on the depositions and still allows the sources to vary as a function of winds and soil dryness. Please extend this section with a more detailed description of your assumptions and the method.*

This isn't really an inversion, so we remove the word from the latter part of the text: we use the data to force the model source variability.

We can't really say whether transport variability was important in the real world, of course, however this model, and several other models, do not simulate big changes in transport from climate change.

It is clear from this reviewer's comments and another reviewer that we need to explain our methodology better. We replace:

“We then conducted simulations where we forced the source variability to match the observationally based deposition variability (TD (x,y,t) from equation 1).”

With

“Normally in this model, the entrainment of the dust into the atmosphere ( $E(x,y,t)$ ) is a function of soil moisture (SM), leaf area index (LAI), snow cover (SNOW), friction velocity (FV), and soil erodibility (SE) (see Zender et al., 2003a for a more detailed description). All but the last variable are time and spatially varying variables used or derived in the land model. The last variable (soil erodibility) is a spatially constant variable indicating the relative effectiveness of each grid box for causing dust generation (Zender et al., 2003b).

$$E(x,y,t)=\text{function}(SM(x,y,t), LAI(x,y,t), SNOW(x,y,t), FV(x,y,t), SE(x,y))$$

In order to force our model to reproduce the observed changes in deposition we add in a term proportional to our deposition changes at each gridbox (derived above from the paleodata):

$$E_{\text{new}}(x,y,t)=TD(x,y,t)*E(x,y,t)$$

In order to be more clear exactly how we are both forcing the deposition to match the obs, while still allowing the model to predict dust based on land surface and atmospheric conditions.

*P 12599 Paragraph starting at line 19: same issue as above. The relative deposition time series you use to modify the source strength – does it not include a temporal variability? Because then it is of course not a surprise that the model captures the variability. . . .*

Yes, exactly: we had to tune the model source to get the deposition right, but once we tuned it, it worked. It is interesting that we had to tune the model to get the right answer: there are processes at work that are not well modeled. Hopefully the above clarification makes this section more clear.

*Technical comments: P 12587 L 6: ..whether human were in the net increasing or . . . There is something wrong with this sentence.*

We replace:

While we know that desert dust is sensitive to perturbations in climate and human land use, previous studies have been unable to determine whether humans were in the net increasing or decreasing desert dust.”

With:

While we know that desert dust is sensitive to perturbations in climate and human land use, previous studies have been unable to determine whether humans were increasing or decreasing desert dust in the global average.

*P 12594, L 9: . . .historical forcing as (Flanner et al., 2009). Should be: .. historical forcing as Flanner et al. (2009).*

We make this change.

*P12595 L 20: The impact of the including dust There is something wrong with this sentence/spell error.*

We fix the spelling error.

*P12603 L 23: Much of the change terrestrial . . . Missing of/in after change.*

We add “in”

*P 12605 L 20: A “.” should be moved.*

We move the “.”

*Anonymous Referee #2*

*General comments:*

*This study reconstructs desert dust variability over the 20th century based on observations and models, and provides estimates of the impact of dust on climate and biogeochemistry*

*along the 20th century.*

*The study is a first and big step towards addressing relevant scientific questions related to the impact of desert dust on the climate system with an integrated approach (inferring variability from observations, including direct and indirect effects, dust effects on ocean and land carbon uptake). It is extremely ambitious and includes a lot of assumptions, some simplifications and major uncertainties. However, the authors include a specific section addressing these uncertainties and convincingly discuss the limitations of their results.*

*I strongly recommend the paper for publication in ACP. I believe this original paper will represent a basic framework for many future modeling studies on the subject.*

*I have only minor specific and technical comments/questions:*

*Specific comments:*

*From Page 12591 L27 to Page 12592 L17 Could you please provide the correlations of the PDSI and precipitation with the in situ Barbados data? Moreover, what is the correlation if you include the recent years (2001-2009)? Are there recent data from the Cape Verde coral record indicating (as the Barbados records) that the dust is still staying high while precipitation in the Sahel is recovering? The extrapolation in this case is one of the crucial assumptions in the paper since North Africa is the major source.*

Yes, it is correct that our extrapolation of the North African source is a critical one: North Africa is the largest source, and we have very little data. There is a new study, which sees a large increase across the 20th century, and we add reference to this study in the text as well as adding in the correlations with the available Barbados data (Barbados data is only available to 2005). Neither the Cape Verde nor the Barbados data extend past 2001, so we can't say what is happening in 2001-2009 in a consistent manner with previous data (which is a huge shame!).

We add the following text:

A new observationally-based study suggests a large increase in dust coming from North Africa during the 20<sup>th</sup> century, which they attribute to land use in North Africa (Mulitza et al., 2010). This study extends over many centuries, and also shows time periods where the inferred precipitation correlates well with dust, while during other time periods, there is an increase in dust, unrelated to climate, which they interpret as a contribution to dust from land use (Mulitza et al., 2010). There are issues with the interpretation of this data, since the small size particles that they interpret as riverine inputs could also be desert dust from farther upwind, however the results of this new observationally based study support the large increase we see during the 20<sup>th</sup> century from North Africa.

Mulitza, S., Heslop, D., Pittauerova, D., Fischer, H., Meyer, I., Stuut, J.-B., Zabel, M., Mollenhauer, G., Collins, J., Kuhnert, H., and Schulz, M.: Increase in African dust flux at the onset of commercial agriculture in the Sahel region., *Nature*, 466, doi:10.1038/nature09213, 09226-09228, 2010.

*Page 12594 L17 It would be interesting to know what is the unforced model dust variability. Is it that the dust in the model remains rather constant or that there is a wrong or shifted variability and/or tendency?*

The model stays roughly constant. We add a line in figure 2 which shows the 'unforced' model results, and discuss this briefly in the paper (attached below). We add:

"This model was not able to simulate this variability without the source being forced to vary with time (dotted line Figure 2)."

*Page 12596 L10 I am just curious here: Why do you use a simulation with constant dust and constant solubility to compare with increasing dust and increased solubility for the ocean response, while for the land biochemistry response you use the radiative forcing simulations (with no dust at all and with the dust variability/increasing trend)?*

Yes, you are correct: this is a little inconsistent. We should have used constant dust for the land case. We didn't think about this beforehand.

*Technical comments: Page 12593 L14 models instead of model*

*Page 12595 L20 The impact of including dust instead of The impact of the including dust*  
We fix this typo.

*Anonymous Referee #3*

*General comments:*

*This study uses available paleodata observations to reconstruct dust variability during the 20th century at various source areas over the globe and a set of models to estimate the global changes in dust sources, distribution and depositions, and the impact of these changes on climate and biogeochemistry. Dust effect on climate is a very relevant current research topic and indeed here it is shown that dust may significantly impact the global climate. The manuscript is well-written, framework and motivations are well described. The approach and methodology are comprehensive and well-grounded, despite several simplifications and uncertainties (in general acknowledged). I recommend the manuscript for publication after a minor revision.*

*Specific Comments:*

*L1: also indirect effects are important.*

Yes, reviewer #1 also commented on this, so we clarify that the radiative effects could be direct or indirectly caused.

*P12589 L18: how can changes in transport (related to circulation changes) be neglected?*

They are not actually neglected, but in this model, they are not large, so it turns out that making this assumption works ok. We hope that the additional description of the model simulations (discussed under Reviewer #1) makes this more clear.

*P12594 last paragraph: the description of the model simulation is not completely clear.*

We hope that the additions for Reviewer #1 make the model simulations more clear.

*L17 at page 12593, L10 at page 12594 and L1 at page 12595 seem to repeat. I do not understand how the model is able to vary the source strength with wind and humidity while the variability is forced to match the observations. How bad is the model dust variability without tuning?*

As discussed under reviewer #1, we add in more detail here, since this confused both reviewers. As discussed under reviewer #2, we add in a comparison to the model without tuning for the deposition.

*P12601, Section 3.2: to extend the validation of the model results over ocean (where P is not available), could you check with sea level pressure data (e.g., the multi-century dataset from the Hadley Center)? Moreover, as far as Figs. 4 and 6 are concerned, I would add also the distinction between land and ocean T variations due to dust.*

There are two good points here: that we really should compare globally average surface T over land, since the data really are taken over land, so we make this change in Figure 4b and the following text: "If we focus on just the land surface temperatures in the model (which the data represents better), the change in surface temperature between 1980-1990 and 1955-1965 are 0.34 and 0.48 °C with and without dust, respectively, while the observations show a change of 0.21 °C (Figure 4b); again the model including the effects of dust changes matches the data better than without the effects of dust changes."

Secondly, that the surface pressure observationally-based estimates can be compared to the model over ocean. We add this as figure 7 (attached below). It looks vaguely like including dust variability improves the model simulations of the increase in sea level pressure over Africa and South Atlantic, but the model with dust variability included tends to decrease sea level pressure over the Southern Indian, and this is the opposite signal in the observations. We add this discussion to the text.

*Technical Comments:*

*P12587 L13: replace aerosols with dust, and use heavy loaded instead of dusty (to avoid repetitions) at L 14.*

We fix.

*P12587 L17: from desert dust changes*

We fix.

*P12588 L10: by instead of through, for instead of during.*

We fix.

*P12589 L1-2: ...about past variability of dust. Here...*

We cannot find this place in the text.

*P12590 L7: ...other studies are characterized by a too large Australian source.*

We fix.

*P12593 L17: For dust modeling, . . .*

We fix.

*P12594 L9: ...as Flanner at al. (2009).*

We fix.

*P12595 L20: including*

We fix.

*P12596 L8: repeated annual cycle*

We fix.

*P12618 Tab. 3: check the last row, the reference is in the 3rd column (and not 4th)*

We fix.

*P12620 Fig. 2: add "relative change" on the y axis. Replace "time trend" in the caption with variation.*

We fix.

*P12624 Fig. 4: (c) is missing. Put (a) and (b) at the beginning of the sentence.*

We fix.

*P12626 Fig. 6: Obs. T in panel d should be replaced by Obs. P (it is precipitation)*

We fix.