Reply to Referee 1.

First of all we want to thank a lot Referee1 for her/his excellent comments and suggestions. As much as possible we tried to address her/his concerns in the following reply.

The different points of Referee1 are in **bold**, our response in normal and main insertions / changes to the revised manuscript are in *italic*.

Additional Figures are proposed for the revised version and are displayed at the end of this reply. Modified Figures from the manuscript are also displayed.

Two major points:

1. More comparisons of the dust distribution to observations are necessary. For the dust can you show some AERONET and other in situ comparisons, including size distribution, and seasonal cycle?

We tried to address this point by adding to the manuscript some comparisons of :

1) Simulated and AERONET AOD for the station of Solar Village, Karachi, Meizera and Kuwait airport. These are stations with reasonably long time series (level 2 obs.) over our period of simulations. We propose monthly comparisons, for which monthly averages are calculated from daily averages and screened for day without observations. A scatter plot for the four stations is proposed (Figure R7). AOD seasonal cycle is more particularly discussed for solar village (Arabian source) and Karachi (influenced by Indo-Pakistanese source with a contribution of anthropogenic sources) cf Figures R8 a and c.

2) Simulated vs. observed AERONET size distribution over the stations of solar village and Karachi , representative of JJAS 2009 (Figure R8 b and d). Observations of size distributions for the studied period show quite a lot of gaps and we thought that choosing one specific year would be good enough given that size distribution is not likely to show a strong inter-annual variability (notably given uncertainties e.g. in AERONET inversions). JJAS was selected because of the relevance for Indian monsoon interactions discussed in the paper.

Text added to the revised manuscript:

….

Additional comparisons of simulated AOD and ground based AERONET retrieved AOD (500 nm) are proposed in Figure for the stations of Solar Village, Meizera, Kuwait airport and Karachi. Dust aerosol dominates over these stations, except perhaps during winter season over Karachi. For both model and observations, monthly averages are built from daily means and account for missing days in observations. Figure .a shows that the model tends in general to slightly underestimate observed AOD. This underestimation is perhaps more pronounced for the Karachi station, as also shown on JJAS comparisons (Figure R). The simulation of AOD seasonal cycles shows an overall consistency with observations (Figure R). However we note that for certain years AOD spring maxima tend to be underestimated by the model over solar village, while summer peaks tends to be overestimated. This slight shift of the seasonal cycle is also discussed in Shalaby et al. (ACPD,2015).

On Figure we compare simulated aerosol size distribution to size distribution retrieved by AERONET inversions and re-binned to match model dust bins (Figure R8). Due to lack of observational data and given the scope of the study, we restrict this comparison to JJAS 2009. Inter-annual variation of JJAS size distribution might anyway be of secondary order, especially given the possible uncertainties in AERONET inversions (Dubovik et al., 2000). For both Solar Village and Karachi, the model tends to show a consistent relative distribution between bins compared to observations. However we can note an overestimation of simulated fine and/or medium bins compared to underestimated coarse bin, especially in the case of Karachi. One of the possible reasons for this might lie in the emission size distribution (Kok et al., 2011) who tends to be more uncertain to represent coarse particles as for example discussed in Mahowad et al., 2014. Other reasons could be linked to accuracy in sources geo-location, removal and transport processes. Bearing in mind observational uncertainties, the implication of a simulated dust size distribution shifted towards smaller particles would be to enhance SW scattering vs. SW absorption and LW emission with implications on radiative forcing discussed further.

…

How sensitive are your results to optical properties and dust size assumptions you are making? Why should we believe your results? Please indicate where your dust optics are from, why they are correct, and show us some more comparisons to convince us you are doing a good job. Please also add a paragraph discussing optical properties sensitivities and how that might impact your results. Consider Perlwitz et al., 2001, for example, and how different the climate response is depending on small changes in optics.

Dust optical properties considered are given in supplementary information of the manuscript with adequate refernces.

Dust bin size and corresponding short wave optical properties for the visible band (350-640 nm) of the RegCM model. These values were determined from a Mie code and considering a dust sub-bin size distribution from Alfaro and Gomez 2001 with parameters detailed in Crumeyrolle et al., 2010. Dust refractive indices were taken from the OPAC data set (d'Almeida et al., 1991). For the visible band the considered refractive index is 1.55 – 0.0055i.

Sensitivity of the results to optical properties and size distribution.

In the revised manuscript we discuss further this point by adding the following paragraph as well as the suggested reference.

… That said, it must be noted that radiative forcings and impacts might strongly depends on dust chemical composition and absorption/scattering properties (Tegen et al., 2001; 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 variation of dust refractive indices as proposed in recent studies (Scanza et al., 2014). This point might be especially important over the Indo-Pakistanese region where 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 elevated heat pump versus dimming over Pakistan and northern India). Some simple tests modifying dust SSA values in RegCM4 and performed 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.

Minor points:

"Comparison of Fig. 2b, d, f and h shows that radiative effects of dust tends to reduce model biases over continental India southern and northwestern re-gions." This is a really important statement, and yet is very difficult to see in the figures. Maybe add another set of plots which show TRIMM (or PERSIAN or APHORODITE) minus the dust case?

Additional plots are proposed in the revised version supplementary material.

Please consider the possibility of anthropogenic sources varying the sources of dust over this period, and incorporate some of the analysis from Ginoux et al., 2012.

Thank you for this suggestion. Indeed the anthropogenic component might be non negligible for explaining the observed dust trend. We point out to this reference in the introduction and conclusion.

For the Rf, could you please show SW and LW separate? There are observations that suggest that over the North African plume, when over desert regions (bright), there is no net Rf of dust (Patadia et al., 2009). Can you capture this type of behavior? I can't really tell from your net RF that you are getting that in the SW. This is likely very dependent on the optics and size distribution your choose.

We made the following modif to the revised version:

a) Add dust radiative forcing efficiency diagnostics (cf Figure R9, b and c).
b) Add in SI the surface and TOA SW and LW radiative forcing components (cf Figure SI 1) There are indeed some sub-regions where the combination of LW and SW forcing induce a net radiative forcing almost equal to zero (e.g the Thar Desert source region).

"the TOA radiative forcing efficiencies (i.e. TOA normalized by AOD) shows relatively less of a warming e_ect in the Indo-Pakistanese and Northern India desert regions due to lower surface albedo." Where is this? Sounds interesting, please include! (you refer to this later also, on p4890, line 18, so it would help to have the figure).

It is an interesting point. We added a figure of dust radiative forcing efficiency (Figure R9) illustrating the differences between Arabian and Indo-Pakistanese dust sources, as well as the evolution of radiative forcing efficiency linked to changes in surface albedo and dust size distributions as one move from sources to the Indian subcontinent.
Furthermore we propose an experiment where Indo-pakistanese dust source are removed (cf reply to Referee2), essentially showing that the contribution of this source is to strengthen the dimming effect and stabilisation over northern India. Indo Pakistanese source effects tends to compete with the positive feedback associated to radiative heating over the Arabian source. Optical properties over the Indo-Pakistanese regions might be a very sensitive point here (cf reply to comment 2).

“Consequently the 2005–2009 pentad (P0509) shows sensibly higher averaged AOD relative to the 2000–2004 pentad (P0004).” Why don’t you use more intuitively obvious casenames, like DUSTY and NONDUSTY? You use these later anyway to explain these, and it will make the text easier to follow.

This is done in the revised version.

English Edits:

“A specific attention” remove “a”“pretty closely” remove ‘pretty’ “convective precipitation tend to be inhibited” tends

Done in revised version.

**“This regional stabilization is induced by a relatively large surface radiative dimming which decreases continental 10 and sea surface temperatures (Fig. 4c), and for which inhibiting e_ect on convection is predominant over dust absorption radiative warming, consistently with a negative simulated TOA radiative forcing (Fig. 4b).” please reword “for which inhibiting effect on convection is predominant” sounds very awkward “to shape out regional contrast” out
our?**

Fixed in the revised version.

“Fine dust transported from Arabian, Indo Pakistanese and Iran sources to northern India are relatively diffusive and induce a moderate radiative” how can dust be diffusive? I think you mean small in magnitude or diffuse??

“This, on average, favor a stabilization” Favors

“and for which regional impact is diffcult to assess.”THE regional impact

“Our work 5 hypothesis is that” , WorkING “strong positive trend are” make verb and subject match

Thanks for pointing out to these errors. We tried to improve the English in the revised version.

Figures.

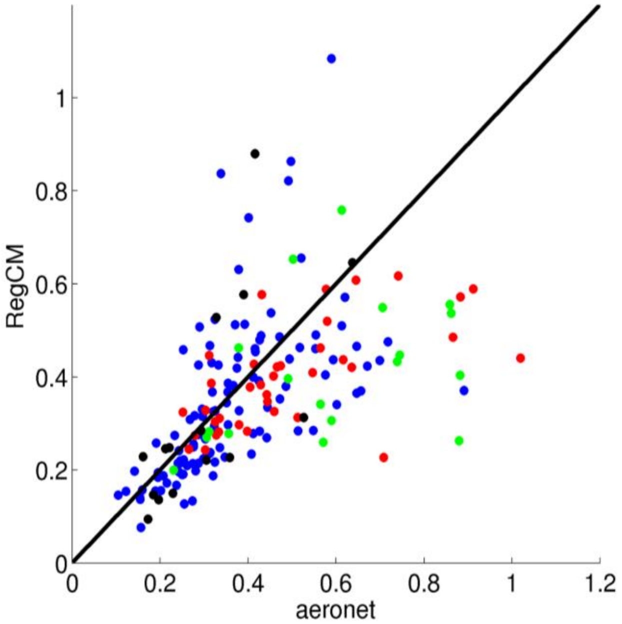

Figure R7.Simulated monthly AOD vs AERONET measured monthly AOD for the period of 2000-2009. Blue dots represents the solar Village Station, red dot represents Karachi, green dots represents Kuwait airport and black dots Meizera.

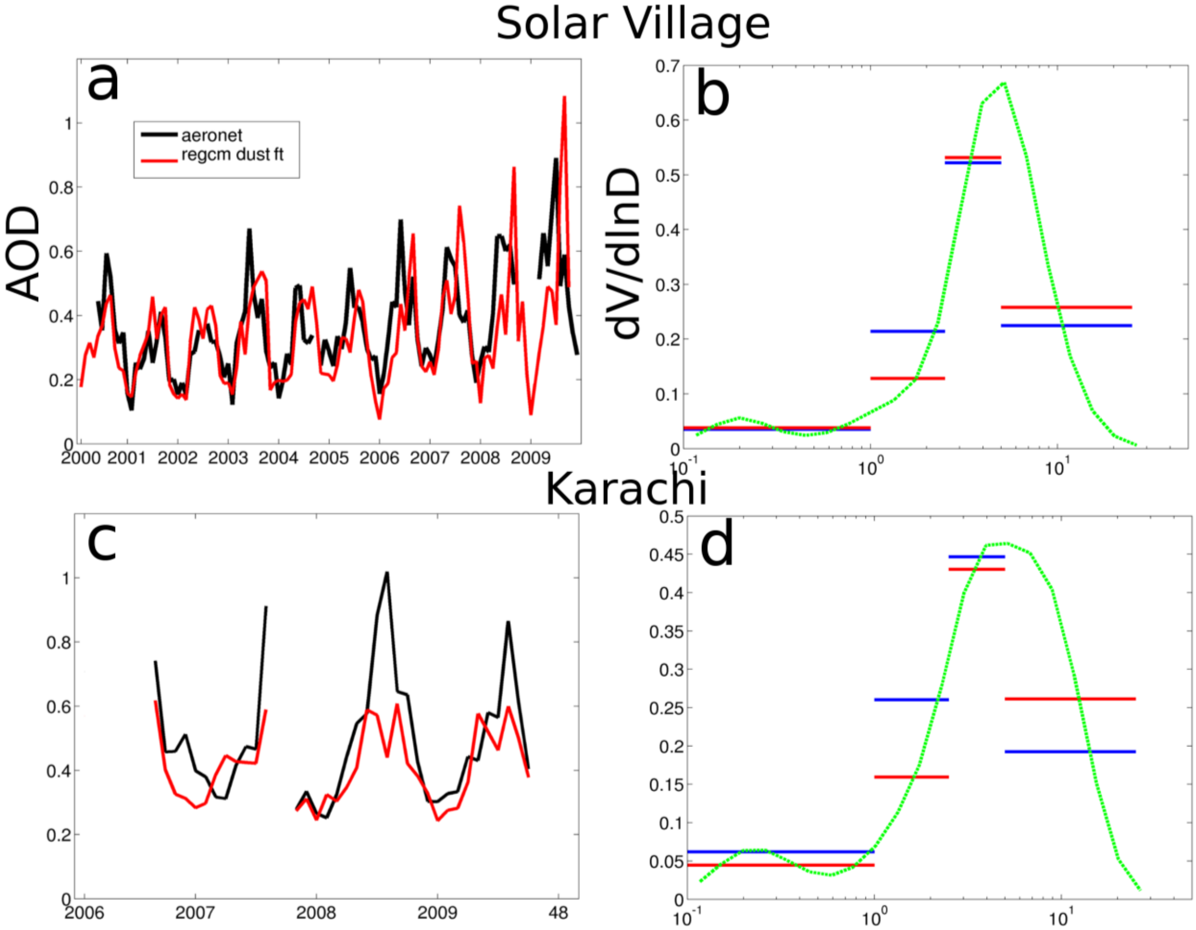

Figure R8. (a) comparison between simulated and AERONET monthly AOD (see text) for Solar Village station. (b) Comparison of simulated and measured aerosol normalized volume size distribution averaged for JJAS 2009 over Solar Village. For comparison, the AERONET distribution (green dotted line) is re-binned to match model size bins (red lines). Blue lines show the corresponding simulated distribution. (c) Same than (a) for Karachi station. (d) Same than (b) for Karachi station.

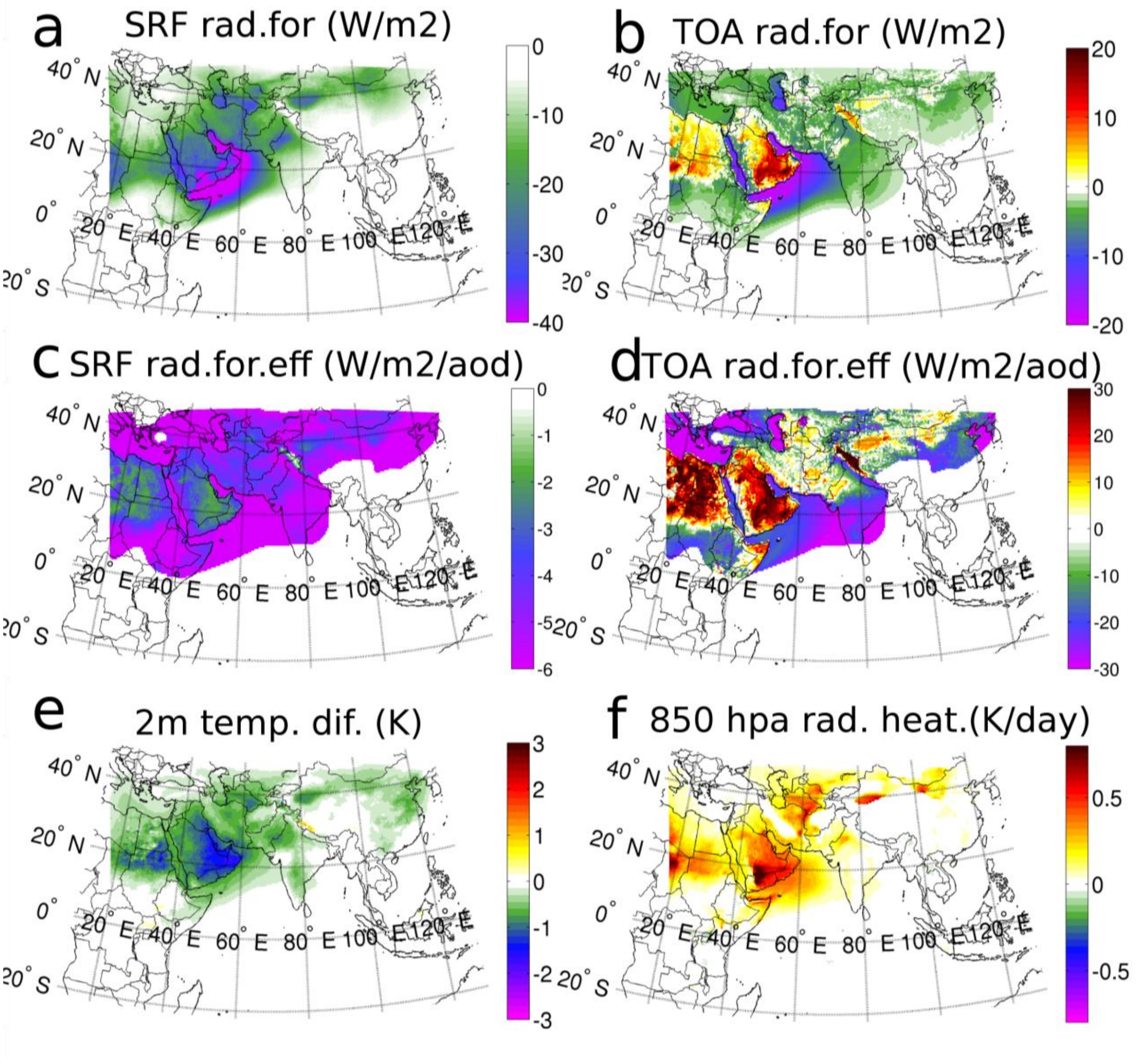

Figure R9. (a) JJAS 2000-2009 Dust aerosol surface radiative forcing diagnostic. (b) JJAS 2000-2009 Dust top of atmosphere radiative forcing diagnostic. (c) and (d) Corresponding surface radiative forcing efficiencies.(e) JJAS 2000-2009 2 m temperature difference between *dust* and *nodust* simulations. (f) 850 hpa radiative heating rate difference between *dust* and *nodust* simulations. All modeling results represent a 3 member's ensemble mean.

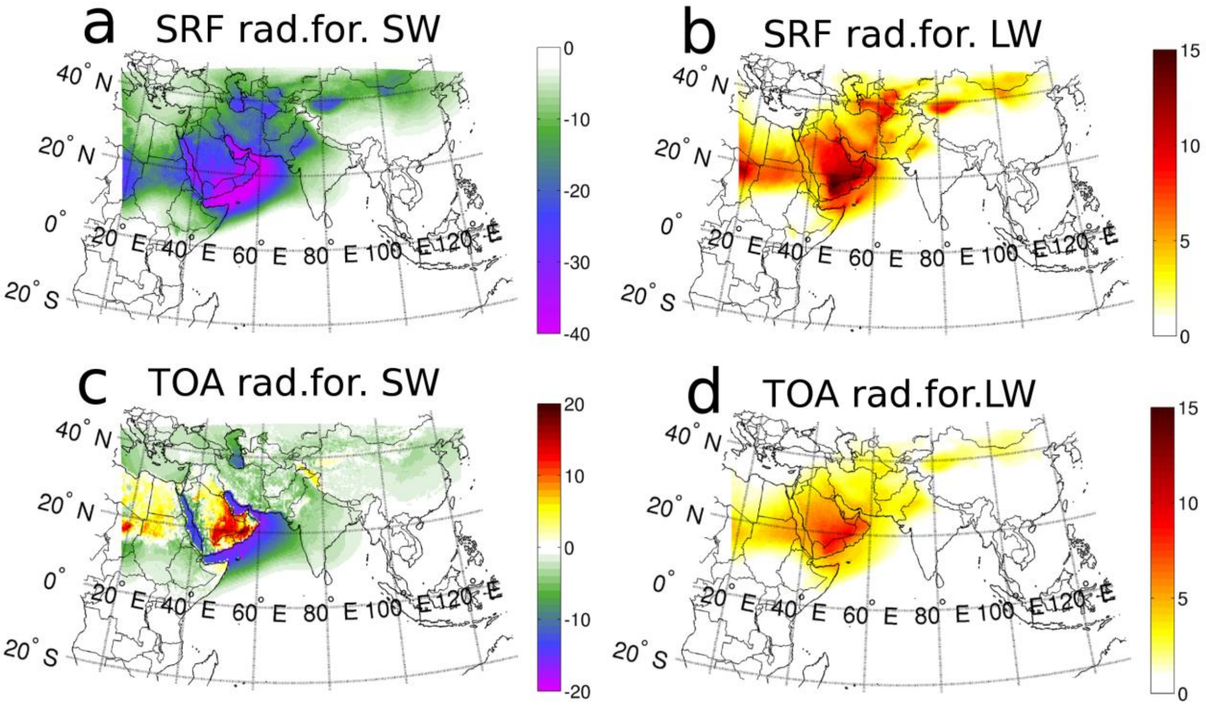

Figure SI 1: SW and LW dust surface and TOA radiative forcing averaged for JJAS 2000-2009.

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-Pakistanese 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 variabilitiy 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-Pakistanese 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 <u>be primarily a feature of climate variability</u>, 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 depends 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-Pakistanese 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 thatremoves 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 anthropgenic 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 its 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 tendsto 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., $7, 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 alwayscalculated together in the simulations?

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

However, as mentioned previously we propose an additional simulation showing that Indo-pakistanese 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 obvi-ous. 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 theinterannual 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

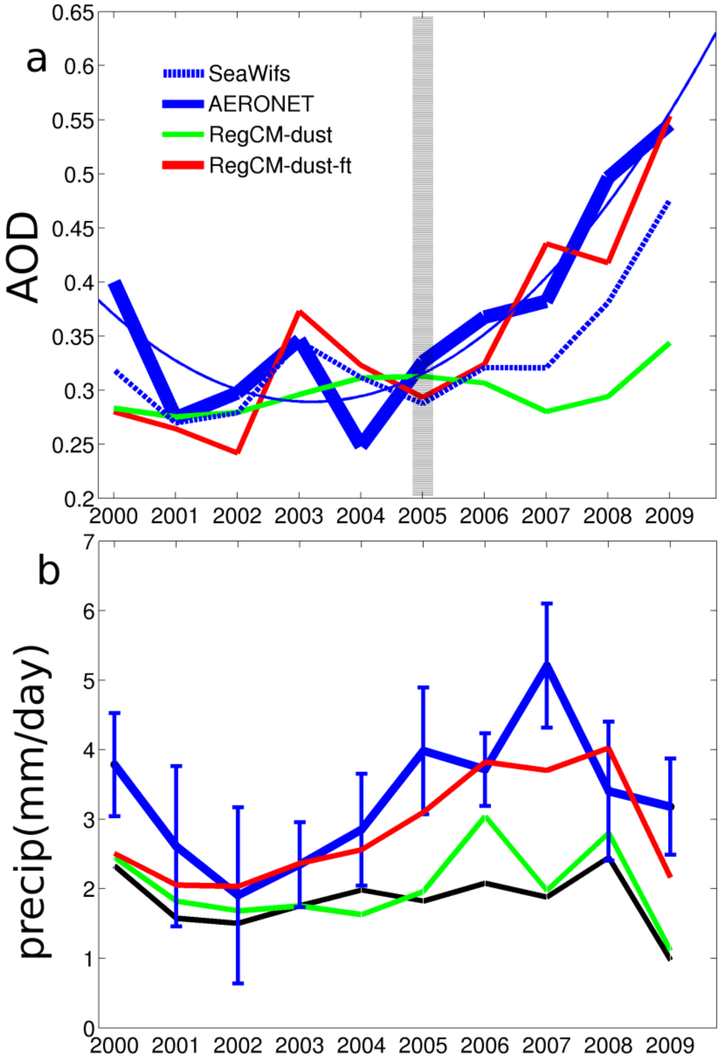

Figure R1: Arabian AOD and Southern India deseasonalized precipitation trends during the decade 2000-2009. **(a)** The thick blue line represents monthly deseasonalised time series of JJAS AOD obtained from the Solar Village AERONET station (monthly product, average of 480-640 nm spectral bands). A quadratic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

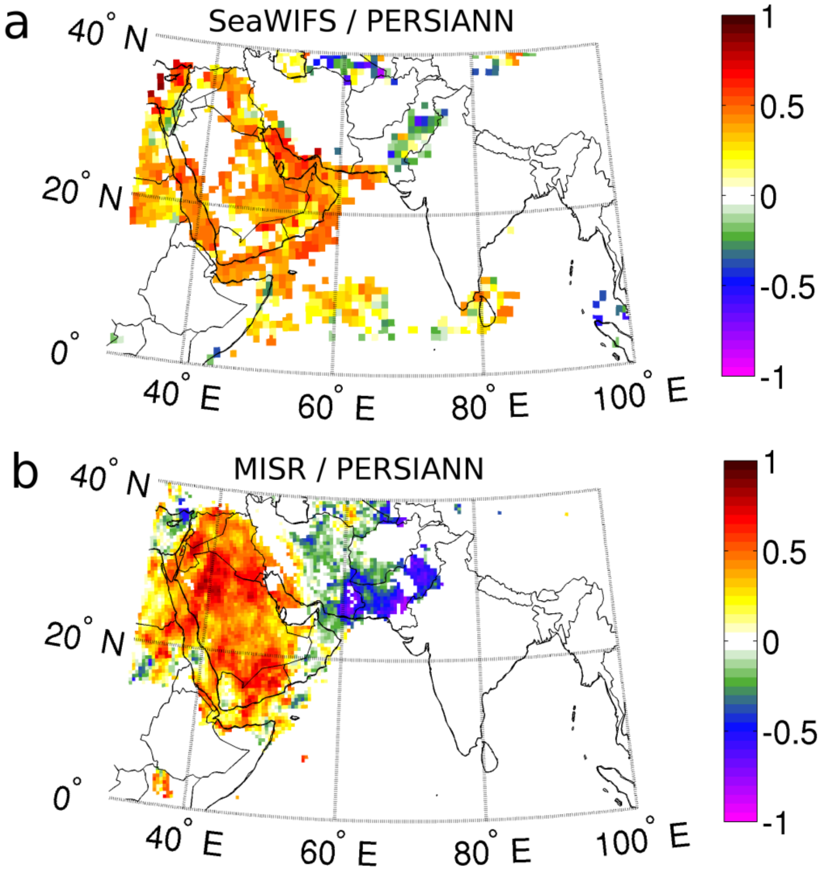

Figure R2: Interannual variability correlation coefficients calculated between deseasonalised summer (JJAS) AOD and deseasonalised JJAS precipitations averaged over a southern India box(5-20N; 60-80E). (a) based on the SeaWIFS AOD retrieval over the 1999-2010 period.(b) based on MISR AOD retrieval over 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.

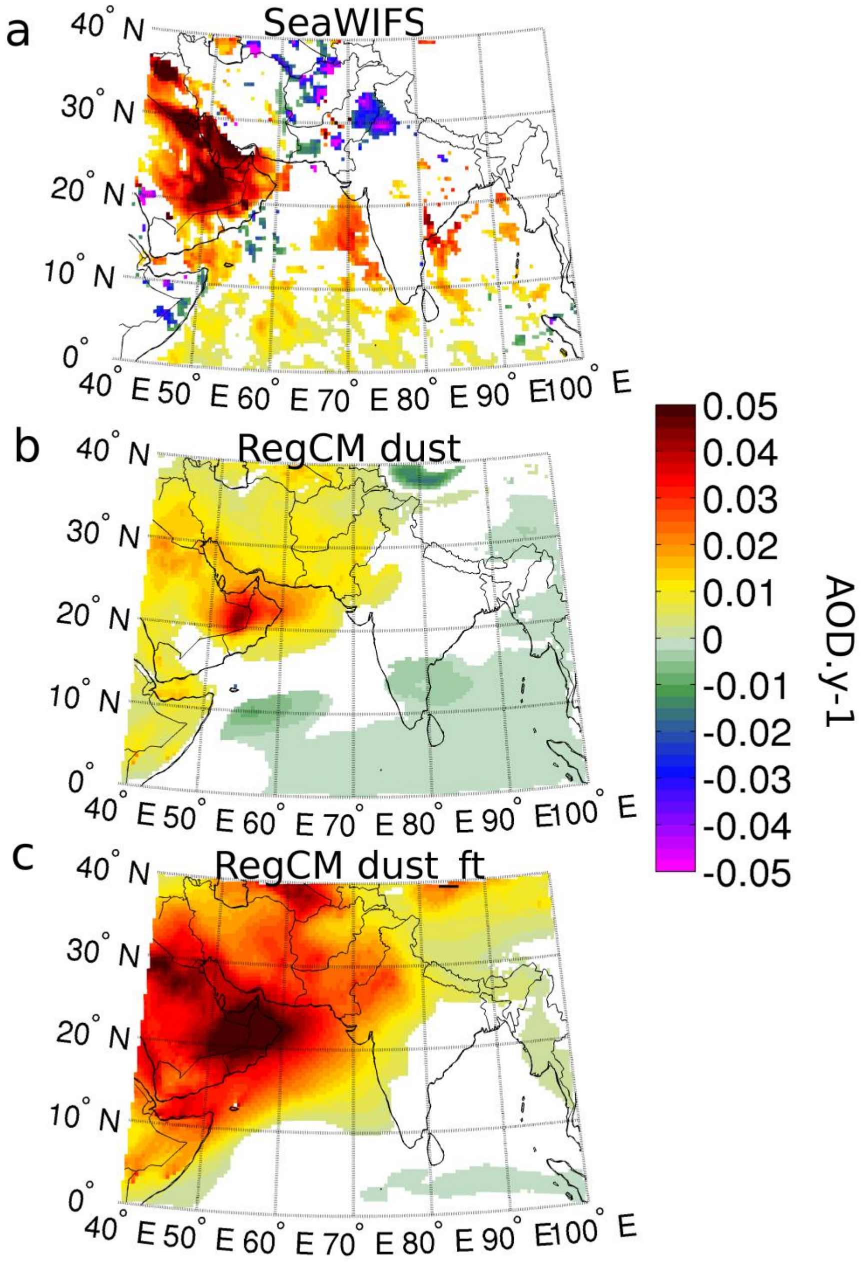

Figure R3. Linear JJAS AOD trend calculated over the 2000-2009 period from: (a) SeaWIFS monthly observations, (b) Model standard *dust* simulations and (d) Model *dust_ft* simulations including a forced emission trend over the Arabian penisinsula. Only statistically significant trends (p-value < 0.05)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

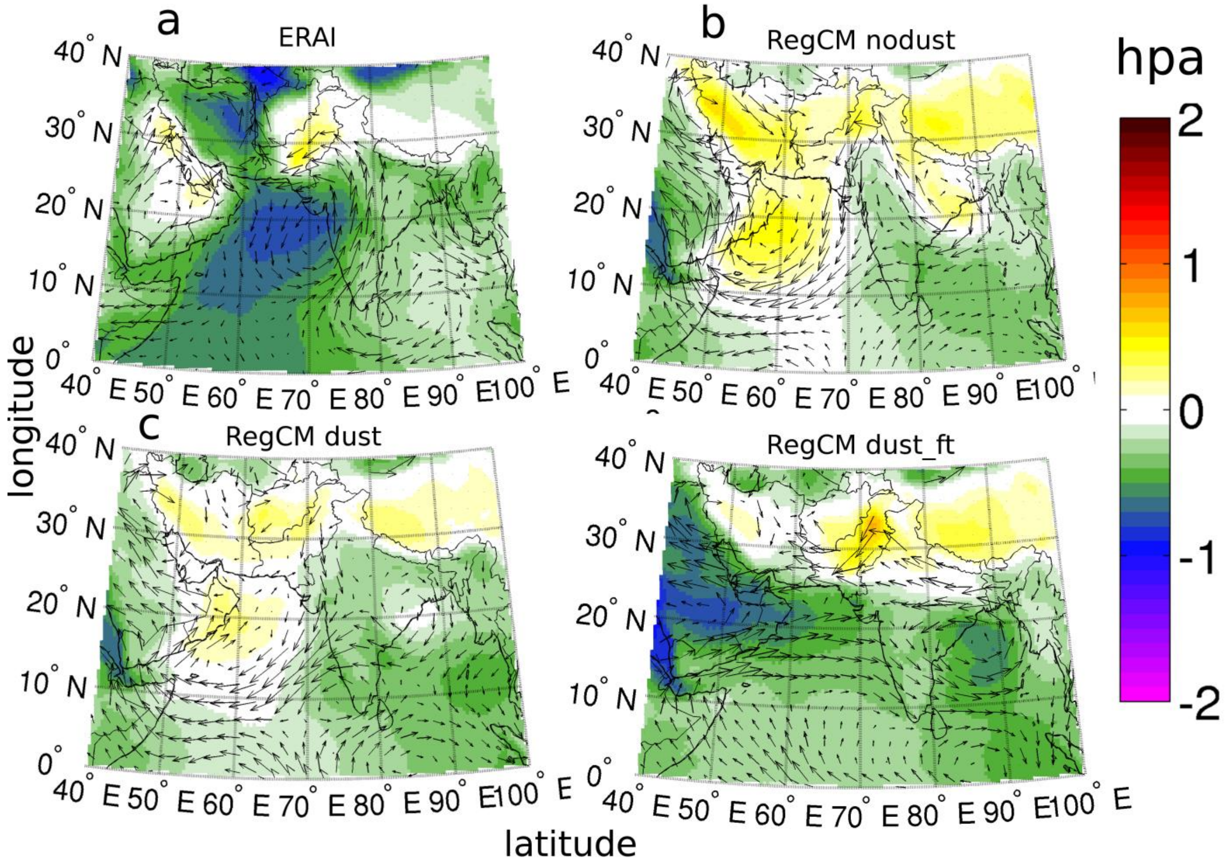

Figure R4: Difference of mean JJAS 850 hpa circulation and surface pressure between "DUSTY" (2005-2009) and "NONDUSTY" (2000-2004) pentads as defined in the text and calculated from : (a) ERAI reanalysis, (b) '*nodust*' simulations, (c) '*dust*' standard simulations, (d) '*dust_ft*' simulations with 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.

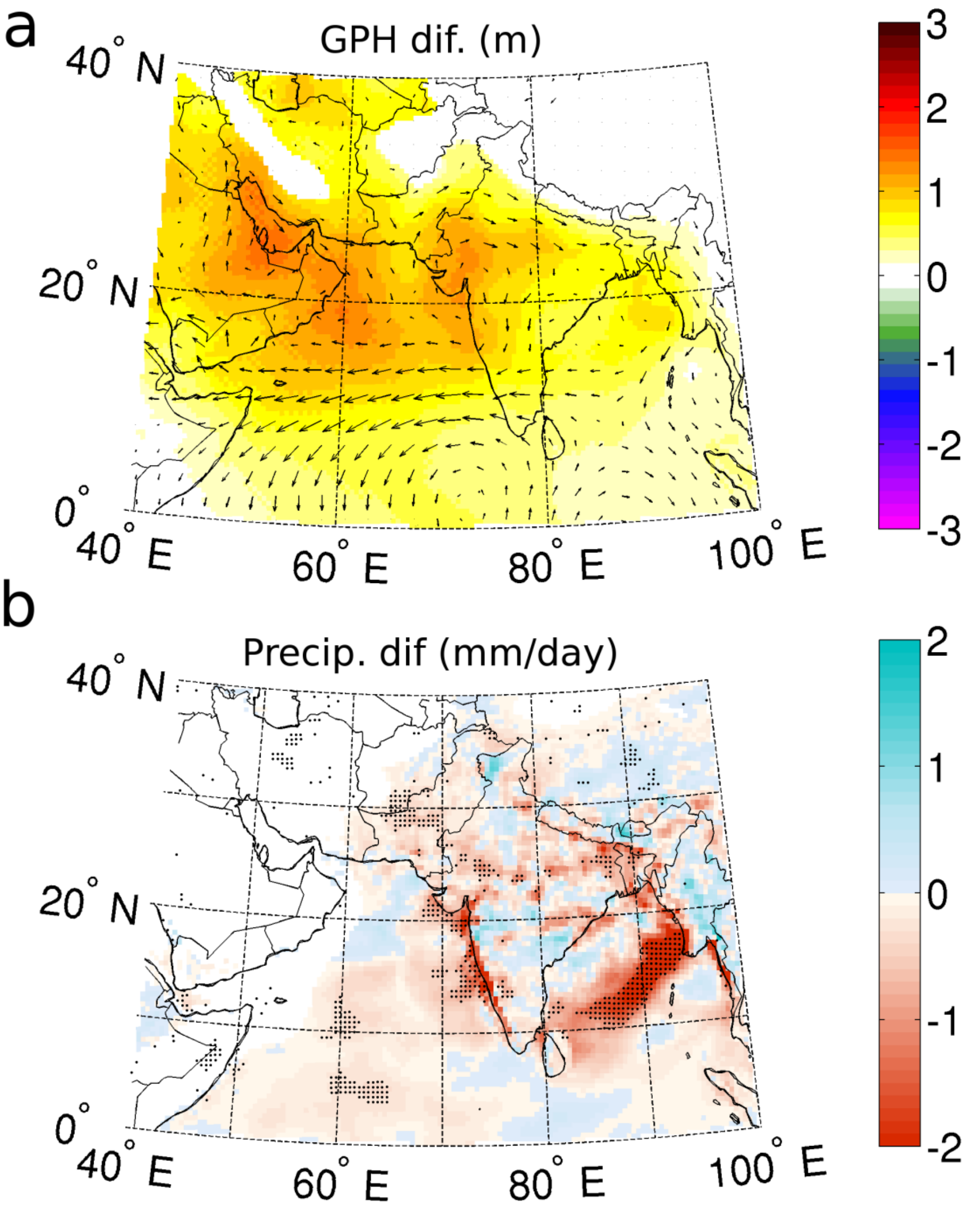

Figure R5. . Impact of the Indo-Pakistanese dust source compared to the dust simulation calculated as *dust_noIP - dust* over the period JJAS 2000-2009. (a) 850 hpa geopotential heights (GPH) and circulation change. (b) Precipitation changes. The dotted region defines statistically significant results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

Increasing Arabian dust activity and the Indian Summer Monsoon

Fabien Solmon (1), Vijayakumar S. Nair (2), Marc Mallet (3)

(1) The Abdus Salam International Center for Theoretical Physics, Strada Costiera 11, 34100 Trieste, Italy

(2) Space Physics Laboratory Vikram Sarabhai Space Centre Thiruvananthapuram Kerala, India, 695 022

(3) Laboratoire d'Aerologie CNRS, Universite Paul Sabatier, 14 av, Edouard Belin, 31400 Toulouse, France

Corresponding Author

Fabien S~~s~~olmon, The Abdus Salam International Center for Theoretical Physics, ESP,
Strada costiera 11 , 34100 Trieste, Italy.
+390402240206, fsolmon@ictp.it

Keywords. Arabian Dust, Decadal Trend, Indian Monsoon Precipitation, Regional climate.

Abstract.

Over the past decade, Aerosol Optical Depth (AOD) observations based on satellite and ground measurements have shown a significant increase over Arabia and the Arabian Sea, attributed to an intensification of regional dust activity. Recent studies have also suggested that west Asian dust forcing could induce a positive response of Indian monsoon precipitations on a weekly time scale. Using observations and a regional climate model including interactive slab ocean and dust aerosol schemes, the present study investigates possible climatic links between the increasing June-July-August-September (JJAS) Arabian dust activity and precipitation trends over southern India during the 2000-2009 decade. Meteorological reanalysis and AOD observations suggest that the observed decadal increase of dust activity and a simultaneous intensification of summer precipitation trend over southern India are both linked to a deepening of JJAS surface pressure conditions over the Arabian Sea. In the first part of the study, we analyze the mean climate response to dust radiative forcing over the domain, discussing notably the relative role of Arabian vs. Indo-Pakistanese dust regions. In the second part of the study, w~~W~~e show that the model skills in reproducing ~~this trends and~~ regional dynamical patterns and southern India precipitation trends ~~patterns~~ are significantly improved only when an increasing dust emission trend is imposed on the basis of observations. We conclude that although interannual climate variability might primarily determine the observed regional pattern of increasing dust activity and precipitation during the 2000-2009 decade, the associated dust radiative forcing might in return ~~however~~ induce a

critical dynamical feedback contributing to enhancing~~ed~~ regional moisture convergence and JJAS precipitations over Southern India.

Introduction.

Indian summer Monsoon rainfall determines to a large extent food production for sub-continental India and has major socio-economic impacts. Simulating monsoon precipitations variability from intra-seasonal to inter-annual time scales is identified as major challenge, especially in the context of climate change and increasing anthropogenic pressures over the Indian subcontinent (Lau, et al., 2008). The complexity of the monsoon system arises from the interactions between physical processes involving atmosphere, land and ocean and operating over a wide range of spatial and temporal scales (Turner, et al., 2012). The role of aerosol as a possible factor modifying these interactions, with consequences on precipitation variability, has been a subject of intense study for the last decade (Lau et al., 2008).

There are basically two mechanisms invoked when discussing the climatic response to direct aerosol forcing over southern Asia. The 'solar dimming effect' (Ramanathan, et al., 2005) proposes that the reduction in surface solar radiation due to absorption and scattering by aerosols, which shows a regional maximum over northern India and Indian ocean, induces a reduction of the north-south surface temperature gradients resulting in a weakening of the Indian summer monsoon. Consistently with this mechanism, the observed summertime drying trend observed over Central Indian region since 1950 has been attributed to increased anthropogenic aerosol emissions through a slowdown of the tropical meridional circulation (Bollasina, et al., 2011). In contrast the “elevated heat pump effect' (Lau, et al., 2006) proposes that radiative heating anomalies due to anthropogenic black carbon (BC) and dust transported over the Himalayan foothill and Tibetan plateau during the dry season and the pre-monsoon enhance meridional tropospheric temperature gradients resulting in a strengthening and earlier onset of the Indian monsoon rainfall. The elevated heat pump effect has however been questioned by Nigam and Bollasina, 2010. Though apparently antagonistic both these mechanisms might be effective at different stage of the pre-monsoon and monsoon development (Meehl, et al., 2008) outlining the complexity of aerosol climate feedbacks operating on different time scales. In addition it has been outlined that the regional impact of Asian aerosol might be reinforced by non Asian sources through long distance transport and global dynamical adjustments (Bollasina, et al., 2013), (Ganguly, et al., 2012), (Cowan, et al., 2011), (Wang, et al., 2009).

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Despite a large focus on anthropogenic aerosol effects justified by the observed intensification of emissions contributing to the “Asian brown cloud” (Ramanathan, et al., 2005), the potential importance of natural, and in particular dust, aerosol has been also recently highlighted (Jin, et al., 2014), (Vinoj, et al., 2014): It is suggested that west Asian dust outbreaks can induce a fast and regional atmospheric response which could explain observed positive correlation between aerosol optical depth (AOD) over west Asia and summer precipitation over India on a weekly time scale. Using global circulation model (GCM) experiments with prescribed sea surface temperature (SST) Vinoj et al. (Vinoj, et al., 2014) attributes the cause of this correlation to the large radiative heating induced by dust radiation absorption over Arabia and the Arabian sea resulting in an intensification of south-westerly moisture convergence towards India. This mechanism involves primarily direct and semi-direct aerosol effects and based on a fast reaction of monsoonal weather systems to dust radiative heating perturbation.

The question of characterizing the impact of west Asian dust on Indian monsoon becomes even more relevant if we consider another striking fact which is the observed recent enhancement of Arabian dust activity as measured by satellite and ground based AOD observations during the past decade. Based on Sea-viewing Wide Field of View Sensor (SeaWIFS) satellite observations, a significant June-July-August ~~(JJA~~ increasing AOD linear trend ~~reaching 0.014 yr-1 oover the Arabian region~~ has been determined for the period 1998-2010 for the Arbian region (Hsu, et al., 2012). This regional trend, associated to a regional increase of dust storm activity, is also detected in ground based photometer measurements from the Aerosol Robotic Measurement Network (AERONET) at the Solar village site in Saudi Arabia (Xia, 2011). To our knowledge, the attribution of this regional emission increase to climatic factors and/or land use change is yet to be fully investigated. Ginoux et al., 2012 discuss the possible increasing contribution anthropogenic dust sources relevant to the region, and ~~(~~we also indicate later some possible connections with the evolution low pressure conditions over the Arabian sea and the Indian monsoon system~~)~~.

In this context, the question we wish to primarily address here is: What are the main characteristic of dust radiative forcing regional climatic feedbacks, and t~~T~~o which extent the recent enhancement of dust activity in the Arabian region could affect the Indian monsoon dynamics and precipitations on decadal time scale? As dust emissions might evolve naturally or/and as a result of climate and land use change ((Mahowald, 2007), (Mulitza, et al., 2010);~~,~~ Yoshioka et al., 2007) characterizing and quantifying the regional climate implications of observed dust variability is especially relevant for a better understanding of the Indian monsoon system variability and its possible evolution.

Toward this goal, we use a 50 km resolution regional climate model coupled to an aerosol scheme and a slab-ocean model together with diverse observation and reanalysis products. A specific attention is paid to the quality of the simulated Indian monsoon circulation and precipitation fields as well as to the representation of aerosols notably in term of sources, optical depth, radiative forcing and heating rates gradients. 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 (Rodwell and Jung, 2008) 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 section 1 we detail the modeling experiments as well as the different data sets and method use for trend calculation. Section 2 focuses on analyzing observed summer AOD and precipitation trends and interannual correlations over the domain. Dust radiative and climatic impacts and the possible links between Arabian dust trend and southern India precipitation ~~the monsoon variability~~ at the decadal scale are then addressed in section 3~~2~~ and 4~~3~~.

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1 Data and methods

1.1 Regional climate model.

We use the International Center for Thoretical Physics (ICTP) regional climate model RegCM4 (Giorgi, et al., 2012) at 50 km resolution. Runs are performed on the COordinated Regional climate Downscaling Experiment (CORDEX)-India domain over the period 1999-2009 including a 1 year spin up. Boundary conditions are provided by ERA-Interim reanalyzes through a 1000 km buffer zone. The Newtonian relaxation to large scale fields applied in the boundary buffer zone is designed to limit as much as possible wave reflections in the domain (Marbaix et al., 2003). Important physical options we used for this~~ese~~ study are the Community Land Model version 3.5 (CLM3.5) (Tawfik, et al., 2011), the University of Washington turbulence scheme (O'Brien, et al., 2012) and the Emanuel convection scheme (Emanuel, 1991) with enabled tracer transport capabilities. The RegCM4 aerosol scheme includes a representation of anthropogenic sulfates, black and organic carbon (Solmon, et al., 2006); (Qian, et al., 2001) as well as sea-salt and dust aerosol~~s~~. For anthropogenic emissions, we use the Regional Emission inventory in ASia (REAS) (Ohara, et al., 2007), (Nair, et al., 2012) completed by the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) emissions (Lamarque, et al., 2010) to account for biomass burning emissions and REAS-uncovered regions. For natural particles, sea salt aerosol emissions are calculated on line and are represented by two (sub and super-micronic) different bins (Zakey, et al., 2008). The dust emission scheme (Marticorena, et al., 1995), (Zakey, et al., 2006) includes updates of soil texture distribution following (Menut, et al., 2013) and emission size distribution (Kok, 2011), (Nabat, et al., 2012). Lateral Boundary conditions for aerosols are prescribed from a decadal climatology obtained from global runs performed using CAM-Chem model (J. von Hardenberg, personal communication, 2014). Dusts are represented using 4 bins and are impacting short and long wave radiation transfer as detailed in Supplementary Information (Table S1). All other aerosols impact the RegCM shortwave radiation scheme through pre-calculated optical properties (Solmon, et al., 2006). Only the first indirect effect is accounted for and applied to sulfate aerosol (Giorgi, et al., 2003).

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Of particular importance for studying aerosol effects (Miller et al., 2004) ;(Zhao, et al., 2011), we implemented ~~f~~in RegCM4 ~~or this study in ReGCM4~~ a “flux corrected” slab ocean parameterization following an approach used in the FMS model (http://www.gfdl.noaa.gov/fms-slab-ocean-model-technical-documentation). This parameterization assumes a 50 m depth ocean mixed layer for which we calculate a prognostic SST through a simple energy budget. The lack of ocean dynamics, diffusion and convection, but also other model surface flux errors are compensated by specifying surface flux adjustments (q-flux adjustments) to the slab temperature tendency equation, notably in order to maintain a realistic SST seasonal cycle compared ~~as close as possible~~ to observations. To derive the q-flux terms, we perform first a “restoring run” (with no interactive dust aerosol) where the slab prognostic SST are restored to observations, taken here as the Optimum Interpolation Sea Surface Temperature (OISST) (Reynolds, et al., 2002), and considering a 5 day restoring time scale. As the slab mixed layer model is integrated (over the 1999-2009 period in this experiment), the restoring heat fluxes (q-flux) calculated through this procedure are archived and ~~are~~ saved in a monthly mean climatology at the end of the restoring run. Once the q-flux climatology is built ~~has been derived~~, the control and experimental “adjusted runs” are performed accounting for q-fluxes (prescribed from the climatology) in the slab ocean temperature equation. Over the domain, seasonal average differences of SST between the q-flux adjusted control experiment and OISST observations varies in the range of -1 to 1 degree, ensuring that prognostic SSTs in the adjusted runs do not diverge much from observations and follow a realistic seasonal cycle. This approach extends previous aerosol regional climate studies based on forced SST over the Indian Monsoon and other domains e.g. (Das, et al., 2014).

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The control experiment consist in a three ensemble members of adjusted runs with no interactive dust aerosol activated (*nodust*). An ensemble of three adjusted runs is then performed with activation of dust (*dust*). Additionally, a sensitivity test consisting in removing the Indo_Pakistanese regional dust source (*dust_noIP*) is also performed. Finally ~~An additional~~ a three ensemble members experiment ~~run~~ is made with imposing an increasing emission trend over Arabia in order to better reproduce observed AOD trends (*dust_ft*)~~)~~. This is done by increasing the saltation flux erodibility factor (Marticorena, et al., 1995) during the run. From year 2004 to 2009 the corresponding increase of erodibility factor is about 30 %, ~~and will be illustrated further~~. 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). With this technique, we increase the filtering of noise *vs.* statistically significant physical signal while performing differences between the ensemble means of perturbed and control runs ~~Results~~experiments. All results, figures and discussion are based on ensemble means.

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1.2 Aerosol Optical Depth trend calculation.

JJAS AOD linear trend calculations are first performed using the Sea-viewing Wide Field of View Sensor (SeaWIFS) monthly AOD (550 nm) products at 0.5 degree, and regrided on the 50 km RegCM grid. Algorithms and validity of AOD retrievals from SeaWIFS atmospheric corrections are discussed in (Sayer, et al., 2012)a and (Sayer, et al., 2012)b. Moreover, as argued in (Hsu, et al., 2012), the SeaWIFS AOD product is recognized as a "stable" data set minimizing sensor calibration impact on trend analysis

For each model grid column, the SeaWIFS~~wifs~~ AOD are first deseazonalised applying a 13-term moving average for trend first guess and a stable seasonal filter for removing of the seasonal cycle (Brockwell, et al., 2002). The deseasonalized times series of JJAS 2000-2009 are then extracted and a linear regression is applied on this subset to determine the JJAS linear trend. Statistical significance of the trend is determined using a F-test and we plot only statistically significant pixels with a significant non zero slope (p-value < 0.05). Over our region of interest this treatment shows much consistency with the results of Hsu et al., 2012 (Hsu, et al., 2012). The same method is applied to simulated monthly AOD time series for model –measurement comparison. Over the particular location of Solar Village, the deseasonalized JJAS AOD time series is also calculated from the Aerosol Robotic Network (AERONET) monthly optical depths and considering the ~~spectral~~ average of AOD measured at 440nm and 640 nm.

In addition to SeaWIF, we also make use of the Multiangle Imaging Spectro-Radiometer (MISR, (Martonchik, et al., 2004)) retrievals for the validation of mean AOD and further interannual variability analysis

1.3 Precipitation trend calculation.

For the ~~recent~~ 2000-2009 precipitation trend calculation over southern India (Figure 1.b), we use~~d~~ the University of East Anglia Climate Research Unit product (CRU) (Harris, et al., 2014), the Tropical Rainfall Measuring Mission (TRMM 3B42) (Huffman, et al., 1995) product, the University of Delaware product (UDEL) (Matsuura, et al., 2009) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) product (Ashouri, et al., 2014)~~, product~~ . For each data set, precipitation monthly time series are first geographically averaged over a continental southern Indian box (5-20 N, 60-80 E). Deseasonalized time series are produced following a similar method than for AOD treatment.~~deaseasonalization~~. A yearly series of JJAS average precipitation is then produced by averaging the different deseaonalized series from each data sets, and keeping the minimum and maximum values for estimation of the spread between different observation data sets.

Additionally for the evaluation of simulated mean JJAS precipitation, we also use the "Asian Precipitation - Highly Resolved Observational Data Integration Towards Evaluation of water resources" (APHRODITE) data set over the 2000-2007 period (Yatagai, et al., 2012).

~~2 Results and Discussion.~~

2 ~~:—~~AOD vs~~/~~ precipitation trends and interannual variability correlations

Linear trends of JJAS AOD, calculated from SeaWIFS observations over our domain (cf section 1), are presented on Figure 1 and Figure ~~Figure~~ 3.a . As already reported in (Hsu, et al., 2012), a significant 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 also reported (Figure 1.a). As discussed in Hsu et al., 2012 a decreasing trend in AERONET retrieved angstrom coefficient has been observed at Solar Village, 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. From the time series in Figure 1~~6~~.a, we note that the JJAS observed deseasonalized AOD ~~trend~~

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tends to steepen around year 2005. Consequently the 2005-2009 pentad~~-~~ shows sensibly higher averaged AOD relative to the 2000-2004 pentad~~-~~. For simplifying the following discussion we will refer to these pentads as “NONDUSTY” and “DUSTY”.

An increasing trend for precipitation over southern and eastern India is also detected in several data sets as illustrated in (Figure 1~~6~~.b). In a rather similar way to Arabian AOD, the observed JJAS precipitation in Figure 1~~6~~.b shows a relative intensification for ~~P0509~~“DUSTY” relative to ~~P0004~~“NONDUSTY” pentads. If we plot the mean surface pressure and circulation differences between ~~“dusty P0509~~“DUSTY””” and ~~“less dusty P0004~~“NONDUSTY””” pentads from ERAI and NCEP2 reanalyzes (Figure 4~~8~~.a and Figure S3), we observe that both data sets show a cyclonic pattern over the Eastern Arabian sea and India with enhanced southwesterly circulation toward continental India. The associated increase of moisture flow over southern India is a likely reason for enhanced precipitations during “DUSTY” ~~P0509~~ pentad relative to ~~P0004~~“NONDUSTY” pentad observed in precipitation data sets on Figure 1~~6~~.b.

Furthermore, the cyclonic pattern found in pentad differences depicts a relative increase of the frequency/intensity of low pressure situations over northern Arabian sea for ~~P0509~~“DUSTY” relative to ~~P0004~~“NONDUSTY” pentad. Such conditions are favorable to enhanced Shamal wind, (Hamidi, et al., 2013), (Notaro, et al., 2013) and could thus be a likely reason for the observed increase of AOD during the decade. On short time scales, it is also known that individual storms moving in the Arabian sea and the northern bay of Bengal can trigger large dust emission from Arabia and the Indo-Pakistanese - Iran desert regions (Kaskaoutis, et al., 2014), (Ramaswamy, 2014). Based on these observations, both enhanced precipitation over India and Arabian dust AOD increase could be linked to lower pressure conditions prevailing over the Arabian Sea during DUSTY ~~PO509~~ relative to ~~P0004~~“NONDUSTY” pentads. Reasons for these conditions are likely a feature of climate decadal variability over the region (Patra et al., 2005) and further analysis is beyond the scope of this study~~.(Note that part of the short time scale AOD/precipitation correlation attributed to dust direct and semi-direct feedbacks (Vinoj, et al., 2014) could also be explained by dynamical systems leading to both high dust emissions/transport and heavy precipitations over India on short time scale) .~~

If the arguments developed above are valid, one should also expect a possible correlation between the inter-annual variability of summer dust AOD and precipitation over southern India. This correlation is not obvious on Figure 1 for in the 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 2.a and b, our analysis reveals clear regional patterns: Over the Indo-Pakistanese source region both MISR and SeaWIFS deseasonalised summer AOD tend to be anti-correlated with southern India deseasonalised precipitations. Inversely, over Arabia, positive correlation coefficients tend to be observed for both

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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 variabilitiy 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-Pakistanese 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.

3 Simulation~~ed~~ of dust radiative forcings, trends and associated feedbacks

3~~2~~.1 Simulation of mean JJAS climate.

In this section we assess the model capacity to simulate the mean observed JJAS monsoon circulation and precipitation over the domain. Comparison of simulated JJAS 850 hpa circulation patterns show an overall consistency with ERA-Interim reanalysis in ~~te~~rm of pattern and intensity as illustrated in Figure 5~~1~~a,b. The main differences are a moderate underestimation of Easterly circulation in the region of the Somalian Jet, and a tendency for the model to overestimate average wind speed ~~circulation intensity~~ over the Bengal gulf and Indonesia. Model mean JJAS precipitations are evaluated using TRMM, PERSIANN ~~–~~and the high resolution APHRODITE data sets (cf section 1). The v~~V~~ariability between observations is illustrated on Figure 6~~2~~, c~~b~~,e and ~~,~~g. As in many modeling studies and due to the complexity of convective and dynamics processes, important precipitation overestimation biases are found in region of low precipitation as well as over the North Eastern Himalayas and over the southern Bay of Bengal (Figure 6~~2~~). Over continental India, the control simulation (*nodust*) tends to produce drier conditions than observed, with a relative bias increasing toward Eastern and Southern India (Figure 6~~2~~,d,f,h).~~.~~ The model shows better results when compared to the high resolution APHRODITE rain gauge based data set (Figure 6~~2~~,g-h). Comparison of Figure 6~~2~~,b and 6~~2~~, d,f,h shows that radiative effects of dust tends to reduce model biases over continental India southern and northwestern regions ~~.~~(see also Figure S4). Biases are however increased over the western bay of Bengal. Overall the simulated mean circulation and precipitation biases obtained in these simulations are either lower, or comparable with CMIP5 state of the art GCMs and multi model ensemble (Sperber, et al., 2013).

3~~2~~.2 Simulation of~~f mean JJAS~~ aerosol optical depth, radiative forcings and heating rates.

The climate response to aerosol via direct and semi direct effect is strongly dependant on radiative forcing gradients as well as the vertical distribution of radiative heating due to aerosol. To evaluate model performance in this regard, the AOD simulated for both anthropogenic and natural aerosol is evaluated using ~~the Multiangle Imaging~~

~~Spectro-Radiometer ~~MISR~~-~~and SeaWIFS products described in section 1 (Figure 7~~3~~). Simulated AOD in regions dominated by anthropogenic emissions (North Eastern India, China, Indonesia) are reasonably captured despite local underestimations for Indian and Chinese megacities. An underestimation of simulated AOD over the Bay of Bengal is however noted, which can be due to uncertainties in emissions, notably for biomass burning (Streets, et al., 2003), and/or an excessive deposition rate due overestimated precipitations as discussed previously. Overall, simulated JJAS 2000-2009 AOD shows a very good agreement with observations both in term of magnitude and spatial gradients, providing additional regional details when compared to existing GCM simulations e.g. (Vinoj, et al., 2014), (Bollasina, et al., 2011), (Lau, et al., 2006). Of particular importance, the dust dominated regions of Arabian peninsula, the Arabian sea and the Indo-Pakistanese desert regions are quite accurately represented in terms of averaged JJAS AOD, although a likely small contribution of non dust aerosol might play in this comparison..

Additional comparisons of simulated AOD and ground based AERONET retrieved AOD (500 nm) are proposed in Figure 8 for the stations of Solar Village, Meizera, Kuwait Airport and Karachi. Dust aerosol mass is known to be dominant over these stations, except perhaps during winter season over Karachi. For both model and observations, monthly averages are built from daily means and screened for missing days in observations. Figure 8 shows that the model tends in general to slightly underestimate observed AOD. This underestimation is perhaps more pronounced for the Karachi station, as also shown on JJAS average AOD comparisons (Figure 7). The simulation of

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AOD seasonal cycles shows an overall consistency with observations (Figure 9 a,c). However we note that for certain years AOD spring maxima tend to be underestimated by the model over solar village, while summer peaks tends to be overestimated. This slight shift of the seasonal cycle is also discussed in Shalaby et al., 2015.

On Figure 9 b,d we compare simulated aerosol size distribution to size distributions retrieved by AERONET inversions and re-binned to match model dust bins. Due to lack of observational data and given the scope of the study, we restrict this comparison to JJAS 2009. Inter-annual variation of JJAS size distribution might anyway be of secondary order, especially given the possible uncertainties in AERONET inversions (Dubovik et al., 2000). For both Solar Village and Karachi, the model tends to show a consistent relative distribution between size bins compared to observations. However we can note an overestimation of simulated fine and/or medium bins compared to underestimated coarse bin, especially in the case of Karachi (Figure 9.d). One of the possible reasons for this might lie in the emission size distribution (Kok et al., 2011) who tends to be more uncertain with regards to representing coarse particles, as for example discussed in Mahowald et al., 2014. Other reasons could be linked to accuracy in sources geo-location, removal and transport processes. Bearing in mind observational uncertainties, the implication of a simulated dust size distribution shifted towards smaller particles would be to enhance SW scattering vs. SW absorption and LW emission with implications on radiative forcing and feedback discussed further.

Over dust dominated regions ~~these regions~~, the net dust surface radiative forcing (Figure 104,a) is dominated by shortwave cooling vs. positive long-wave surface

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warming as ~~which is~~ reported on supplementary material (Figure S1). This induces a surface temperature cooling illustrated on Figure 10,e which can reach -2K in sub-regions of Arabia. Over the ocean, a surface cooling is also obtained through the slab ocean response, but tends to be less effective due to larger surface thermal inertia. SST cooling reaches up to -1 C close to Oman Gulf with a decreasing gradient towards India (Figure 10, c~~b~~). As a result of both dust optical properties and surface albedo, top of atmosphere radiative forcing (TOA) is mostly positive over the high emission region of the Arabian peninsula, and becomes negative above the ocean and continental India. Note that i~~I~~n comparison to Arabian peni~~s~~nsula, the TOA radiative forcing efficiencies (i.e. TOA normalized by AOD~~)~~ reported on Figure 10, d) show~~s~~ less of a warming effect in the Indo-Pakistanese ~~and Northern India~~ desert regions essentially due to lower surface albedo. Over continental India the TOA radiative forcing efficiencies becomes largely negative due to relatively dark albedo and also due to the fact that long range transported dust from Arabian and Indo-pakistanese sources are finer and more scattering. Uncertainties and regional variability in dust size distribution and ~~and~~ optical properties might affect the magnitude and even the sign of the radiative forcing simulated ~~proposed~~ here with potential consequence on regional climate feedbacks as discussed further.

Atmospheric radiative heating rate anomalies primarily associated to dust radiative absorption, are presented on Figure 10~~4~~,f~~d~~ and Figure S2. Mean simulated values for JJAS ranges from more than 1 K/Day over source regions of Arabia to about 0.3 K/day in the core of the Arabian dust outflow, located between 850 and 600 hpa. Over India, the JJAS dust radiative warming at 850 hp reaches about 0.05 to 0.1 K/day. These values are in the range of different observational studies (Moorthy, et al., 2009),

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(Kuhlmann, et al., 2010), (Nair, et al., 2008). We note that when radiative and moist processes feedbacks are combined, the diabatic heating induced by dust is however significantly lower than the 2K/day warming reported in (Vinoj, et al., 2014) which can also explain differences further discussed in section 3.

3~~2~~.3 Mean monsoon response to dust radiative forcing.

Regional climate adjustments to dust radiative forcing are first discussed by comparing '*dust*' and '*nodust*' simulations (as defined in section 1) for JJAS 2000-2009. Figure 11~~5~~ presents 850 hpa circulation and geopotential height (GPH) anomalies induced by dust direct and semi-direct over the domain. Two patterns emerge from this comparison: The first one is a low GPH anomaly centered over southern Arabian Peninsula associated to a cyclonic circulation, and the second one a positive GPH anomaly roughly centered over North Eastern India associated to an anti-cyclonic anomaly. Regions of large positive or negative values in 850 hpa GPH difference patterns tend to match ~~pretty~~ closely the regional TOA radiative forcing patterns (Figure. 10b). Over Arabia, dust radiative warming is maximum due to high concentration of dust while dust surface cooling efficiency is relatively reduced due to high surface albedo. This induces a deepening of the Arabian thermal low (Figure 11~~5~~) and dry convection collocated with the maximum of dust radiative warming (Fig S2, c and d). On its southern part, the cyclonic circulation anomaly is associated to an intensification of the Somalia jet and Eastward circulation between 10 and 20 N and 50 to 75 E. This intensification induces an enhanced convergence of moisture flux toward southern India and an increase of convective activity and precipitations over the southern Indian continent (Figure 11~~5~~ and S2 d, e). From these simulations we estimate that this mechanism could enhance average precipitation by up to 10 % in southern India thus contributing to improve the model dry bias (Figure. 6~~2~~ a).Up to roughly 20N, our results show much similarity with GCM results notably reported in (Vinoj, et al., 2014). One noticeable difference however is, while (Vinoj, et al., 2014), obtain an increase of precipitation over northern Arabian sea, north western India and Pakistan, convective precipitations tend to be inhibited for these regions in our case. This regional stabilization is induced by a relatively large surface radiative dimming which decreases continental and sea surface temperatures (figure 10~~4~~ ,e~~e~~), ~~–~~and predominate over dust diabatic ~~absorption radiativ~~e warming effects~~-~~. This is consistent with a negative simulated TOA radiative forcing (Figure 10~~4~~ b). On average, the combined contribution of 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 11).

In order to illustrate further this point, we perform an additional experiment where the 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 12). Due to its geographic position and regional surface characteristics, the Indo Pakistanese dust source contributes relatively more than Arabia to the negative TOA radiative forcing and the

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dimming signal obtained over India. In this regards the Indo-Pakistanese source related effects tends to "compete" with the positive feedback associated to large radiative warming efficiencies over the Arabian Peninsula.

That said, it must be noted that radiative forcings and impacts might strongly depends on dust chemical composition and absorption/scattering properties (Perlwitz et al., 2001; 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 variation of dust refractive indices as proposed in recent studies (Scanza et al., 2015). This point might be especially important over the Indo-Pakistanese region where simulated 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 which can potentially results in an opposite dynamical feedback (in this case an enhancement of elevated heat pump effect over Pakistan and northern India). Some simple tests modifying dust SSA values in RegCM4 and performed 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 note that we do not account for possible dust indirect effects on warm and ice cloud microphysics for which there is still a considerable debate and for which regional impacts are difficult to assess in this study.

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3~~2~~.4 Coupling of Arabian dust increasing activity and precipitation variability over the 2000-2009 decade.

Our working 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, and perhaps contributing to, a positive impact on circulation and precipitation over southern India. Focusing ~~now~~ on model results we see that, although the standard *dust* simulation is able to capture a slightly positive AOD trend over part of the Arabian Peninsula, this trend is nevertheless largely underestimated when compared to observations (Figure 3~~7~~ a and b). 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 4~~8~~.b and c, meaning that the model does not reproduce properly increasing occurrences or/and intensification of Shamal conditions during the decade. 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). In terms of dust AOD, the uncertainties in dust emissions parameterizations could further worsen errors in simulating adequately regional climatic trends (Evan, et al., 2014).

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However, since dust trigger a potentially important climatic feedback over the region, it is possible that failure in capturing the increasing Arabian dust trend contributes also to failure in capturing a proper trend in regional climate. To explore this issue, we perform an additional experiment where dust emissions are forced in order to reproduce more realistically the observed JJAS AOD increasing trend (see section 1.2 and Figure 1~~5~~.a and Figure 3~~7~~.b and c). This constraint is applied only over the Arabian Peninsula and eventual trend visible over other regions are primarily a results of Arabian dust transport or simulated spontaneously in response to simulated climate. On the JJAS AOD time series (Figure 1~~5~~.a) we can note that the adjusted model shows enhanced AOD for ~~P0509~~“DUSTY” pentad relatively to ~~P0004~~“NONDUSTY” pentad in a relatively similar way to observations. In term of climatic impact, simulated circulation and surface pressure changes between ~~P0004~~“NONDUSTY” and ~~P0509~~“DUSTY” pentads show a rather different behavior whether considering *nodust*, *dust* only, or adjusted *dust_ft* simulations (cf section 1), especially over the Arabian Sea and southern India (Figure 4~~8~~). 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 4~~8~~, b and c) and no enhanced westward circulation toward the Indian coast, unlike what is observed in reanalyzes (Figure 4~~8~~a). 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 8 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 alone shall not be considered as the main driver for explaining regional circulation changes, and also points out to model limitations. With this in mind, the simulations still 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

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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. The simulated impact of this feedback on summer precipitation trends over southern India is depicted on Figure 1~~5~~.b: S~~s~~imulated JJAS precipitations show an increasing linear trend in *dust_ft* deseasonalized JJAS simulations of about 0.11 mm.day-1.y-1 and close to the value of the JJAS trend calculated from observations (0.13 mm.day-1.y-1), when no statistically significant trends are detected in *nodust* and *dust* simulations.

4~~3~~. Conclusion

Overall our results emphasize the possible two-way interaction between dust emissions variability and the summer regional climate variability in the Indian monsoon domain for inter-annual to decadal time scale. 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, Patra et al., 2005) 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

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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. Please note however that the entire feedback loop has not been fully demonstrated here since we used forced emission trends.

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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). Nevertheless, it is likely there has been an impact of the anthropogenic aerosol trend on Monsoon rainfall during the studied decade, as for example discussed in Bollasina et al., 2011 (who conclude in general to a drying effect of anthropogenic aerosol on continental India). Note that in magnitude, the measured dust decadal 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).

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In view of these results, capturing the positive feedbacks between dynamics and dust emission trends in climate models could lead to a more realistic representation of precipitation decadal variability over India. This is even more relevant when considering the emergence and potential importance of “anthropogenic dust sources” as discussed in Ginoux et al., 2012. However, the present study, as well as (Evan, et al., 2014), show that current dust ~~parametrisation~~parameterizations and implementations ~~used~~ in climate and Earth System models have ~~show~~ difficulties to reproduce observed regional AOD inter-annual and decadal variability. I~~I~~mprovement of models whether they deal with dust emissions processes, regional land use change and surface wind speed downscaling are still ~~thus~~ of primary importance.

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Figure Legends.

Figure 1. 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 deasesonalised AOD time series obtained from SeaWIFS AOD interpolated on the Solar Village station. The green lines represents the monthly deseasonalized time series (as well as the corresponding quadratic fit) of JJAS AOD simulated by the model in *dust* simulation. The red lines represents the monthly deseasonalized time series (as well as the corresponding quadratic fit) 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.

Figure2. Interannual variability correlation coefficients calculated between deseasonalised summer (JJAS) AOD and deseasonalised JJAS precipitations averaged over a southern India box(5-20N; 60-80E). (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 year number is less than 8.

Figure 3. 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-value < 0.05) are represented (cf Data and Methods). All modeling results represent a 3 member's ensemble mean.

Figure 4. 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 5. Mean 850 hpa JJAS wind intensity and direction as seen in (a) the ERAI reanalysis and (b) the RegCM *nodust* simulation for the period 2000-2009 and over the CORDEX-India domain. All modeling results represent a 3 member's ensemble mean.

Figure 6. (a) Mean JJAS 2000-2009 precipitation simulated by the model in "*nodust*" configurations. (b) Relative difference in precipitation between *dust* and *nodust* simulations for JJAS 2000-2009 and calculated as *(dust –nodust / nodust) X 100*. (c) JJAS 2000-2009 TRMM precipitation. (d) Relative difference (bias) between *nodust* and TRMM precipitations for observed precipitation level > 0.2 mm/day. (e-f) Same than (c-d) for the PERSIANN data set. (g-h) Same than (c-d) for the APHRODITE data sets, but calculated for JJAS 2000-2007 only. All modeling results represent a 3 member's ensemble mean.

Figure 7. JJAS 2000-2009 AOD seen from the (a) MISR sensor and (b) as simulated by RegCM "*dust*" simulation for the full CORDEX-India domain. JJAS composite averages are built form monthly observations and model outputs. Regions of missing observations are screened out from the model averages. (c, d) Same as (a, b) but using the ~~for the~~ SeaWIFS AOD observations. All modeling results represent a 3 member's ensemble mean.

Figure 8. Simulated monthly AOD vs AERONET measured monthly AOD for the period of 2000-2009. Blue dots represents the solar Village Station (46.40E, 24.90N), red dot represents the Karachi station (67.03E, 24.87N), green dots represents Kuwait A~~a~~irport station (47.98E, 29.22N) and black dots the Meizera station (53.8E, 23.15N).

Figure 9. (a) comparison between simulated and AERONET monthly AOD (see text) for Solar Village station. (b) Comparison of simulated and measured aerosol normalized volume size distribution averaged for JJAS 2009 over Solar Village. For comparison, the AERONET distribution (green dotted line) is re-binned to match model size bins (red lines). Blue lines show the corresponding simulated distribution. (c) Same than (a) for Karachi station. (d) Same than (b) for Karachi station.

Figure 10. (a) JJAS 2000-2009 Dust aerosol surface radiative forcing diagnostic. (b) JJAS 2000-2009 Dust top of atmosphere radiative forcing diagnostic. (c) and (d) Corresponding surface radiative forcing efficiencies.(e) JJAS 2000-2009 2 m temperature difference between *dust* and *nodust* simulations. (f) 850 hpa radiative heating rate difference between *dust* and *nodust* simulations. All modeling results represent a 3 member's ensemble mean.

Figure 11. Dust impact on the mean monsoon dynamic and precipitations over the period JJAS 2000-2009. (a) 850 hpa geopotential heights (GPH) and monsoon circulation dust induced anomalies calculated as the GPH difference between *dust* and *nodust* simulations. (b) Dust induced precipitation anomaly. The dotted region defines statistically significant results at the 95 % confidence level. All modeling results represent a 3 member's ensemble mean.

Figure 12. Impact of the Indo-Pakistanese 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.

Figures.

Figure 1.

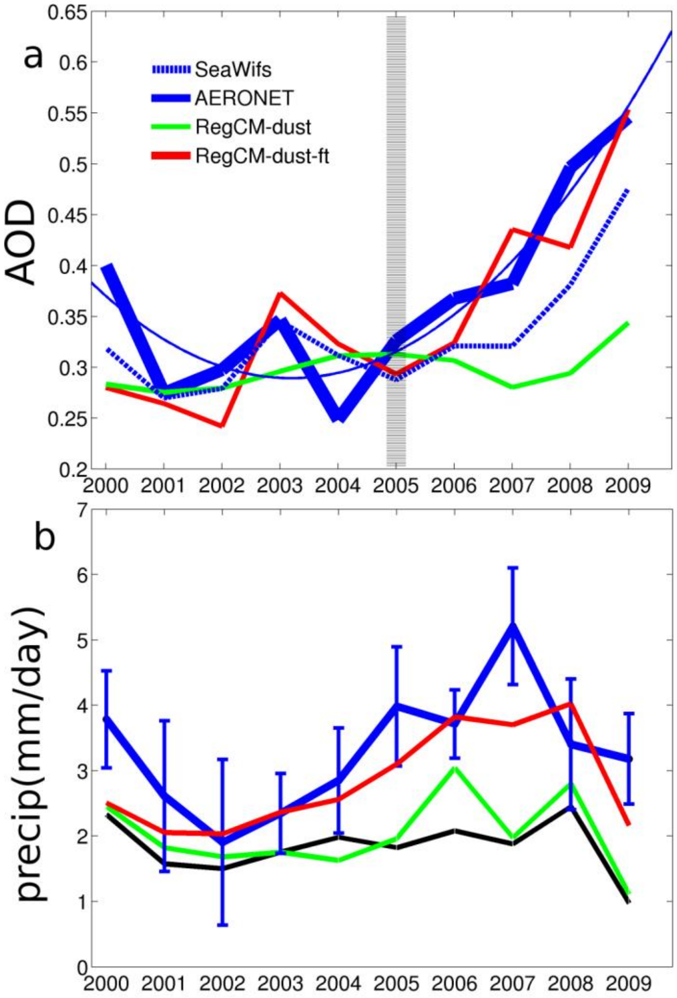


Figure 2.

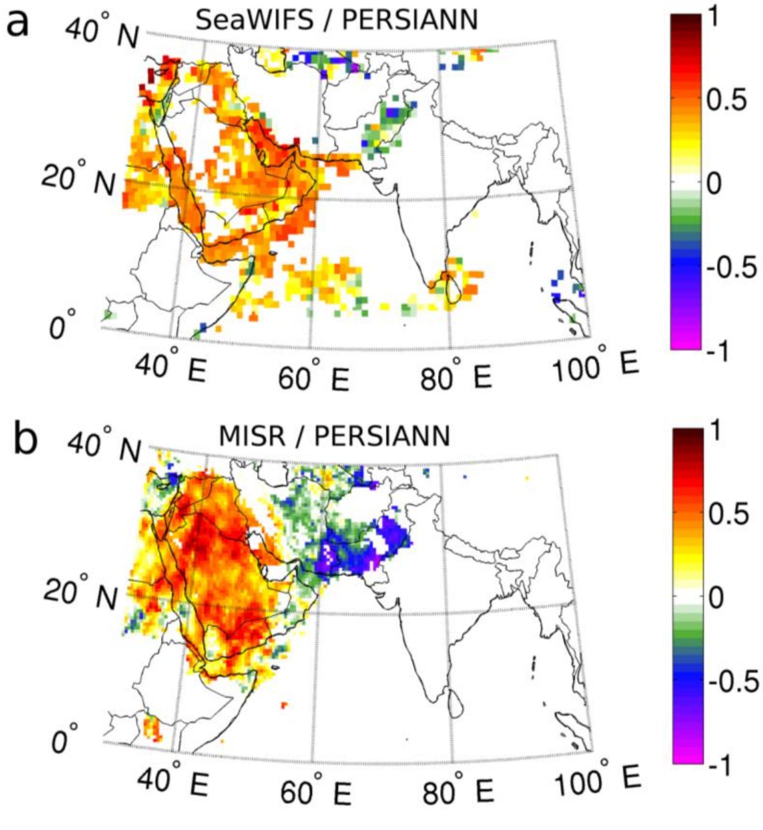

a
SeaWIFS / PERSIANN
40° N
20° N
0°
40° E
60° E
80° E
100° E
1
0.5
0
-0.5
-1
b
MISR / PERSIANN
40° N
20° N
0°
40° E
60° E
80° E
100° E
1
0.5
0
-0.5
-1

Figure 3.

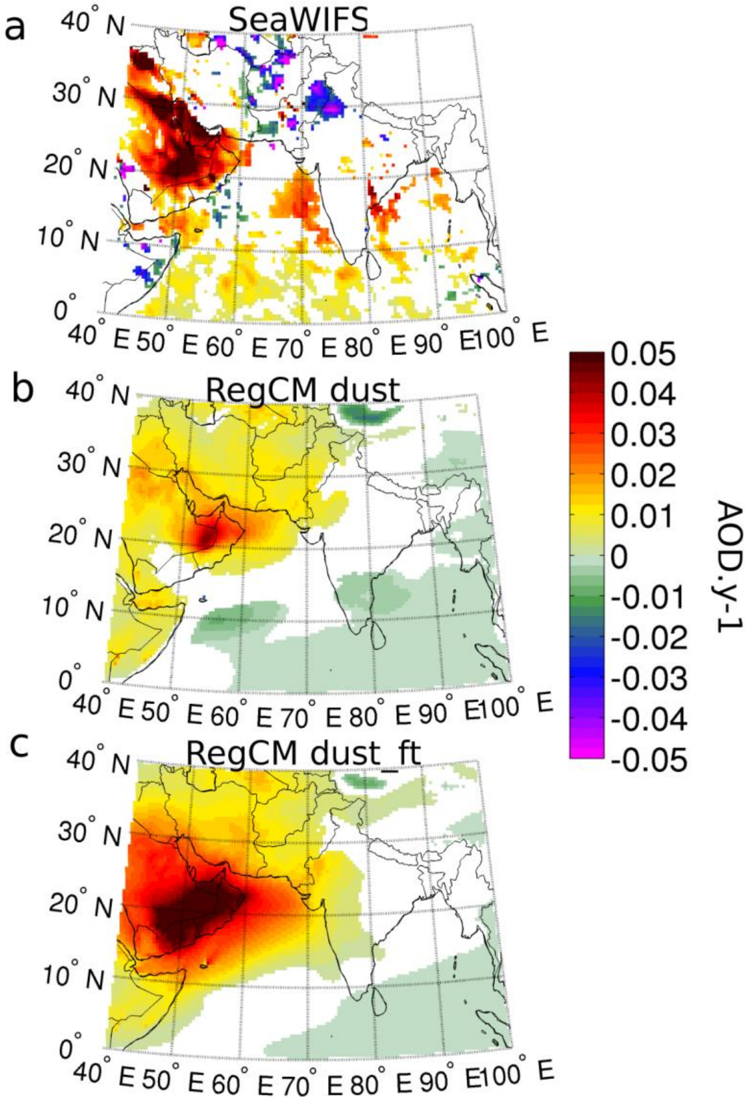

a
SeaWIFS
b
RegCM dust
c
RegCM dust_ft
40° N
30° N
20° N
10° N
0°
40° E 50° E 60° E 70° E 80° E 90° E 100° E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
AOD.y-1

Figure 4.

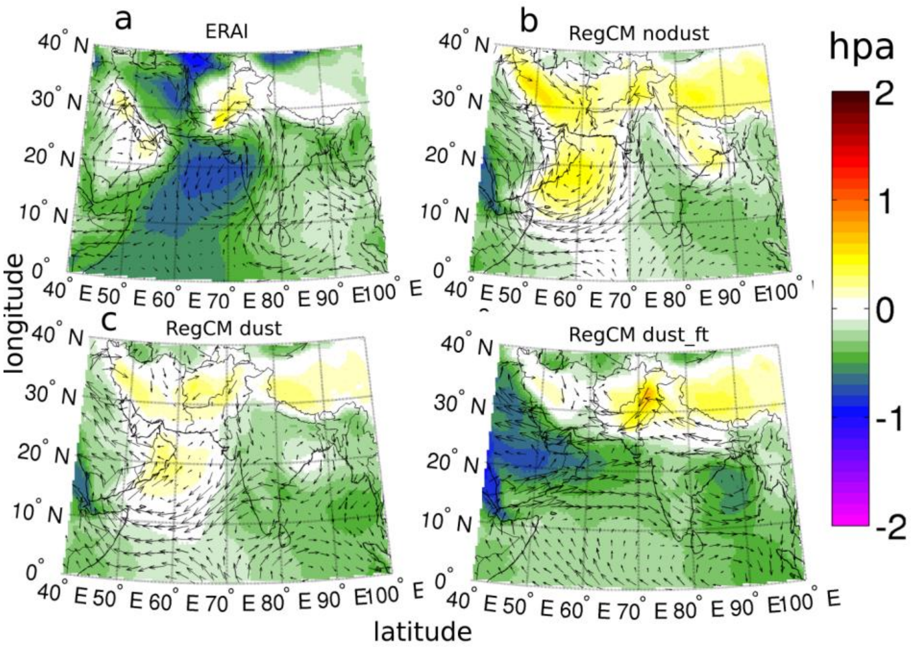
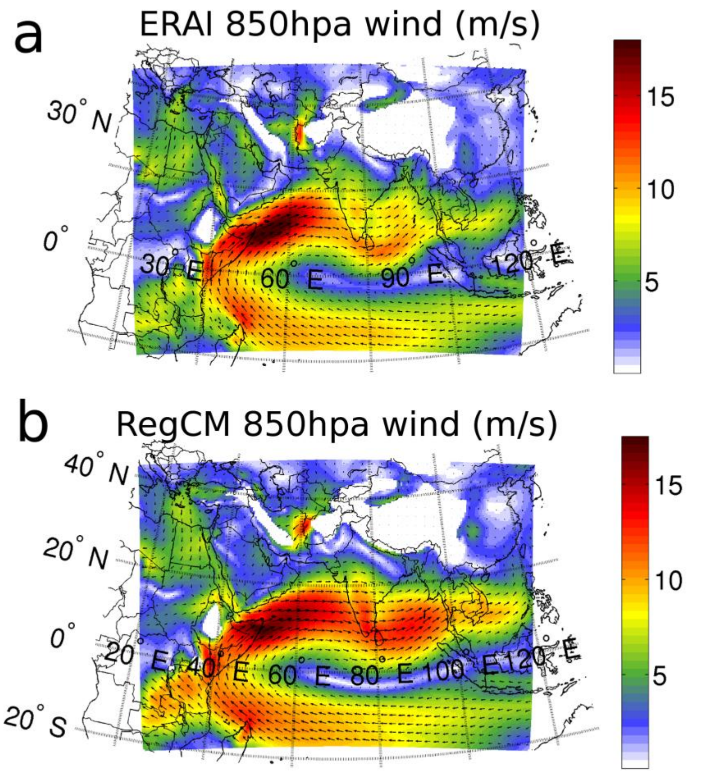

a
ERAI
b
RegCM nodust
c
RegCM dust
RegCM dust_ft
hpa
2
1
0
-1
-2
40° N
30° N
20° N
10° N
0°
40° E 50° E 60° E 70° E 80° E 90° E100° E
longitude
latitude

Figure 5.


a
ERAI 850hpa wind (m/s)
30° N
0°
30° E
60° E
90° E
120° E
15
10
5
b
RegCM 850hpa wind (m/s)
40° N
20° N
0°
20° S
20° E
40° E
60° E
80° E
100° E
120° E
15
10
5

5

Figure 6.

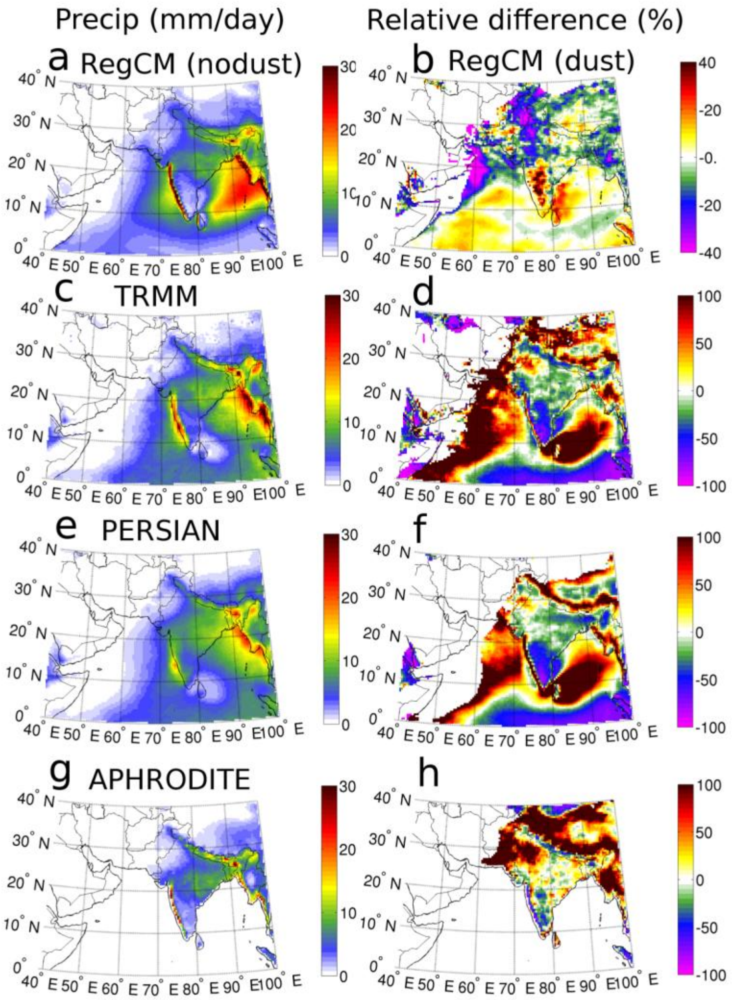

Precip (mm/day)
Relative difference (%)
a RegCM (nodust)
b RegCM (dust)
c TRMM
d
e PERSIAN
f
g APHRODITE
h
40° N
30° N
20° N
10° N
0°
40° E 50° E 60° E 70° E 80° E 90° E100° E
0
10
20
30
40
-20
-0.
-20
-40
100
50
0
-50
-100

Figure 7.

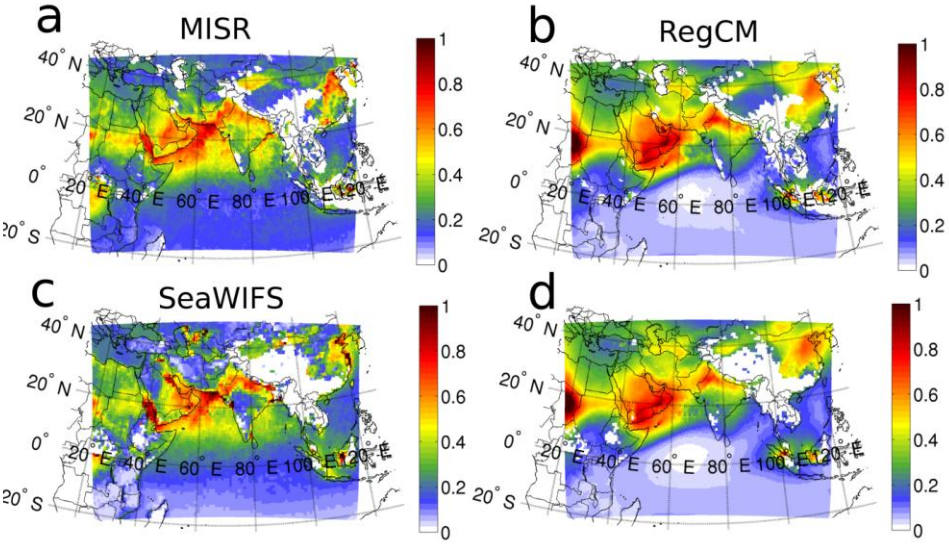

a
MISR
b
RegCM
c
SeaWIFS
d
40° N
20° N
0°
20° S
20° E
40° E
60° E
80° E
100° E
120° E
0
0.2
0.4
0.6
0.8
1

Figure 8

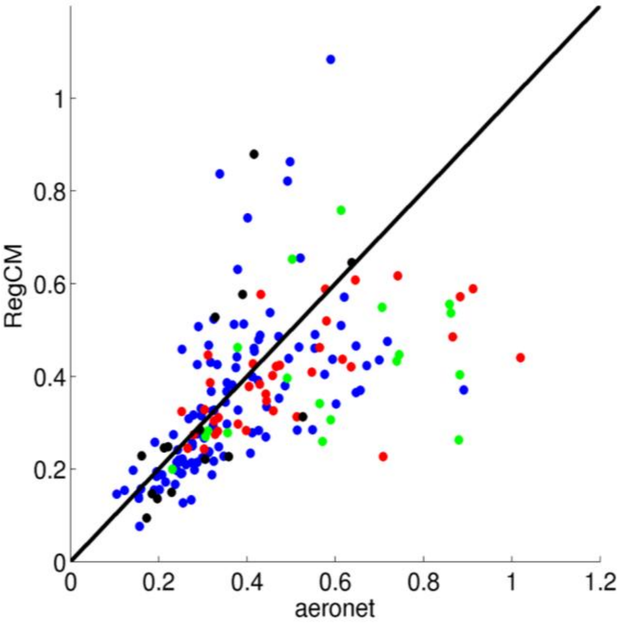


Figure 9.

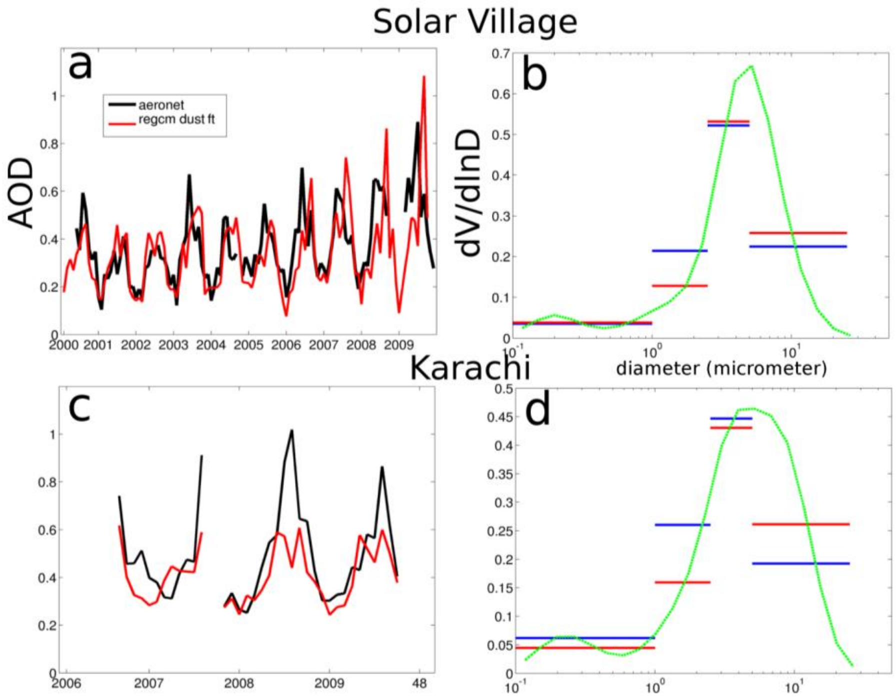

Solar Village
a
aeronet
regcm dust ft
AOD
0
0.2
0.4
0.6
0.8
1
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
b
dV/dlnD
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^{-1}
10^{0}
10^{1}
diameter (micrometer)
Karachi
c
0
0.2
0.4
0.6
0.8
1
2006
2007
2008
2009
48
d
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
10^{-1}
10^{0}
10^{1}

Figure 10.

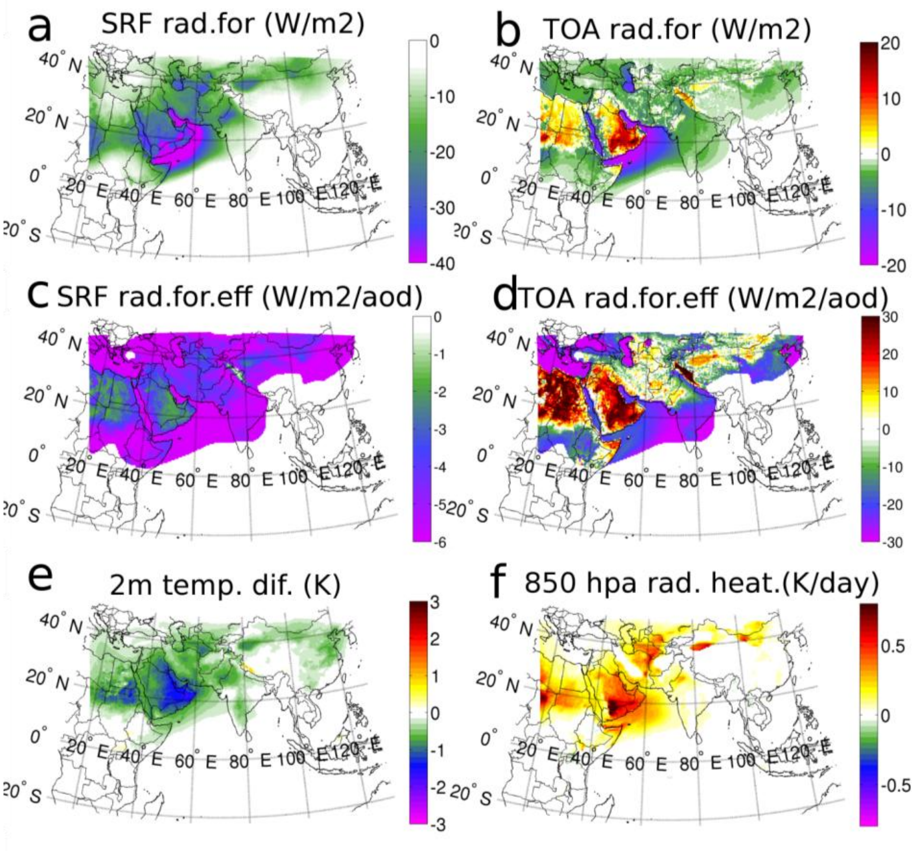

a SRF rad.for (W/m2)
b TOA rad.for (W/m2)
c SRF rad.for.eff (W/m2/aod)
d TOA rad.for.eff (W/m2/aod)
e 2m temp. dif. (K)
f 850 hpa rad. heat.(K/day)
40° N
20° N
0°
20° S
20° E
40° E
60° E
80° E
100° E
120° E
0
-10
-20
-30
-40
20
10
0
-10
-20
0
-1
-2
-3
-4
-5
-6
30
20
10
0
-10
-20
-30
3
2
1
0
-1
-2
-3
0.5
0
-0.5

Figure 11.

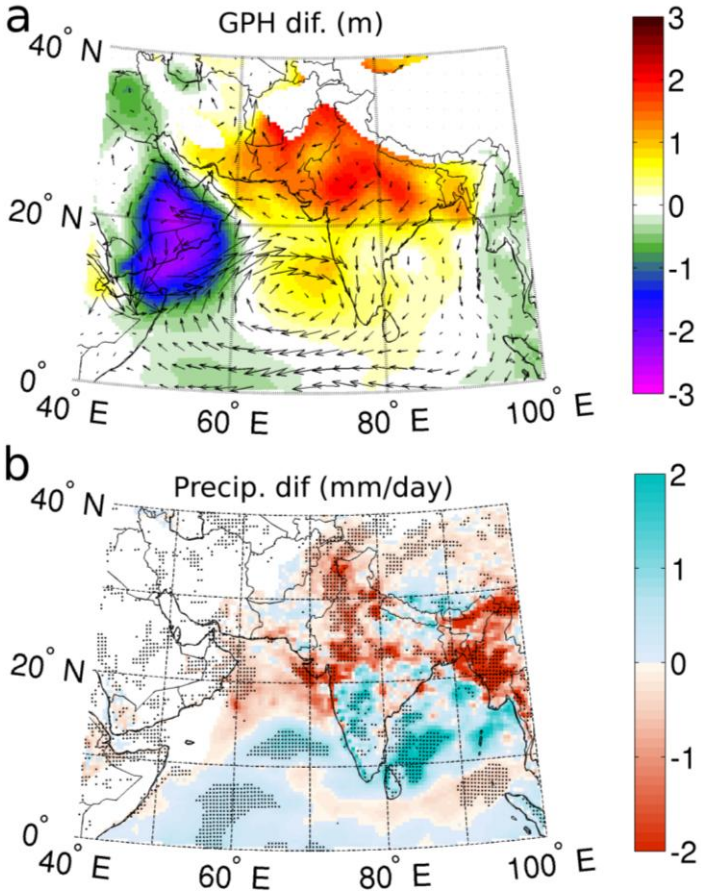
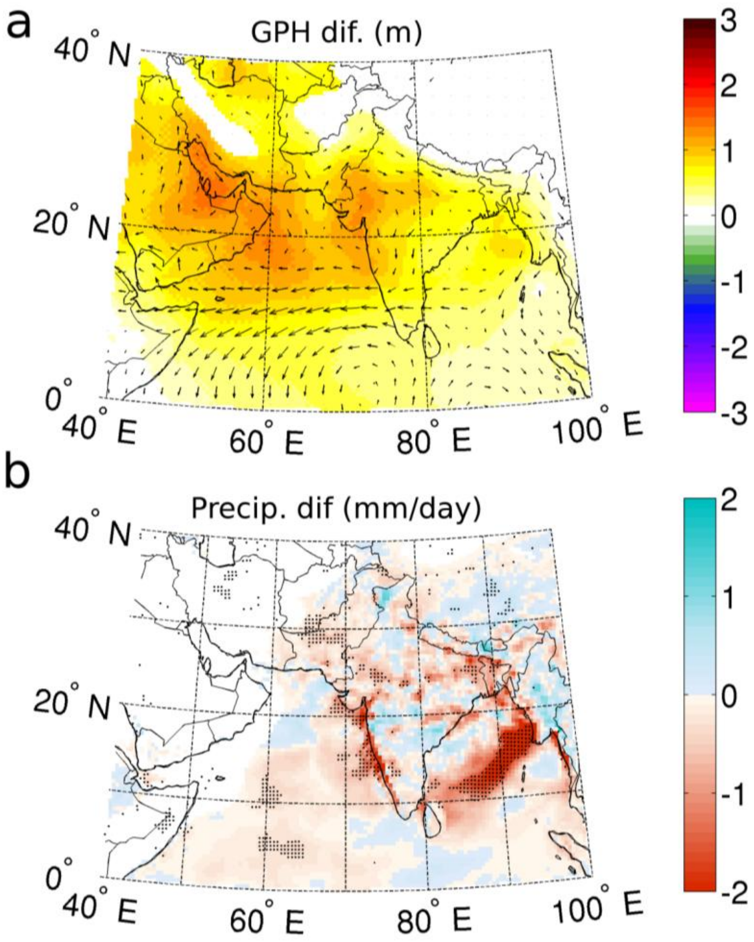

a
GPH dif. (m)
40° N
20° N
0°
40° E
60° E
80° E
100° E
3
2
1
0
-1
-2
-3
b
Precip. dif (mm/day)
40° N
20° N
0°
40° E
60° E
80° E
100° E
2
1
0
-1
-2

Figure 12.


a
GPH dif. (m)
40° N
20° N
0°
40° E
60° E
80° E
100° E
3
2
1
0
-1
-2
-3
b
Precip. dif (mm/day)
40° N
20° N
0°
40° E
60° E
80° E
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2
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-2

~~Figure 7.~~

~~Figure 8.~~