

## **Reply to referee 2.**

First of all we want to thank a lot referee 2 for taking the time to read in details the manuscript and making excellent comments on the paper. As much as possible we tried to address his/her concerns in the following reply.

The different points of referee 2 are in **bold**, our response in normal font and the main proposed insertions / changes to the revised manuscript are in *italic*.

Additional Figures are also proposed for the revised version and are displayed at the end of this reply ( and also as part of the reply to reviewer 1). Modified Figures from the manuscript are also displayed.

## **Major points:**

**1) My biggest reservation concerns Figure 6 that shows interannual variations in Indian precipitation and AOD over the Arabian Peninsula (retrieved from the SeaWiFs instrument and the AERONET photometer at Solar Village). Both observed variables show general increases over the decade between 2000 and 2009. However, there is less agreement among interannual variations. For example, the Arabian dust concentration is unusually high during the last two years of the period, when Indian rainfall is trending downward. In addition, the precipitation variations show high autocorrelation, so there is the chance that some of the visual agreement may be the result of unrelated variations. The authors need to quantify this agreement, since this is central to the article (and especially the article title). They should compute correlations between the two variables for NH summer. This correlation is a key claim of the article and needs to be demonstrated. Furthermore, Figure 6 would be more effective at the beginning of the article, because it is the motivation for the calculations and analysis that follow.**

Indubitably reviewer 2 has a major point here. Despite we identified this lack of inter-annual correlation on Figure 6, we admittedly did not address properly this issue, and gave more attention to the general trend of precipitation and AOD, as well as to the pentad average differences. Of course a clear handicap here is the rather short time series of continuous aerosol optical depth measurements which limit the statistical analysis of inter-annual variability.

Proposed analysis: As suggested by Reviewer 2 and in order to get more insights from available observations, we calculated correlation coefficients between summer (JJAS average) deseasonalised observed AODs (based on SeaWIFS and MISR) and summer (JJAS average) deseasonalized precipitation over southern India (based on PERSIANN).

We propose to add a new Figure (Figure R2) to the manuscript and to include the text hereafter. This analysis, together with the discussion on observed decadal trend and pentad differences, is moved to section 2 of the revised manuscript (just after “data and methods”) as suggested by Reviewer 2. Figure 6 becomes Figure R1.

.....

*If the arguments developed above are valid, one should expect a possible correlation between the inter-annual variability of dust AOD and precipitation over southern India. This correlation is not obvious on Figure R1 for the local case of Solar Village AOD. In order to get a more regional picture, we extend our analysis by calculating inter-annual correlations between observed deseasonalised summer AOD (based SeaWIFS and MISR data) and deseasonalized summer precipitation over the previously defined southern India box (based on the PERSIANN data set). We consider the 1999-2010 period for SeaWIFS and 2000-2010 for MISR, excluding pixel with JJAS AOD < 0.2 in the process. Pixels with less than 8 years of valid JJAS observations over the period are excluded of the correlation calculation as well. Evident caution must be taken while interpreting the values of correlation coefficients due to the limited sample size. Nevertheless, on Figure R2, our analysis reveals clear regional patterns: Over the Indo-Pakistani source region both MISR and SeaWIFS deseasonalised summer AOD tends to be anti-correlated with southern India deseasonalised precipitations. Inversely, over Arabia, positive correlation coefficients tend to be observed for both MISR and SeaWIFS. This analysis has been repeated using the TRMM precipitation data set with no significantly different results (not shown here). Despite the fact that correlations are not very strong, the homogeneity of regional patterns and their consistency through different observational data sets lead us to think that a relation exists between the interannual variability of dust sources activity and Indian precipitation. This relation is in line with the previous argument linking cyclonic activity in Arabian sea, associated with more summer precipitation over India and Pakistan, and enhanced Arabian dust emissions. Contrarily to the Arabian Peninsula, the Indo-Pakistani region is affected by Indian monsoon rainfall. The anti-correlation obtained over this region could thus possibly be explained by enhanced particle wet deposition and/or inhibiting effect of soil moisture on dust emissions during rainy years.*

Rq: The dust climatic feedbacks depicted in our manuscript shows also some consistency with these correlation patterns: Dust present over Northern India and Pakistan tends to be associated with a dimming effects (as illustrated by an additional experiment described further), while a possible enhancement of southern India precipitation would be associated with positive anomaly AOD over Arabia (via the mechanisms discussed in the paper). Of course this does not imply a causal relationship.

In conclusion: This additional analysis fit with the arguments developed in the paper. We are however aware of possible lack of robustness of these correlations due to small sampling size.

We performed the same analysis with a different precipitation data set (TRMM) with no big quantitative and qualitative changes on correlation coefficients patterns.

In addition to the above modifications, we propose:

- To emphasize the fact that dust shall not be not be considered as the main driver of precipitation variability (cf further response to reviewer 2). Nonetheless there could be some positive feedbacks, associated to dust radiative forcing and perhaps important for modeling monsoon variability.
- If required by Reviewer 2 and Editor, we could modify slightly the title in order to reduce the emphasis on the “trend discussion” and outline more the “average effect” discussion. The revised manuscript abstract and introduction have already been slightly modified in this direction. However we think that the discussion about a possible relation between dust and rainfall decadal trends, even if still uncertain, could be a subject of interest and further investigation for the community.

**2. The larger issue is that there are many drivers of regional precipitation, especially on interannual time scales, and it is not obvious why Arabian dust should have the dominant influence.**

This is actually a claim we did not (or at least intend to) make in the paper. Our interpretation was cautious in this regard: “.... *From these results we suggest that while the cyclonic changes observed between pentad in reanalysis might be primarily a feature of climate variability, the likely associated increase in JJAS west Asian dust emission and Arabian sea AOD could however determine an important positive feedback contributing to intensify westerly circulation and humidity flux convergence towards the south-western Indian coast.*”

However we totally agree with reviewer 2 on the fact that many factors influence monsoon precipitation (and dust emission) inter-annual and decadal variability in a complex way. Our main point is that a trend in regional dust radiative forcing such as the one observed during the 2000-2010 decade could play a role in this complexity, and might be worth considering in climate models. This position has been clarified in different part of the revised manuscript (conclusion notably, cf reply to comment 6).

**3. The model’s calculated trend in Arabian dust mobilization is small compared to that inferred from the observed AOD retrievals, so the authors carry out an additional experiment where they artificially increase Arabian dust. This raises the question of whether they could have reproduced the observed precipitation variations by artificially increasing the dust concentration over other sources, especially those within the Indian subcontinent itself, for example, within the Thar Desert or Indus Valley.**

This is indeed a very good point that we tried to address by:

- a) Running a new *dust\_ft* simulation by forcing the positive dust emission trend only for the Arabian Peninsula. Figures R3.c and Figure R4.b are modified accordingly. The discussion is modified as follows:

....

*When dust tendency is forced however, a westward convergence is obtained between 5 and 20 N, and surface pressure pentad differences over the Arabian sea switch from positive to slightly negative (Figure R4 d). The cyclonic pattern and southward flow clearly seen in reanalyzes is however not well reproduced by the simulation which instead tends to generate a cyclonic pattern shifted to eastern India and Bengal gulf. This indicates that dust radiative trends only shall not be considered as the main driver explaining regional circulation changes, and also point out to model limitations. With this in mind, the simulations tend to show some relatively improved circulation and surface pressure changes when dust are present, and especially when the increasing dust trend is more realistically forced. From these results we suggest that while the cyclonic changes observed between pentad in reanalyzes might be primarily a feature of climate variability, the likely associated increase in JJAS west Asian dust emission and Arabian sea AOD could however determine a possibly important positive feedback contributing to intensify westerly circulation and humidity flux convergence towards the south-western Indian coast.*

- b) We also added a specific sensitivity experiment where Indo-Pakistanese sources are not considered and discussed the mean effect compared to the *dust* experiment. A new Figure as well as the following paragraph have been added accordingly. Our reply to Reviewer 1 on radiative efficiencies shall be also of interest here.

...

*On average, the combined Arabian and Indo Pakistanese dust sources appear to have a dual signature resulting in strengthening the Somalian jet, moisture convergence and precipitation over southern India, while inhibiting convective precipitation and decreasing monsoon intensity north of about 20 N (Figure 5).*

*In order to illustrate further this point, we perform an additional experiment where Indo Pakistanese dust sources are removed (*dust\_noIP*). By analyzing the difference between *dust\_noIP* and *dust* we see that taking into account the Indo-Pakistanese sources results in an inhibition of convergence and precipitation over India (Figure R5). Due to its geographic position and regional surface characteristics, the Indo Pakistanese dust source contributes relatively more to the negative TOA radiative forcing and the dimming signal obtained over India. In this regards the Indo-Pakistanese source relate effects tends to “compete” with the positive feedback associated to large radiative warming efficiencies over the Arabian Peninsula.*

**4. Uncertainty in dust radiative forcing: dust trends over the Arabian peninsula are inferred from retrievals of AOD either from satellite instruments or a single AERONET station at Solar Village. This retrieved AOD represents the influence of all aerosols, and not just dust. The authors attribute (line 53 and the article title) this AOD trend to dust mobilization, but without providing evidence. This is a key uncertainty that needs to be emphasized. (The authors should also check if other AERONET stations within the peninsula showed the same trends as Solar Village. This agreement would be expected if there really is a feedback between Indian monsoon anomalies and dust mobilization over the peninsula.)**

We agree with Reviewer2's concerns in this regards. However the attribution of AOD increase over Arabia to dust activity is addressed for example in Hsu et al.,2012, which is a study we are "heavily" relying on. First the increasing AOD trend is mainly due to a strengthening of seasonal cycle, which shows maxima during the known dust peak emission season over Arabia. Second a decreasing trend in angstrom coefficient is also detected at the solar village aeronet station which indicates an enhanced contribution of larger particles (dust in this case) to AOD over the decade. This point is clarified in the revised manuscript when discussing AERONET and SeaWIFS trend:

*Linear trends of JJAS AOD, calculated from SeaWIFS observations over our domain (cf section 1), are presented on Figure R1 and R3.a . As already reported in (Hsu, et al., 2012), a strong positive trend is found over the Arabian Peninsula region. In addition, a positive AOD trend observed at the AERONET station of solar village (Xia, 2011) is reported (Figure R1.a). A decreasing trend in angstrom coefficient has been also observed at Solar Village ( Hsu, et al., 2012) indicating an enhanced contribution of larger particles to AOD over the decade. Together with the fact that AOD trends are due to an amplification of seasonal cycle coincident with dust seasonal maximum, this indicates that the Arabian region AOD positive trends are mainly due to increasing dust emission activity vs a possible anthropogenic contribution.*

Unfortunately, there are no AERONET stations over Arabia with long time series comparable to solar village (we do use other AERONET stations for validation in reply to Reviewer1 however). Beside AERONET, SeaWIFS observations (and other satellite products) confirm the regional AOD increase over Arabian Peninsula, which is interpreted as a result of enhanced dust activity in different studies (Hsu et al., 2012, Pozzer et al., 2013).

**5. Even assuming that there is a decadal trend in dust AOD (and not just total AOD), the radiative forcing used to perturb the circulation in the regional model is highly uncertain, and this needs to be acknowledged because it can change even the sign of the precipitation anomaly, as shown in a nice article by the lead author in 2008. In summary, the**

**perturbation to climate and precipitation depends upon the forcing which contains two different levels of uncertainty: the dust radiative properties like single scatter albedo, and the dust concentration itself that has an uncertain relation to the retrieved AOD. The authors need to give more emphasis to how this uncertainty affects their attribution of trends in Indian precipitation to Arabian dust.**

We again totally agree with Reviewer 2's comment and note that this point was also emphasized by Reviewer1. We further emphasize these uncertainties in the revised manuscript.

...

*That said, it must be noted that radiative forcing and impacts might strongly depend on dust chemical composition and absorption/scattering properties (Solmon, et al., 2008), which exhibit a large regional variability (Deepshikha, et al., 2005) but are unfortunately poorly constrained by observations. In the present simulations we do not account for regional variations of dust refractive indices as proposed in recent studies (Scanza et al., 2014). This point might be especially important over the Indo-Pakistani region where dust aerosol effective single scattering albedo might be close to its critical value in relation to surface albedo. A slight change in optical properties and/or a misrepresentation of size distribution could result in a change in the sign of radiative forcing resulting in opposite dynamical feedback (in this case enhancement of EHP versus dimming over Pakistan and northern India). Some simple tests modifying dust SSA values in RegCM4 and run over the same domain tend to show that the more absorbing the dust, the more intense is the positive feedback on convergence and precipitation over India (S. Das personal communication, 2015). Finally we do not account for possible dust indirect effects on warm and ice cloud microphysics for which there is still a considerable debate and regional impacts difficult to assess.*

Rq : We would like to point out that some colleagues working with RegCM4 have been investigating the sensitivity of the dust feedback to SSA, independently from this study. Their conclusion is that increasing dust absorption leads to an intensification of dust induced convergence and precipitation over India. Reversely more scattering dust tends to inhibit this feedback. However since the model configuration used is quite different from the one used in the present study (e.g. no slab ocean, which is an important factor) and since these colleagues have proposed a manuscript for publication it is not possible for us at this point to include extra material beyond the proposed qualitative discussion.

**6. There are many processes that potentially contribute to variations in monsoon precipitation, and the authors need to give more discussion to whether these might influence their modeled trends. For example, there are other aerosols in their model,**

**including anthropogenic species. I don't think the prescribed emission of anthropogenic aerosols has any trend within the decade being simulated, but the authors should note this explicitly. In addition, the simulations with calculated dust mobilization (the 'dust' case) contain additional sources outside the Arabian peninsula, including within the Indian subcontinent. The authors should carry out an additional simulation that removes non-Arabian sources, or alternatively, a simulation that includes only non-Arabian sources. Otherwise, with the current experimental setup, it is impossible to attribute observed precipitation trends solely to Arabian dust.**

We did not consider any trend in anthropogenic aerosol emissions, which are representative of 2000-2010 decade. There have been increasing AOD trends measured over India and attributed to anthropogenic aerosols over this decade. These trends are significant only during the dry season (Babu et al., 2013). We acknowledge that there is probably an impact of the anthropogenic aerosol trend on Monsoon, as for example analyzed Bollasina et al., 2011 over a longer time period (concluding to a regional drying tendency linked to anthropogenic aerosol).

In addition to aerosols there are other global and regional players contributing to the precipitation variability (e.g Indian Ocean Dipole, ENSO ..). As mentioned previously we do not see dust variability as the main driver of precipitation variability at the decadal scale.

These points have been added to the discussion and especially to the conclusion of the manuscript.

....

*Using observations and a regional climate model, we suggest that an increasing Arabian dust emission trends could have impacted the Indian monsoon circulation and contributed to explain observed increasing 2000-2009 summer precipitations over southern India. There are potentially many global and regional players contributing to monsoon precipitation inter-annual and decadal variability (e.g. Indian Ocean Dipole, ENSO, etc) and dust radiative forcing shall not be considered as the main driver of the observed precipitation interannual and decadal variability. Dust radiative forcing might however determine a positive dynamical feedback favoring the establishment of lower pressure conditions over the Arabian Sea likely associated with both enhanced Arabian dust emissions and precipitation over southern India*

*This study does not consider any trend in anthropogenic aerosol emissions during the decade. Increasing AOD trends attributed to anthropogenic pollution have been measured over continental India, though mostly significant during the winter season (Babu et al., 2013). There has been probably an impact of the anthropogenic aerosol trend on Monsoon rainfall during the studied decade, as for example discussed in Bollasina et al., 2011.*

*In magnitude, the measured dust AOD trends over Arabia and the Arabian Sea are equally if not more important than AOD trends attributed to pollution increase over India (Babu, et al., 2013) and during the decade. In view of these results, capturing the positive feedbacks*

*between dynamics and dust emission trend in climate models could lead to a more realistic representation of precipitation decadal variability over India.*

....

Finally as mentioned earlier, we performed a new experiment where increasing dust emission trend is forced only over Arabia (cf reply to comment 3).

## **Minor points:**

**5: replace 'implications' with 'impacts'?**

Done in the revised manuscript.

**12: 'has been a subject of intense study for the last decade.' Provide an example of a citation?**

We chose to put Lau et al., 2008 BAMS paper here for an overview.

**23: 'elevated heat pump effect' (Lau, et al., 2006)' The relevance of this mechanism to Indian precipitation has been questioned by Nigam and Bollasina, who should be cited:**

**Nigam, S., and M. Bollasina (2010), "Elevated heat pump" hypothesis for the aerosol monsoon hydroclimate link: "Grounded" in observations?, J. Geophys. Res., 115, D16201, doi:10.1029/2009JD013800.**

Thanks for the suggestion this important reference has been added to the revised manuscript' introduction.



63: 'Mahowald, 2007'. Yoshioka et al. 2007 should also be cited: Yoshioka M, Mahowald NM, Conley AJ, Collins WD, Fillmore DW, Zender CS, Coleman DB (2007) Impact of desert dust radiative forcing on Sahel precipitation: relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming. *J Clim* 20:1445–1467.

Reference added

91 : '(CORDEX)-India domain'. Is this domain large enough to see the effects of dust radiative heating? The length scale of influence, the Rossby radius of deformation, is especially large in the Tropics, and if the forced response extends to the model boundaries (where the circulation is prescribed via the lateral boundary condition), there may be artificial reflection. (This may be less of a problem if there is enough damping at the boundaries.)

Rodwell and Jung QJRMS 2008 show that a change in Saharan dust radiative heating excites circulation changes as far downwind as India and the West Pacific.

MJ Rodwell, T Jung, 2008, Understanding the local and global impacts of model physics changes: An aerosol example. *Quarterly Journal of the Royal Meteorological Society* 134 (635), 1479-1497

This is again a very valid comment. Note that we acknowledge the limitation of the regional climate model approach in the introduction of the study.

*In our approach, we believe that the simulation domain size is large enough to capture important regional dynamical feedbacks to the aerosol radiative perturbation. As a caveat we acknowledge that large scale dynamical feedbacks arising from the possible aerosol induced excitation of planetary waves cannot be accounted for using a limited area model. Knowing in which proportion the effective regional climatic response to aerosol forcing is primarily dominated by regional vs. global dynamical adjustments is however a matter of debate (Ramanathan, et al., 2005), (Bollasina, et al., 2011), (Ganguly, et al., 2012) (Cowan, et al., 2011).*

In the revised version we add the reference to the reference paper of Rodwell and Jung, 2008.

The Newtonian relaxation to large scale fields applied in the boundary buffer zone (of about 1000 km) is designed to limit as much as possible wave reflections in the domain (Marbaix et al., 2003).

In addition, when studying aerosol feedbacks over the domain, we obtain signals that present similarities with previous GCM based studies in term of broad features (for dust as shown in this study compared to Vinoj et al. 2014, but also for anthropogenic aerosols, unpublished material).

**114: 'Of particular importance for studying aerosol effects (Zhao, et al., 2011), we implemented for this study a flux corrected slab ocean parametrisation...' In addition to citing Zhao, you should cite Miller et al who specifically considered the ocean representation and its effect upon the perturbation by Arabian dust to Indian monsoon rainfall.**

Thanks a lot for this suggestion. We indeed missed this important citation which is totally appropriate here. It has been added to the revised version.

**In order to limit the effect of internal variability on our analysis of the aerosol feedbacks, we impose a small random perturbation in boundary conditions to every ensemble members during the run following (O'Brien, et al., 2011).' Please explain this in more detail. What happens if this perturbation is not added?**

....

*With this technique, we increase the filtering of noise vs. statistically significant physical signal while performing the difference between the ensemble means of perturbed and control experiments. Results, figures and discussion are based on these ensemble means.*

**179: 'overestimate circulation intensity over the Bengal gulf and Indonesia.' What is the specific meaning of 'circulation intensity'?**

Replace by "average wind speed"

**181: 'APHRODITE data set' Was this data set introduced and described in the previous section with the other precipitation data sets. What is its resolution? Should it be preferred over the Indian subcontinent (line 188), where it indicates a lower model bias?**

The corresponding reference is given in data and method. This data set has a high spatial resolution and obtained from rain gauge observation networks. In some studies it is cited as a reference product for Asian precipitations.

**189: 'Comparison of Figure 2,b and 2, d,f,h shows that radiative effects of dust tend to reduce model biases over continental India southern and northwestern regions.' It should be noted, however, that dust increases the precipitation bias over the western Bay of Bengal.**

Yes indeed. This was added to the text.

**Section 2.2: It should be noted explicitly that the only model quantity that can be directly compared to observations is the total AOD. This is important because the dust radiative forcing in the model depends upon additional assumptions. First of all, it depends upon the simulated dust distribution. The model may get the correct total AOD, while misestimating the contribution by dust. Are there any measurements that can be used to isolate the presence of dust in the observations? Ackerman et al 1982 provide older observations of dust radiative forcing and size resolved dust mass.**

**Ackerman, S. A. and S. K. Cox, The Saudi Arabian heat low: aerosol distribution and thermodynamic structure, J. Geophys. Res., 87, 8991-9002, 1982.**

This is noted explicitly in the revised version.

Please refer also to the response to Reviewer 1 (including new Figures) for additional comparison of simulated AOD and size distribution vs. AERONET AOD and size distributions.

**Second, forcing depends upon the particle radiative properties like the single scatter albedo. The values assumed for this study needs to be specified explicitly (along with the citation from which they are derived), because this albedo is not well-constrained from observations, and models tend to use a wide variety of values, resulting in greatly varying forcing estimates given similar model AOD. The lead author here provides a good demonstration of this sensitivity for Saharan dust.**

**Solmon, F., M. Mallet, N.Elguindi,F.Giorgi,A.Zakey,andA.Konare Ì A(2008),Dust aerosol impact on regional precipitation over western Africa, mechanisms and sensitivity to absorption properties, Geophys. Res. Lett., 35, L24705, doi:10.1029/2008GL035900.**

A table of aerosol optical properties was proposed in supplementary information. References have been added for the optics and underlying size distribution, and the discussion about uncertainties linked to these parameters is developed in the revised version (cf reply to major comment 5 and reply to Reviewer 1).

**(Figure 3) the panels should be assigned letters to match the caption description. What is the difference of the RegGCM values in c and d? Also, satellites have trouble retrieving aerosols over bright surfaces and this can result in artificial gradients along coastal regions. How much uncertainty is there in these AOD retrievals? Wouldn't the study be improved by using the MODIS Deep Blue retrievals that are designed to detect aerosols over land?**

Figure 3 is modified.

We did not include comparison to MODIS deep blue over land because of the period studied and due to the fact that trend and correlations analysis are based on SeaWIFS and MISR (supposed to be more stable products). Rq: data should be reprocessed with deep blue version 6 now. We also want to keep the number of Figure and analysis at a reasonable length. Please consider that some ground based comparisons, giving more insight on model performances, have been added in reply to Reviewer 1.

**267: 'On average, the Arabian and Indo Pakistanese dust sources appear to have a dual signature' How do you distinguish the separate effects of Arabian and local (e.g. Thar desert) sources on the perturbed circulation, given that their effects are always calculated together in the simulations?**

We actually meant to distinguish dust present over Pakistan, northern India and northern Arabian sea (encompassing a contribution of long range Arabian dust and Indo-Pakistani source) from dust present over Arabia.

However, as mentioned previously we propose an additional simulation showing that Indo-Pakistani region contributes relatively more to the dimming /drying signal due to their position and regional surface albedo.

**290: 'Our work hypothesis is that, if the above mechanisms are valid, the observed increasing dust AOD trend over Arabia over the decade 2000-2010 might have been associated with a positive impact on circulation and precipitation over southern India.' Good correspondence of the (all-aerosol) AOD and precipitation time series is not obvious. For example, precipitation peaks in 2007, when the Solar Village aerosol loading is not particularly large. Moreover, AOD is higher in 2008 and (especially) 2009, when the precipitation seems to be on a downward trend. The authors should calculate the interannual correlation of summertime AOD and precipitation anomalies, and discuss this at the beginning of the article to motivate the experiment.**

Please refer to reply to major comment 1.

**Figure 6 (caption): 'A quadratic regression fit, showing the progressive intensification of observed dust activity is superimposed (blue curve).' The Solar Village AERONET site retrieves the AOD from the combined effect of all aerosols. What is the basis for attributing the upward trend solely to dust?**

Please refer to response to major comment 4 and discussion on angstrom coefficient trend.

**Figure 6: Please explain whether the time axes of the two panels are comparable. The precipitation time series seems to stop before the AOD time series.**

The Figure 6 ( now Figure R1) has been modified to show consistency between the time axes and the seasonal average of both deseasonalised JJAS AOD and precipitations.

**297 'JAS observed deseasonalized AOD are better represented by a quadratic vs linear regression' If this is true, why calculate linear trends in Figure 7?**

Linear trends were calculated to facilitate the comparison with Hsu et al., 2012 (figures and discussion), who performed linear trend analysis.

**334: 'These deficiencies are likely to be due to uncertainties in coupled convective and dynamical processes over northern Arabian Sea, Pakistan and Bengal gulf which are extremely challenging to capture properly in climate models (Turner, et al., 2012).' Alternatively, the underestimation of emission by Arabian dust sources could be due to circulation variability in the vicinity of dust sources that is not captured by the regional model?**

Yes that is what we suggest in :

...

*Consistently with the arguments developed before, a likely reason for this underestimation is related to the fact that cyclonic pattern found in reanalyzes pentad difference is also not properly captured by the model as shown in Figure 8.b and c, meaning that the model does not reproduce properly increasing occurrences or/and intensification of Shamal conditions during the decade.*

**Figure 8: I agree with the authors that increasing Arabian dust emission creates a low over the Arabian Sea, but the onshore flow (bringing moist monsoon air onto the Indian subcontinent to supply precipitation) looks different between the regional model and the ERAI reanalyses**

Yes we totally agree with this point :

*... With no dust, or when dust increasing emission tendency is not forced, the model tends to reproduce an anti-cyclonic pattern over the Arabian Sea (Figure 8, b and c) and no enhanced westward circulation toward the Indian coast, unlike what is observed in reanalyzes (Figure 8a). When dust tendency is forced however, a westward convergence is obtained between 5 and 20 N, and surface pressure pentad differences over the Arabian sea switch from positive to slightly negative (Figure 8d). The cyclonic pattern and southward flow clearly seen in reanalyzes is however not well reproduced by the simulation which instead tends to generate a cyclonic pattern shifted to eastern India and Bengal gulf. This indicate that dust radiative trends only shall not be considered as the main driver explaining the regional variability and also point out to model limitations. Still, the simulations tend to show some relatively improved circulation and surface pressure changes when dust are present, and especially when the increasing dust trend is more realistically forced.*

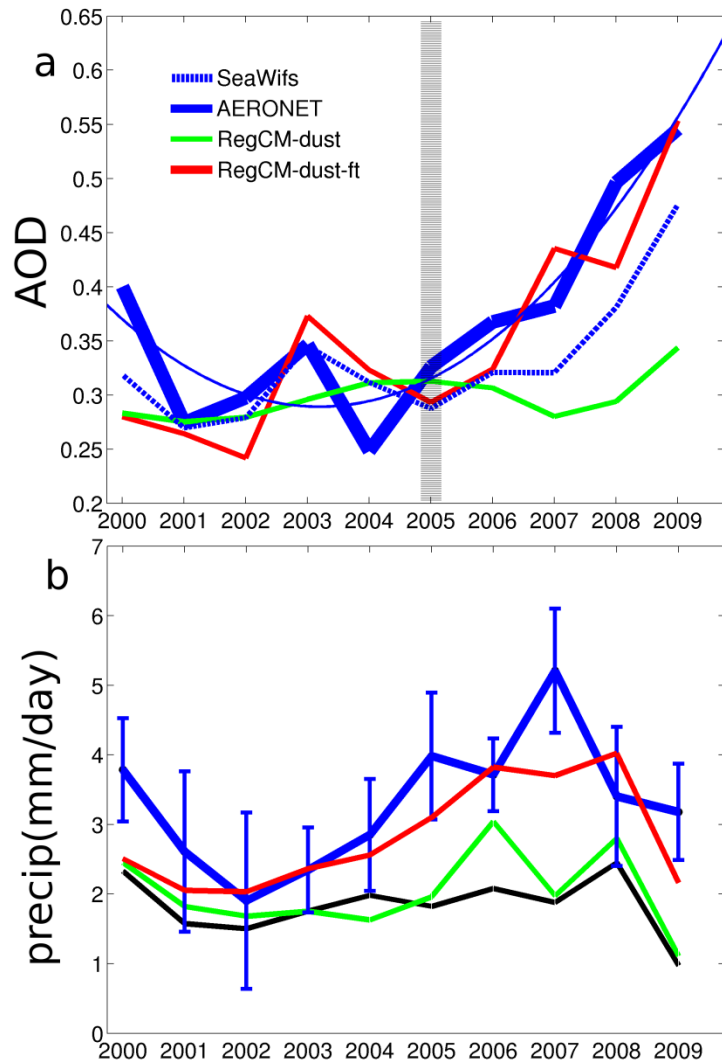
**379: 'Dust radiative forcing might determine a positive dynamical feedback'. This is possible, but it should be noted that the influence of the monsoon anomaly on dust mobilization is not demonstrated by the model experiments.**

We agree and the text was modified in this regard.

**382 'The measured dust 2000-2009 AOD trends over Arabia and the Arabian Sea are equally if not more important as AOD trend reported for continental India and attributed to anthropogenic pollution increase (Babu, et al., 2013).' This is a key assertion of the article but the importance of dust needs to be demonstrated, because the Arabian peninsula AOD includes contributions from other aerosols.**

Cf previous replies to the different major comments. We propose to maintain this argument in the revised conclusion.

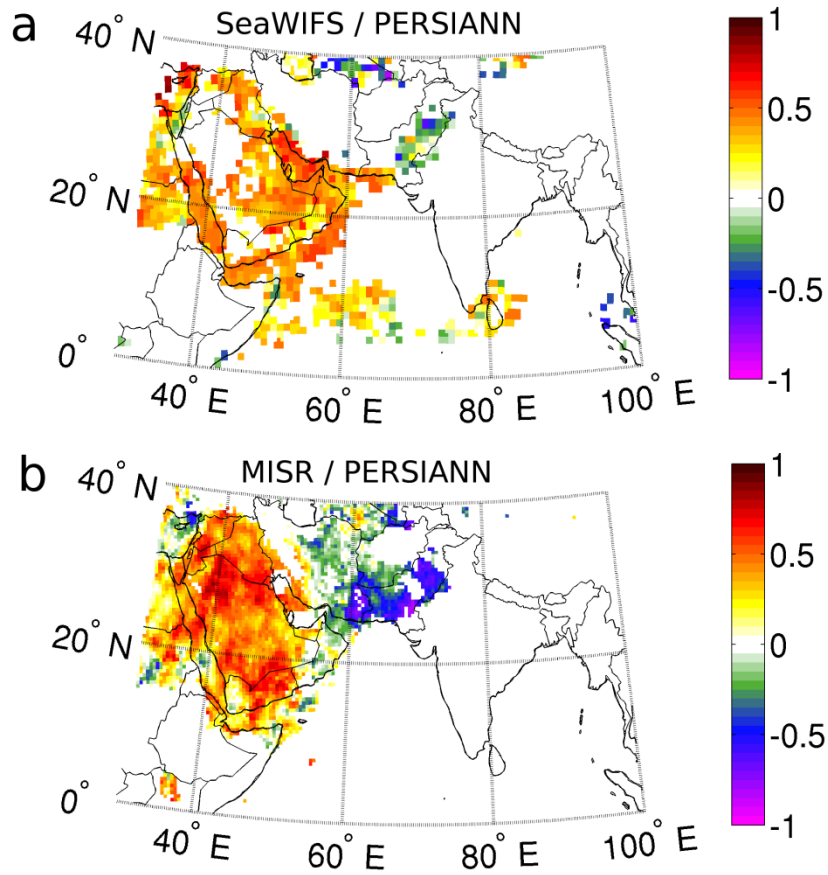
## Figures



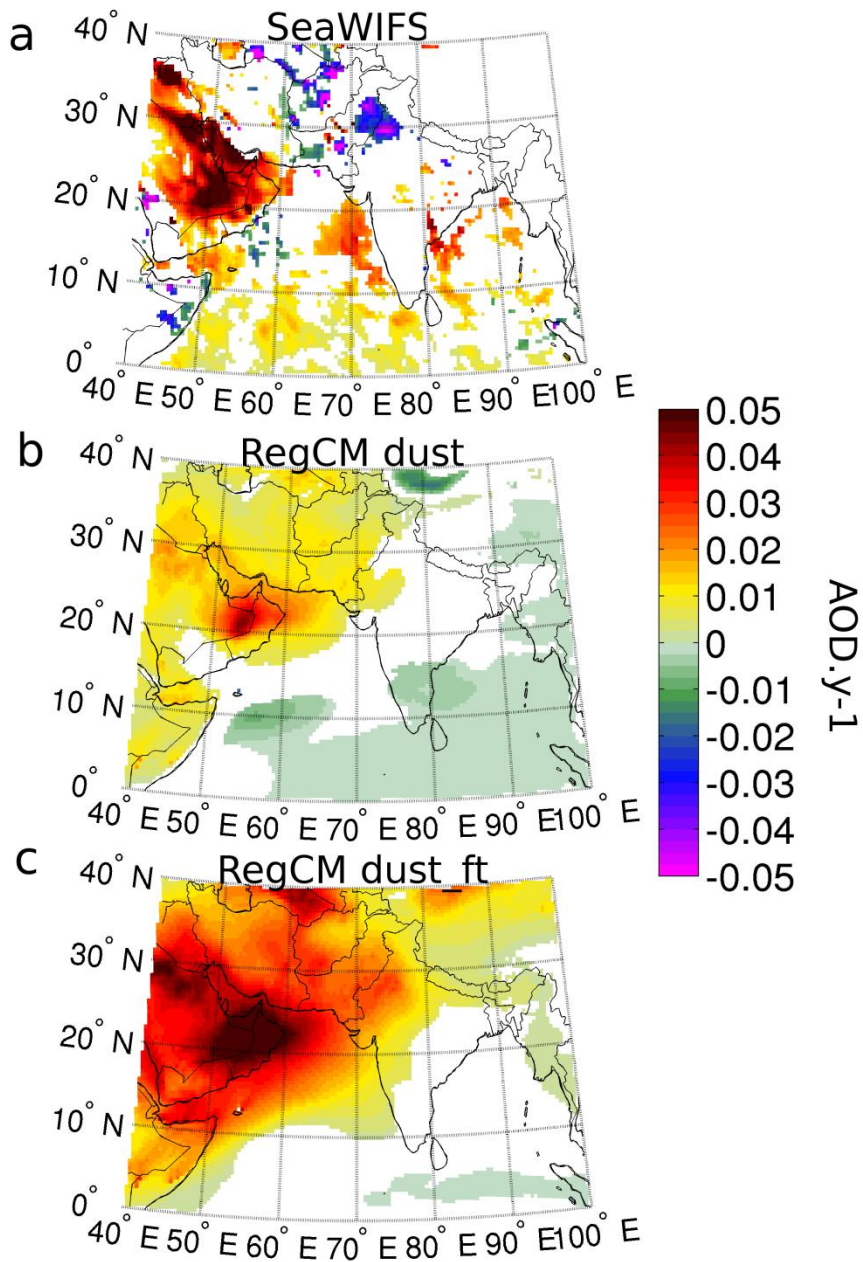
**Figure R1:** Arabian AOD and Southern India deseasonalized precipitation trends during the decade 2000-2009. **(a)** The thick blue line represents monthly deseasonalised time series of JJAS AOD obtained from the Solar Village AERONET station (monthly product, average of 480-640 nm spectral bands). A quadratic regression fit, showing the progressive intensification of observed dust activity is superimposed (blue curve). The blue hatched line represents the deseasonalised AOD time series obtained from SeaWIFS AOD interpolated on the Solar Village

station. The green lines represents the deseasonalized time series of JJAS AOD simulated by the model in *dust* simulation. The red lines represents the monthly deseasonalized time series of JJAS AOD simulated by the model with forced dust emission trends (*dust\_ft* simulation). **(b)** The blue line represents the yearly time evolution of observed continental precipitation averaged for JJAS, over a southern India box (5-20N; 60-80E) and for different data sets (TRMM, CRU, PERSIANN). The blue bars materialize the amplitude between maximum and minimum values amongst observations for a given year. The equivalent deseasonalized JJAS average simulated precipitations are reported for the *nodust* simulations (black line), the *dust* standard simulations (green line) and the forced emission trend *dust\_ft* simulations (red line). All modeling results represent a 3 member's ensemble mean.

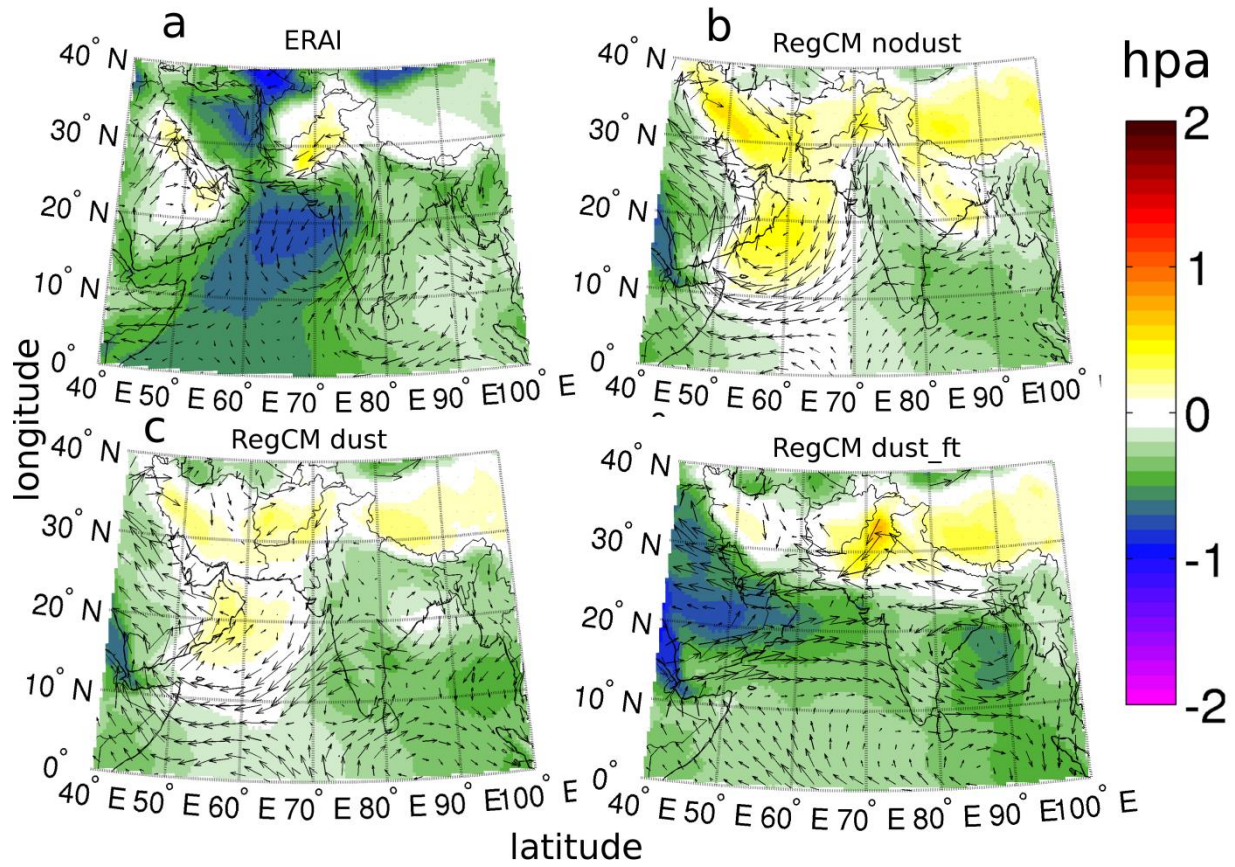




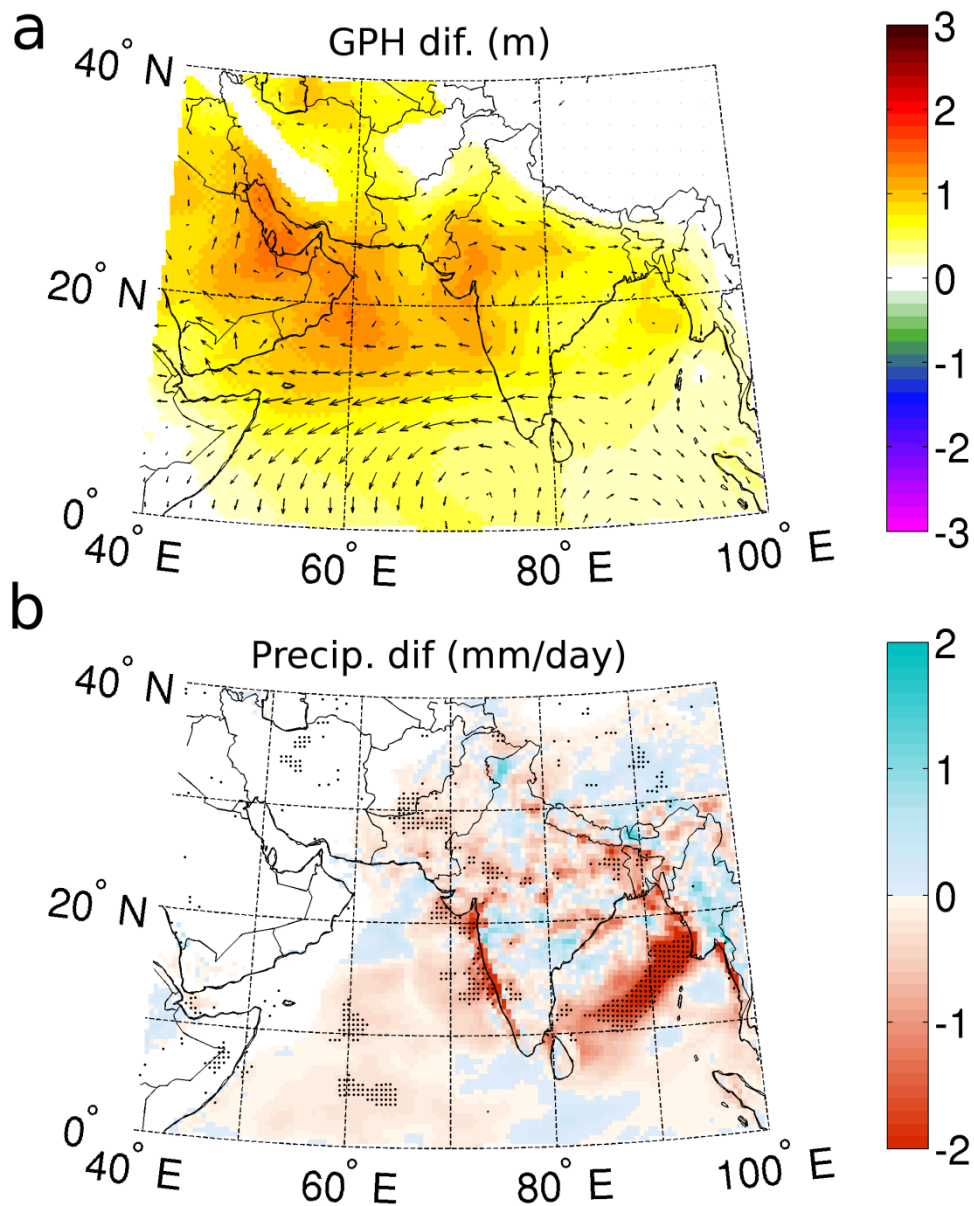
**Figure R2:** Interannual variability correlation coefficients calculated between deseasonalised summer (JJAS) AOD and deseasonalised JJAS precipitations averaged over a southern India box(5-20°N; 60-80°E). (a) based on the SeaWiFS AOD retrieval over the 1999-2010 period.(b) based on MISR AOD retrieval over the 2000-2010 period. Pixel showing monthly AOD < 0.2 are excluded from the calculation as well as pixel for which sampled valid years is less than 8.



**Figure R3.** Linear JJAS AOD trend calculated over the 2000-2009 period from: (a) SeaWIFS monthly observations, (b) Model standard *dust* simulations and (d) Model *dust\_ft* simulations including a forced emission trend over the Arabian peninsula. Only statistically significant trends ( $p\text{-value} < 0.05$ ) are represented (cf Data and Methods). All modeling results represent a 3 member's ensemble mean.



**Figure R4:** Difference of mean JJAS 850 hpa circulation and surface pressure between “DUSTY” (2005-2009) and “NONDUSTY” (2000-2004) pentads as defined in the text and calculated from : (a) ERAI reanalysis, (b) ‘*nodust*’ simulations, (c) ‘*dust*’ standard simulations, (d) ‘*dust\_ft*’ simulations with forced emission trend over Arabia. As a complement to ERAI, an equivalent graph has been produced from NCEP reanalyzes and displayed in Figure SI. All simulated results represent a 3 members ensemble mean.



**Figure R5.** . Impact of the Indo-Pakistani dust source compared to the dust simulation calculated as *dust\_noIP* - *dust* over the period JJAS 2000-2009. (a) 850 hpa geopotential heights (GPH) and circulation change. (b) Precipitation changes. The dotted region defines statistically significant results at the 95 % confidence level. All modeling results represent a 3 member's ensemble mean.

