Author Response to Reviewer #4

Please note that we have provided a document containing revised figures and tables, both for the main article and for the supplemental material. In our responses to the reviewers, we will refer to these revised figures and tables, rather than the original.

This paper describes a set of climate model experiments focused on the biomass burning season over southern Africa, to study how biomass burning aerosols affect the hydrologic cycle there. The authors demonstrate that absorbing aerosols, scaled to be as absorbing as indicated by TOMS/AERONET retrievals, stabilize the lower troposphere, enhance convergence of moist air from the Atlantic, and increasing cloud and precipitation in the region. I feel this study could make a worthwhile contribution to the literature on the topic and recommend its publication once the points below are addressed.

We thank the reviewer for their detailed comments on the manuscript and for recommending its publication. We address the reviewers concerns one by one below.

1. The authors should expand the discussion of comparison with other studies. A couple more that could be included are Koren et al., 2004; Miller et al. JGR 2004.

We thank the reviewer for pointing out these relevant papers. Below we make some comparisons to these two papers as the reviewer suggests. We also ask the reviewer to examine our response to Reviewer #3 (second to last point) where we make several additional comparisons to other papers, particularly the paper we very recently discovered in press in the *Journal or Geophysical Research, Tummon et al.* [*Simulation of the direct and semi-direct effects on the southern African region during the biomass burning season, in press, JGR*].

Miller et al. [2004]:

• In their paper, absorbing dust was found to decrease evaporation and precipitation globally but increase rainfall over deserts. Globally, compared to CTRL, MOZEX, HIGHEX, and SSAEX reduce precipitation by -0.05, -0.06, and -0.06 mm d^{-1}, respectively, while WHITE increases global average precipitation by +0.01 mm d^{-1}. Of course, as shown in Figure 5 (revised figures and tables), absorbing aerosols from bb tend to slightly increase precipitation locally in the main biomass burning region of the tropics, where atmospheric conditions are favorable to instability. Compared to CTRL and area-averaged globally, evaporation decreases in MOZEX, HIGHEX, and SSAEX by -0.06 mm d^{-1}; there is a slight increase in global evaporation in WHITE (0.01 mm d^{-1}).

• *Miller et al.* [2004] found that radiative heating within the boundary layer is compensated mainly by a change in the surface sensible heat flux via the ground temperature. We find this too in all of our cases for ASO - sensible heat reductions are larger than latent heat reductions for all experiments (except for the experiment with non-absorbing aerosols in the bb region WHITE).

• *Miller et al.* [2004] also find a larger solar anomaly over the Sahara due to increased cloud cover associated with increased absorbing aerosols that increase upward motion (or decrease subsidence). <u>As we point out in the abstract of the manuscript, cloud increases (decreases) serve to reinforce (counteract) the surface radiative cooling tendency of the aerosol over land for increased absorbing (scattering only) aerosols.</u> The importance of aerosol-cloud interactions that occur solely due to direct and semi-direct effects are highlighted in the recent review article in ACPD by *Koch and del Genio* [ACPD, 10, 7323-7346, 2010, www.atmos-chem-phys-discuss.net/10/7323/1020/]. In this article, the authors outline in detail the disparate results obtained from studies which have examined the semi-direct effect of absorbing aerosols. Different studies, both observationally-based and model-based, have shown that the semi-direct aerosol effect can have a positive (decreased clouds) or negative (increased clouds) effect on the surface energy balance depending on multiple factors such as aerosol optical properties, vertical distribution of aerosols (particularly with regards to their vertical distribution relative to cloud), the underlying stability of the atmosphere in the region (e.g. convergent or divergent region) [*Koch and del Genio,* ACPD, 2010], and large-scale cloud distributions themselves (e.g., *Randles and Ramaswamy*, 2008, in the Asian context).

• *Miller et al.* [2004] (their Figure 19) find increased low-level cloud over the Sahara where they have the strongest dust forcing; we also find increased low-level cloud in our biomass burning region when the bb aerosol are absorbing (i.e. not WHITE, where the opposite occurs).

Koren et al. [2004]

• This paper used observational data from MODIS to assess the impact of bb aerosol in the Amazon. They demonstrate that cumulus cloud cover is reduced due to increased smoke. They argued that the smoke stabilized the boundary layer and thus reduced convective activity and boundary layer cloud formation.

• We did not get the same result; we found that as the amount of absorbing bb increased in southern Africa (e.g. HIGHEX, SSAEX), we had an invigoration of clouds and precipitation, particularly in the tropics where the atmosphere is favorable to instability.

• As *Johnson et al.* [2004] point out, absorbing aerosol over shallow cumulus clouds inhibits cloud development, stabilize the surface layer, and reduce surface evaporation; this may have been the case in the *Koren et al.* [2004] study. However, *Johnson et al.* [2004], using a cloud-resolving model (large-eddy model), also found that clouds could be enhanced (i.e. a negative semi-direct effect) if absorbing aerosols were above the boundary layer (page 9741, first sentence of manuscript).

• *Erlick et al.* [2006] investigated the effect of lowering cloud albedo in the tropics in a single column radiative transfer model. This experiment could be an analog for an aerosol semi-direct effect. They found that increasing absorption within the cloud increased convection, vertical moisture transport, and middle and high clouds. The impact of changed cloud albedo depended on the degree of heating perturbation and the stabilization tendency of the atmosphere (i.e. the dryness of the atmosphere and availability of evaporation of the surface, which itself depends on the amount of incident solar radiation at the surface, itself dependent on the extinction from clouds). Thus, they determined that a complex chain determined the impact of absorptivity, and one has to carefully sift through the conditions for which the study was done (including model characteristics). Thus, both solutions (i.e. reduced or increased stability/clouds could be correct but under different atmospheric and surface conditions, and care has to be taken in the interpretation. Amazon smoke effects on climate could differ from that in Africa.

• Our study may be more similar to *Lau et al.* [2006] and *Randles and Ramaswamy* [2008] where absorbing aerosols enhanced upper level convection and low-level convergence that carried moisture to increase clouds. In effect, anomalous Walker- and Hadley- like circulations form as a result of the aerosol diabatic heating of the atmosphere [e.g. *Lau et al.,* 2009].

• Another observational study, *Brioude et al.* [2009] investigated the effects of bb aerosol over marine stratocumulus off the coast of California in summer using GOES and MODIS data combined with the FLEXPART model. They found that biomass burning aerosols enhanced low-level cloud cover, particularly for high humidity conditions and for decreased lower tropospheric stability conditions.

• The results of these studies and many more indicate that there is clearly no resolution of the impact the aerosol semi-direct effect (i.e. heating by absorbing aerosols) has on clouds and the hydrological cycle. The sign of the semi-direct effect can depend on the AAOD, the vertical distributions of aerosols relative to clouds and the boundary layer, the location where the absorbing aerosols like (e.g. convergent or divergent) region, and other factors that are discussed in detail in the very recent review paper by *Koch and del Genio* [ACPD, 10, 7323-736, 2010, www.atmos-chem-phys-discuss.net/10/7323/2010/].

2. The authors state in several places that the biomass burning aerosols stabilize the atmosphere, however Fig. 4 suggests rather that they destabilize and actually enhance convective activity. This should be clarified.

We attempt to explain this conundrum in the first paragraph of the "Discussion and conclusions" section. If one takes the perspective of a single atmospheric column over land, biomass burning aerosol would, according to the usual view of the semi-direct effect, stabilize the column because aerosol extinction would cool the surface and absorption would heat the atmosphere aloft. As *Johnson et al.* [2004] show, however, if absorbing aerosol are within and above the boundary layer, these aerosols may have a destabilizing effect and cause a negative semi-direct effect (cooling due to increased clouds rather than warming due to decreased clouds); this appears to be the case in our simulations. Additionally, over the ocean, because our SSTs do not respond to the aerosol forcing, we do not obtain column stabilization (this could also occur due to a lagged SST cooling compared to the quicker cooling of the land surface). In our simulations, rising motions induced by aerosol heating draw in low-level air from the Atlantic Ocean. This has the effect of increasing clouds and precipitation over the land mass, particularly in the tropical rain belt. The effect we discuss here is similar in many ways to the recent results of *Lau et al.* [2006] and *Randles and Ramaswamy* [2008], and *Lau et al.* [2009], which examined the effects of south Asian absorbing aerosols and the Saharan dust plume on climate, respectively. This same phenomena was also shown in *Roeckner et al.* [2006], which also, unlike the present study and aforementioned studies, included a fully-coupled ocean model.

3. How are OC and BC independently scaled to match AOD and SSA? Table S2 indicates that BC mass is smaller for SSAEX than for HIGHEX, and OC is larger for SSAEX than for HIGHEX. This seems backward?

Please see the response to Reviewer #2 General Comment #2 where we give a much more detailed description of our method of BC and OC mass adjustment. For HIGHEX, in any given gridbox we are scaling the OC plus BC mass up to mach the "observationally-based" map of AOD (Figure 1 a); we attempt here to keep the ratio of BC/OC the same as in MOZEX so that our single scattering albedo is the same. Note that the realized AOD and SSA in HIGHEX could be different from that of the "observationally-based" maps and MOZEX, respectively, if HIGHEX has different relative humidity from that assumed in solving Equations (1) and (2) (please see details in the response to Reviewer #2 for these equations and assumptions used to solve them). In SSAEX, we both scaled the OC plus BC mass in a given gridbox to match the "observationally-based" map of AOD and changed the BC/OC ratio to match the "observationally-based" map of SSA. Since SSAEX is slightly less absorbing than MOZEX or HIGHEX (SSA is 0.91 for SSAEX compared to 0.9 for the other experiments) it makes sense that it has less absorbing BC and more mostly-scattering OC than these other two experiments.

4. Why do the scaled AODs and SSAs still not match the observations averaged over the region? I also agree with another reviewer that trying an experiment with smaller SSA, e.g. like from Abel et al. or SAFARI estimates would be very instructive.

Please see the detailed response to Reviewer #2 General Comment #2. While we agree with the Reviewer that examining the response of the model to an even more absorptive biomass burning plume could be instructive, we believe that given the results of this experiment, as well as previous modeling efforts (e.g. *Randles and Ramaswamy* [2008] which did consider a regional SSA of 0.85, but over Asia), such an experiment would likely give a response of the same sign as HIGHEX and SSAEX, but with perhaps larger magnitudes. Therefore, we do not feel such an experiment is warranted at this time, and would not necessarily be justified by the data. Both *Haywood et al*. [2003] and *Abel et al.* [2005] suggest that a single scattering albedo of 0.89±0.01 is appropriate for aged-regional biomass burning haze in southern Africa. Also, as *Magi* [2009] points out, it may be more appropriate to model the bb aerosol in southern Africa with the optical properties of regional haze rather than those of fresh fires, given the scales involved in simulating aerosols in climate models.

5. The changes to model AOD and SSA were applied only to the aerosols below 4km. What portion of the original model aerosols is above 4km? Also TOMS, OMI is most sensitive to high-altitude aerosol and so is perhaps most applicable to the higher-level aerosol. So it seems inconsistent to ignore the high-altitude aerosol.

Figure S.1 (revised figures and tables) shows the vertical distribution of BC and OC mixing ratio for MOZEX. The majority of the BC and OC mass is below 600 hPa. The vertical distribution of black carbon from MOZART has been validated against observations by *Koch et al.* [2009]. As noted by *Koch et al.* [2009], most global models do not sufficiently confine BC to lower model levels due to either weak upper-level removal processes or excessive vertical diffusion. As shown by Figure 9 in *Koch et al.* [2009], above about 400-600 hPa, regardless of the location of observation (four Western-hemisphere sites were considered), MOZART overestimates the amount of BC relative to the airborne observations. An important semi-permanent feature in the southern African atmosphere during austral winter is the absolutely stable layer (~500 hPa), which tends to trap bb aerosols [*Tyson et al.,* 1996]. For these reasons, and combined with the observation of *Haywood et al.* [2003] that biomass burning aerosol tended to be well-mixed in the African boundary layer, we only increased BC and OC below approximately 4 km (~600 hPa). Otherwise, we would have exacerbated the positive bias in BC aloft.

6. I am concerned that a totally different response might occur in an experiment with ocean response. Can the authors argue that ocean response would not change the results?

This is an important point to address, as it is a common concern for studies using atmosphere-only GCMs. Regarding this we'd like to make a number of points:

• First, we do not believe that in this particular study and in this particular region, that inclusion of an ocean response would change the results, at least not qualitatively. We have several reasons for this:

  a) <u>Other studies that have included the effects of ocean response see similar changes</u>:
     - As mentioned in the text and in #2 above, *Roeckner et al.* [2006] used the ECHAM5 model coupled to the Max Planck Institute ocean model (MPI-OM). They found that increased absorbing aerosols over southern Africa decreased shortwave surface radiation and increased atmospheric radiation. These changes led to decreases in surface air temperature over land, increased precipitation and soil moisture, and anomalous circulation from the Atlantic into southern Africa at 850 hPa. All of these findings are consistent with the present study.

- *Lau et al.* [2009] use the NASA fvGCM coupled to a mixed layer ocean model to explore the impact of absorbing Saharan dust on the water cycle. They find that the Saharan dust layer increases upward motion in the eastern Atlantic and spurs anomalous low-level westerlies that increase moisture transport from the central and eastern Atlantic and produce rainfall over the oceanic region off of West Africa and further inland, while suppressing rainfall over the central Atlantic and further west. Their results are similar to *Miller et al.* [2004]. The increased clouds and convection that occur act as a positive feedback for the cooling effects of aerosol on the surface. This study does point out that the interactive SSTs damp the effects of the atmospheric feedback relative to an atmosphere-only, but that if the extent and absorptivity of the aerosol layer is sufficient, the damping does not outweigh the aerosol effects. In their study, *Lau et al*. [2009] consider SSA in the range of 0.8-0.94 and AOD from their dust layer is on the order of 0.4. These optical properties could be considered similar to our cases HIGHEX and SSAEX. We therefore suspect that the Elevated Heat Pump (EHP) effect in our simulations (particularly HIGHEX and SSAEX) would be strong enough to overcome any damping effects of cooler SSTs over the Atlantic.

b) The effect of the real aerosols is already included in the observed SSTs. The control simulation itself is not completely isolated from biomass burning effects, because the prescribed, observed SSTs already have been affected by the presence of bb aerosols in the real atmosphere.

c) When we apply observed SSTs as the lower boundary condition, we remove the uncertainty in the lower-boundary forcing that may be derived from use of a mixed-layer ocean or fully coupled ocean model. The accuracy of the sea state can be an important factor in driving convection and cloud distributions. In using a mixed-layer or fully coupled ocean model, we would need to first verify that the lower boundary was being simulated accurately - typically a difficult problem and beyond the scope of the present study. There is a balance that has to be kept in perspective. Prescribed SSTs based on observations offer the right lower boundary conditions but the atmospheric interactions are unable to make the SSTs respond and an important feedback is missed. On the other hand, not having the correct atmosphere-ocean balance in terms of surface heat and moisture fluxes would skew the changes. Further, would a full ocean model be expected to yield a more complete result? Probably yes, so that even a mixed-layer model may not suffice for a comprehensive examination of the problem. However, as has happened with investigations of several other phenomena in the past, the use of atmosphere only models that are realistic in part because of being driven by the observed SSTs offer a useful first platform from which we may explore the impact of forcing agents on climate. This is expandable to do mixed-layer and then full ocean studies using the same atmospheric model. Though these extensions are beyond the scope of the present study, we underscore the Reviewer's reasoning that investigations in all modes are needed. In fact, a question that again unfortunately is outside the scope of the current study is why our results are consistent with the *Roeckner et al.* [2006] result, which does use a fully-coupled ocean-atmosphere model. As a noteworthy point, we add that studies with greenhouse gas (e.g., CO_2) effects on the present-day climate graduated from atmosphere-only to coupled oceans in an evolving manner.

d) Atmospheric-only simulations remain useful tools and have been successfully utilized to gain much understanding of the climate. We list a few examples here:
   - *Liu et al.* [2002] used atmospheric general circulation models to produced realistic representations of the present day Sahara, to examine the impact of an increase in

atmospheric CO_2 of on percent per year for 80 years, and found that the Sahara shifts northwards in a number of models (defined by the Sahelian precipitation).

- *Held and Soden* [2006] used the GFDL AGCM and found that the Sahel precipitation changes were comparable to observed decreases; however, this feature was not reproducible to the same degree with a coupled model.

e) We use a well-acclaimed atmosphere process model that offers a basis from which to explore the direct and semi-direct of aerosols in the biomass burning region of southern Africa before progressing to more complicated models that can include the oceanic-atmospheric interaction. Yet it remains very interesting that *Roeckner et al.* [2006], which used a fully coupled ocean-atmosphere model, did not obtain qualitatively different results from our atmospheric-only model!

7. I suggest integrating the supplemental material into the main manuscript.

We agree that some of the supplemental material, specifically the horizontal depictions of OC and BC mass and the information in Table S.1 could find a place in the main manuscript (we now introduce these in the revised figures and tables as Figure 2 and part of Table 2). We feel that the supplemental material presented in Figures S.2-S.4 (revised figures and tables) could complicate the manuscript because a lengthy discussion of the observational data would be required. It is also difficult to draw anything other than qualitative comparisons with the observational data in these figures because of differences in data resolution, both temporal and spatial. We could, however, bring attention to the fact that the addition of aerosols helps to reduce the positive model bias in surface air temperature in the main biomass burning region compared to CRU, and that this bias is best reduced in HIGHEX and SSAEX where we have introduced close-to-observed AODs. Also, though the changes in the hydrologic cycle are small compared to model biases, the sign of the change in these parameters in the experiments HIGHEX and SSAEX are in the right sense to reduce model biases. We could also include the plots of the CTRL experiment climate as a reference for the other plots which show changes in climate parameters relative to this case (e.g. Figure S.2 a-d only in the revised figures and tables).

8. In the supplemental comparison of model with climate (T, precip, cloud, etc) I suggest comparing results from one of the more realistic model simulations like SSAEX rather than CTRL. Although maybe the various simulations would not be distinct from CTRL on these scales. Please add some discussion of this comparison of model and observed climate.

As stated above, it is also difficult to draw anything other than qualitative comparisons with the observational data in these figures because of differences in data resolution, both temporal and spatial. As we point out in #7, the addition of aerosols helps to reduce the positive model bias in surface air temperature in the main biomass burning region compared to CRU, and that this bias is best reduced in HIGHEX and SSAEX where we have introduced close-to-observed AODs. For the other observations (precipitation, low-level clouds, WVP), the changes for all experiments are small compared to the model biases, and thus do not make for interesting figures. However, we do note that inclusion of absorbing aerosols (MOZEX, and more so for HIGHEX and SSAEX) have *sign* changes in these quantities that help to reduce the bias relative to the observations. We still caveat that these comparisons are very coarse and should remain qualitative.

9. Supplemental Table 1: I suggest showing the model and TOMS/IMO AOD values in the table.
This data is already presented in Figure 3 for four of the stations. We add two columns to Table S.1 to indicate the percentage of the number of days in ASO from *EP*-TOMS or AERONET used in constructing Figure 1a.