We thank Dr. Perez Garcia-Pando, Dr. Stephen Nesbitt, and one anonymous referee for their valuable comments and constructive suggestions on the manuscript. Below, we explain how the comments and suggestions are addressed and make note of the revision we made in the manuscript.

## Dr. Perez Garcia-Pando

***Do the simulations represent a "free" climate simulation? It is not clear whether the model is re-initialized every few days with the reanalysis or not. If the model is reinitialized every few days, it is not surprising that the circulation simulated is similar to the reanalysis on the seasonal scale. The dust radiative effects would probably differ depending on the inclusion of re-initialization due to changes in the circulation and slower adjustment processes. It would be important that the authors clarify this aspect in the text.***

We thank Dr. Perez Garcia-Pando for his short comment on the manuscript.

The simulations in our study are “free” runs (i.e., the simulations were driven by lateral boundary conditions continuously without re-initialization every few days). The simulations were initialized on April 10 and conducted as continuous runs for Apr. 10-Aug. 31 every year from 1995-2009. We clarified this in the model description section: “The simulation of each year runs continuously for April 10th-August 31st. Only the results from June 1st to August 31st each year (referred as the NAM season hereafter) are used in the analysis to minimize the impact from the chemical and land surface initial conditions.”

## Dr. Stephen Nesbitt

***General comments:***

***This paper describes model-simulated effects of dust on the North American Monsoon circulation and precipitation. The paper shows that model represents at least the long term mean aerosol conditions are well represented in Arizona, and the model overall represents the conditions during the active phase of the NAM well. The model indicates that there are important changes in the circulation and moisture fluxes and changes the surface and TOA radiation balance that influence the precipitation distribution. The paper overall is sound in my opinion, however I do have some suggestions for minor revision, further explanation, and a bit of clarifying analysis that are detailed below.***

We thank the reviewer for a detailed review. Both text and figures are revised as the reviewer suggested.

***Specific comments:***

- ***1. 31737, L27: I suggest using a more technical term rather than "stacked up". Also, in describing the NAM results (and Fig. 1), it seems that the highest dust concentrations are in AZNM mountains and the eastern side of the Mexican plateau (not on the western side), which seems to contradict the abstract.***

We change the “stacked up” to “accumulated”.

Figure 1, 2, and 5 all show the maximum dust concentrations over the deserts that are on the western side of the Mexican plateau. Therefore, it’s consistent with the description in the abstract.

- ***2. 31739, L2: Please specify which version of WRF-Chem you are using.***

The v3.2.1 of WRF-Chem is used in this study. It’s clarified in the model description section.

- ***3. 31740, L 15-20: It should probably be made more clear that the second indirect effect of aerosol on clouds and precipitation (effectively decreasing effective radius with increasing aerosol) are included (is that correct?), including aerosol***

***scavenging, but the radiative effects (i.e. changes on decreased effective radius on cloud albedo) are not included. In this way, precipitation efficiency changes with changes in AOD are represented. Have you tried a run where all indirect effects are turned off? This would isolate the role of the tropospheric heating versus changes due to precipitation efficiency.***

In fact, both 1st (changes in cloud albedo due to changes in cloud drop effective radius) and 2nd (changes in precipitation efficiency and cloud lifetime due to changes in cloud microphysics) indirect effects for stratiform (large-scale) clouds are simulated in this study. In our simulations, dust mainly concentrates near the source region, where there are very few clouds (especially precipitating clouds), so dust concentrations are very low over the NAM precipitation region. In addition, the simulation (at 36 km horizontal resolution) in this study shows that >90% of total precipitation comes from convective cloud. However, the convective cloud parameterization doesn't include aerosol-cloud microphysics interaction in current version of WRF-Chem (note that most climate models have not yet included aerosol-cloud interactions in convective cloud parameterizations). Therefore, although the episodic intrusions of dust to the NAM precipitation region may cause changes of cloud and precipitation through indirect effects, their long-term climatological impact may not be significant in our simulations, particularly for the current version of WRF-Chem that doesn't treat dust effect by acting as ice nuclei (IN). The overall dust effects are dominated by its direct (heating) effect.

It's clarified in the model description section "Although aerosol activation to cloud droplet (Cloud Condensation Nuclei (CCN) effect) is included in the cloud microphysical parameterization of stratiform (large-scale) clouds to account for cloud chemistry and aerosol wet deposition [Gustafson et al., 2007], dust 1st and 2nd indirect effects on the NAM system are not investigated in this study because the simulated dust coincides minimally with the NAM precipitation region. In addition, dust effect by acting as ice nuclei (IN) is not treated in the current version of WRF-Chem." And in the summary section "Last, dust indirect effects on convective cloud and precipitation are not represented in the current convective parameterization, but convective precipitation dominates the total precipitation during the NAM season (generating over 90% of precipitation in the simulations). In addition, the dust aerosol cannot be activated as ice nuclei (IN) to influence clouds in the Morrison microphysics scheme in this study. Despite the low occurrence of dust over the NAM cloud/precipitation region, episodic intrusions of dust to the CORE region due to anomalous transport could result in aerosol indirect effects that deserve further study in the future."

We note that it is hard to isolate the direct and indirect effects of dust by turning off the indirect effects, because the indirect effect is tightly coupled with the cloud chemistry and wet scavenging in WRF-Chem. The shut down of indirect effects will also turn off the cloud chemistry and wet scavenging for aerosols.

- ***4. 31743, L6: should be "mostly located in Arizona, Fig. 1".***

Corrected.

- ***5. 31744: Can these and subsequent figures be zoomed in over the NAM region? I think it is unnecessary to show the eastern US and more detail could be shown.***

Now all the figures of spatial distributions are zoomed in over the NAM region, except the Figure 1 shows the NAM region corresponding to the simulation domain.

- ***6. 31744: L10: It seems as though the model tends to underestimate the southerly flow in Arizona from the Gulf of California relative to NARR. However, the NARR tends to overestimate the Gulf of California LLJ (Mo and Berbery 2004).***

It is added in the discussion about Figure 2 "Overall, the model simulated wind circulation is consistent with the reanalysis data, although the model tends to simulate weaker southerly flows in Arizona from the Gulf of California compared to the reanalysis data. However, Mo and Berbery [2004] found that the NARR reanalysis overestimates the Gulf of California low-level jets during the NAM season."

- ***7. 31744: L15-29: It is encouraging to see that the model appears to simulate the seasonal mean AOD correctly, however, it would be even more encouraging to see the daily statistics compared in a more rigorous way (with IMPROVE and AERONET). Averaging the monsoon season together as presented in Fig 3 does not meaningfully relate variability because all outliers are averaged away, and the***

***monsoon onset and withdrawal dates vary so much for the NAM.***

Now following the reviewer comment, we add Figure 4 for daily AOD from the measurements of AERONET, MODIS, and MISR and simulations by WRF-Chem at the AERONET site Maricopa and the corresponding discussion “The simulated AOD near the dust source region is also evaluated with the AERONET, MODIS, and MISR measurements at the AERONET site Maricopa (Figure 4). In general, the model captures the AERONET measured AOD, although the simulated AOD has smaller variation compared to the AERONET measurements, which may be due to uncertainties of local emission sources during the simulations. The model simulates climatological summer-mean AOD of 0.11 at site Maricopa, which is comparable to the AERONET measured value of 0.13 and the MISR retrieved value of 0.18. MODIS retrieved a much higher value of 0.33. Compared to the AOD value of 0.07 from the sensitivity model simulations without dust emissions, the dust contributes ~45% of AOD at the site Maricopa.”

- ***8. 31746, L8: Also see Nesbitt et al. (2008, JHM), Gochis et al. (2009, Atmosphera) for comparisons of remotely sensed precipitation estimates in the NAM.***

References are added.

- ***9. 31747, L10: Also see Schiffer and Nesbitt (2012, J. Clim., early release) for a discussion of the moisture fluxes during the NAM. This includes discussion as to the southerly vs. easterly fluxes as discussed later in the paper.***

The discussion of moisture fluxes is added together with a new figure (Figure 7). Please refer to our response to comment #14 below.

- ***10. 31748, L8: You should probably point out that the changes over the core region were not statistically significant.***

We add in section 4.2.2 “The dust-induced precipitation over the CORE region is not statistical significant.”

- ***11. 31748, L18: Dust can also act as CCN.***

We add the discussion in section 4.2.2 “Although the model simulates the dust CCN effect on stratiform (large-scale) clouds, there is no treatment of dust as ice nuclei (IN). In addition, dust indirect effects on convective cloud and precipitation are not represented in the current convective parameterization, while convective clouds generate over 90% of precipitation during the NAM season in the simulations. Therefore, dust indirect effect is also limited over the three sub-regions in our simulations.”

- ***12. 31748, 23: Please revise to "As in Fig. 7, ..."***

Corrected.

- ***13. 31751, L10: There are no results on the diurnal cycle presented in the paper, can you refer to a figure?***

The dust-induced change of diurnal amplitude and phase of NAM precipitation is negligible and hence not shown. We add a discussion in section 4.2.2 “The dust-induced change of diurnal cycle of NAM precipitation over the three regions is also investigated. There is no significant dust-induced change of diurnal amplitude and phase of NAM precipitation (not shown), which is related to the low dust concentration and therefore negligible impact on atmospheric stability over the precipitation region.”

- ***14. General (minor) comment: It would be useful to see some more plan view diagnostics, like how the structure of the monsoon high, position of the low level jets, and moisture convergence are changed between the WRF-Chem runs with and without dust forcing. The vertical cross sections are interesting, but do not relate how the monsoon structures might change (easterly vs. southerly moisture fluxes, etc.). Perhaps a topic for a future study. In this way, the changes could be related to known meteorological modulators of NAM precipitaiton (e.g., Higgins 2004, Schiffer and Nesbitt 2012, etc.).***

We added Figure 7 and 11 to show WRF-Chem simulated distribution of sea level pressure (SLP) and integrated moisture fluxes, and their dust-induced changes over the NAM region, respectively. The corresponding discussion is added in section 4 “The NAM circulation is driven by pressure gradient induced by the thermal contrast between land and ocean. Figure 7 shows the monthly mean spatial distribution of sea level pressure (SLP) anomalies and integrated moisture fluxes from the WRF-Chem simulations over the NAM region. The SLP anomalies are calculated by subtracting the domain-averaged value from the SLP at each grid. The Sonoran low-pressure center due to surface heating over the desert is well simulated by the model. The simulation also captured the moisture transport from the Gulf of California towards AZ particularly during July and August. During the two summer months, our simulation showed that moisture transport from the Gulf of California originates from southeasterly flow from the Gulf of Mexico that crosses over the Sierra Madre Occidental (SMO) before turning more southerly over the Gulf of California and directing moisture to AZ. This suggests that the Gulf of Mexico and the land east of the SMO also provide important moisture sources for the NAM precipitation (Adam and Comrie 1997). The importance of the east-to-west cross barrier moisture flux over the SMO has been noted by Higgins et al. (2004) and Schiffer and Nesbitt (2012).” and “Figure 11 shows the spatial distributions of monthly mean dust-induced change of SLP and integrated moisture fluxes from the WRF-Chem simulations in June, July, and August averaged for 1995-2009 over the NAM region. Over the deserts, dust leads to a small surface cooling due to reduction of radiation (Figure 5). The surface cooling is too small to induce changes in SLP during July, but the increase in SLP is more notable in August. The diabatic heating resulted from dust leads to an anomalous cyclonic circulation centering over the desert region, which transport more moist air from the Pacific Ocean and Gulf of California towards the SMO and increases the precipitation in northwestern Mexico. This anomalous westerly to southwesterly moisture flux counters the cross barrier moisture flux over the SMO shown in Figure 7, leading to moisture flux convergence and enhanced precipitation. The anomalous cyclonic circulation also enhances cloud and precipitation in the AZNM and TXNM regions in July. The reduced SLP over AZNM and TXNM generates a larger anomalous cyclonic circulation in August that continues to bring in moist air to the SMO and TXNM regions.”

## Anonymous Referee #1

***General comments:***

- ***The paper could be accepted by ACP after some minor modifications:***
  ***The radiative effects of dust aerosols are determined by the dust refractive indices, which should be regions, dust sizes, and wavelengths dependent. The authors used the refractive index the same as Saharan dust (1.53 + 0.003i), so the concluded results may be similar to Saharan dust. The authors should state this issue more clearly or use a different refractive index (such as the one from Asian deserts) to see any differences.***

We agree with the reviewer that the dust refractive indices (mainly the imaginary part) are highly dependent on the mineral components of dust, which will affect the dust absorptivity. Measurements of the Southwest US dust optical properties are required to constrain the dust absorption in this study. Following the reviewer comment, we stated this issue more clearly in the summary "First, in the absence of measurements of optical properties of dust from the Southwest US deserts, this study uses the same refractive index of dust as our previous studies over West Africa [Zhao et al., 2010 and 2011]. The imaginary part of dust refractive index is uncertain [e.g., Balkanski et al., 2007; McConnell et al., 2010; Zhao et al., 2011] and may change the dust-induced atmospheric diabatic heating, which triggers the NAM circulation and precipitation change. In order to constrain the dust absorption, measurements of the optical properties of the Southwest US dust are required in the future."

- ***Page 31738: "Therefore" should be "However"?***

We change the sentences to "The dust emitted from the Southwest US deserts is less than that emitted from the Saharan desert and the Asian deserts; however the NAM system is also weaker than the monsoon systems over West Africa and Asia. Therefore, dust could still have significant effect on the NAM system."

- ***Model description: Is the 10-m wind related to the stability conditions for the dust source function? Is the dust size distribution lognormal? Is the dust lifting related to the soil moisture? A brief statement at the dust emission scheme will be better.***

Yes, 10-m winds are related to the stability conditions for dust emissions. The size distribution of emitted dust follows the log-normal distribution. The dust emission flux is a function of soil moisture. A brief description of the GOCART dust emission scheme is added in model description section "The GOCART dust emission scheme [Ginoux et al., 2001] was first coupled with MADE/SORGAM in WRF-Chem by Zhao et al. [2010] to investigate the sensitivities in simulating the size distributions and optical properties of Saharan dust to emitted dust size distributions and aerosol size treatments during the dry season (from January to February) of 2006 over West Africa and understand the various radiative forcings of Saharan dust and how they jointly affect the hydrological cycle at a regional scale [Zhao et al., 2011]. As described in Ginoux et al. [2001], the GOCART scheme calculates the dust emission flux *G* as

$$G = CSs_p u_{10m}^2 (u_{10m} - u_t)$$

where *C* is an empirical proportionality constant, *S* is a source function which defines the potential dust source regions and comprises surface factors, such as vegetation and snow cover, $s_p$ is a fraction of each size class of dust in emission, $u_{10m}$ is the horizontal wind speed at 10 m, $u_t$ is the threshold wind velocity below which dust emission does not occur and is a function of particle size, air density, and surface soil moisture. The size distribution of emitted dust is assumed to follow log-normal distribution corresponding to the MADE/SOGAM aerosol model [Zhao et al., 2010]. More details about the coupling of GOCART dust emission scheme with WRF-Chem can be found in Zhao et al. [2010]."