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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Do biomass burning aerosols intensify drought in equatorial Asia during El Niño?" *by* M. G. Tosca et al.

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Reviewer #1 (Anonymous):

We thank this anonymous reviewer for a carefully constructed set of detailed suggestions. We modified the text of the manuscript to address almost all of the reviewer's suggestions. These suggestions have considerably strengthened the manuscript.

Detailed Response to Reviewer #1 Comments

This paper discusses the impacts of Indonesian biomass burning on the climate of equatorial Asia. The study uses the CAM atmospheric GCM with a slab ocean to investigate the response of the model to biomass burning aerosol by considering a high biomass burning El Niño year (1997) to a low biomass burning La Niña year (2000). The authors find that their simulated

biomass burning aerosols tend to decrease surface temperatures and reduce convection and precipitation over the region. They support their findings by analyzing relationships between satellite observations of precipitation and aerosol optical depth.

This study represents an additional important contribution to the growing body of literature on the affects of absorbing aerosols on the Asian region. It is very well written, and should be considered for publication in ACP after some mostly minor revisions.

Specific Comments:

Abstract line 14: Is the 10% decrease you refer to the effect of high-low fire years? You should make this clear.

We find a 10% decrease in mean precipitation between the high fire and low fire simulations. To better clarify this a sentence has been added to the abstract:

'We assessed the radiative and climate effects of anthropogenic fire by analyzing the differences between the high and low fire simulations.'

Introduction, Page 23322, Paragraph 2: You should make it clear that "smoke" aerosols contain OC+BC.

We clarify the use of the word smoke by replacing 'aerosols' with 'smoke' in the first sentence of the above-mentioned paragraph:

'Heil et al. (2005) estimate that the amount of smoke, defined as the sum of black carbon (BC) and organic carbon (OC) aerosol components, released from tropical forest and peatland fires in Indonesia during the 1997 El Niño was 12 Tg yr^{-1}.'

Introduction, Page 23323, First paragraph (continued from previous page): You have a good discussion of the literature regarding affects of aerosol absorption over the Asian region; however, you may be omitting some important studies that draw a different conclusion – namely that aerosol absorption may increase precipitation (particularly in Asia [e.g. Lau et al., 2006; Randles and Ramaswamy, 2008]. I think that there is still considerable debate on the response *of regional climates to aerosol absorption, and it is highly dependent on the region and the time of year considered. This point is worth mentioning here, rather than just citing papers that support the conclusions of this paper.*

We have added several sentences to the end of this paragraph to illustrate the state of science more completely:

'In tropical regions dominated by oceans, surface cooling and tropospheric heating often increase atmospheric stability and reduce convection. Numerous empirical studies link sea surface cooling with increased surface pressure and decreased surface convergence (Graham and Barnett, 1987; Hackert and Hastenrath, 1986). Cooler ocean temperatures decrease surface winds, and the combination reduces convection (Raymond, 1995). Direct tropospheric heating combined with surface cooling from smoke reduces latent heat fluxes and can alter the hydrologic cycle (Rosenfeld, 1999; Liepert et al., 2004; Ramanathan et al., 2001b). Tropospheric heating from BC over the Indian subcontinent also alters the monsoon circulation, with subsequent impacts on precipitation and the hydrologic cycle (Chung and Ramanathan, 2002; Chung et al., 2002). Ackerman et al. (2000) linked reduced subtropical cumulus cloud coverage over the Indian Ocean to BC-induced atmospheric heating. A similar effect was observed in the Amazon where cloud cover decreased by approximately 50% in response to a fire-induced increase in aerosol optical depth (AOD) of 0.6 averaged over the entire Amazon basin during August–September of 2002 (Koren et al., 2004). Modeling studies by Cook and Highwood (2003) link decreased convective cloud cover to increased stability caused by aerosol absorption. Rosenfeld (1999) observed suppression of tropical convection by optically thick wildfire smoke. Simulations forced with fossil and biofuel-derived brown haze find that absorbing aerosols reduce precipitation by as much as 5% through a doubling of atmospheric heating (Ramanathan et al., 2005). Its important to note, however, that climate forcing by anthropogenic aerosols may not always reduce precipitation. Both Lau et al. (2002) and Randles and Ramaswamy (2008) find substantial increases in convection over east Asia resulting from higher tropospheric

concentrations of absorbing aerosols. The authors attribute precipitation increases to changes in monsoon circulation and increases in mid-troposphere stability.'

Introduction, Page 23323, Second paragraph: You state "Surface cooling and tropospheric heating increase atmospheric stability and reduce convection." This is not entirely clear, and there is a large body of literature that contradicts this statement, particularly if you are considering the 3-D world rather than just a single atmospheric column. For example, see Lau et al., 2006. I would not make this statement without caveats.

The reviewer makes a good point: when considering a simple atmospheric column, atmospheric warming aloft and surface cooling might increase lower tropospheric stability–reducing convection–especially if the column had previously been unstable. A previously stable column may become unstable at higher altitudes with the introduction of aerosols within the boundary layer. Additionally, once we expand beyond a simple column, advection and other circulation processes may alter the simple column hypothesis. Considering the conclusions of Lau et al. (2006), who suggest that BC-induced atmospheric warming on the slopes of the Tibetan plateau actually produces instability in the middle and upper troposphere, it is not fully accurate to state: 'surface cooling and tropospheric heating increase atmospheric stability and reduce convection.' Thus, we have amended the sentence to include certain caveats:

'In tropical regions dominated by oceans, surface cooling and tropospheric heating often increase lower tropospheric stability and reduce convection.'

Methods, Page 23326, Paragraph 2: How were SSTs handled, exactly? Were boundary conditions exactly the same for the El/La Niño/a years (i.e. were the only differences due to the response of the slab ocean to the aerosol forcing)? Please make this perfectly clear, so the reader can attribute your results to only aerosol forcing.

Each simulation was initialized with identical boundary conditions, including all other aerosol emissions (sulfur, dust, etc.). Climate parameters were initialized using equilibration simulations for the coupled SNICAR-CAM-SOM, performed at UCI prior to this study. The only difference in initial boundary conditions was the OC/BC emissions dataset. We reconstructed

OC/BC industrial emissions from an inventory by Tami Bond (Bond et al., 2004). There was very little difference between industrial emissions during the high and low fire years. As described in the paper, biomass burning BC/OC emissions were estimated using the Global Fire Emissions Database (van der Werf, et al., 2006). There were large differences in emissions between high and low fire years, as expected. Therefore, SSTs responded only to differences in BC/OC aerosol forcing. The paragraph has been amended to incorporate this information:

'We forced CAM3 with monthly emissions of BC and OC from GFEDv2. In one simulation we prescribed GFEDv2 fire emissions from 1997 to represent a high fire (El Niño) year (Fig. 1). In a second simulation, we prescribed fire emissions from 2000 to represent a low fire (La Niña) year. All other aspects of the two simulations were identical, including initial conditions, allowing us to isolate the climate response caused by fire-induced aerosol forcing. We performed two forty-year simulations using these two sets of annually repeating GFEDv2 fluxes. We excluded the first 10 years from each simulation to account for spin-up effects, including adjustments to the hydrologic cycle. In our analysis we defined fire-induced climate anomalies as the difference between the high and low fire simulations.'

The slab ocean model responded to the different aerosol loadings in the two simulations, causing changes in SSTs. The changes in SSTs were a consequence of deviations in the ocean mixed layer energy budget. The SST anomalies in the two simulations dynamically interacted with the atmosphere by means of radiative and turbulent energy fluxes, but because of the simplified structure of the slab model, they did not respond to larger scale processes such as ENSO-driven changes in ocean circulation. Thus, the climate responses described here should probably be interpreted primarily as the short-term response (over a time span of several months) of the atmosphere-surface ocean system in equatorial Asia to aerosols from El Niño fires. An important next step (as described below in the discussion) is to repeat this analysis with a prognostic fire emissions model and a fully coupled ocean-atmosphere general circulation model to examine longer term fire–ENSO feedbacks mediated by changes in ocean

circulation.'

Methods, Page 23326, Paragraph 3: I think here, or in the discussion, you should speculate on the sensitivity of your result to the assumption that emissions are in the boundary layer.

We are currently preparing a manuscript for publication that analyzes plume injection heights in this region. Our preliminary analysis of 9 years of MISR plume data reveals that nearly all plumes were contained within the boundary layer for Borneo and Sumatra, defined by an interpolation of 6-hourly GEOS assimilations (Figure R1). This is substantially higher than the 80% or so of 2006 Alaskan plumes within the BL, presented by Kahn et al. (2008). Thus, our assumption that emissions are injected in the BL may be ok for this study region. Plumes injected above the BL can be expected to cause more semi-direct heating (and minimally alter direct surface cooling). This could impact our central conclusion, either through further precipitation suppression, or other unknown climate impacts. Given that we do not find any substantial evidence for deeper injection, if possible we would prefer not to speculate about this topic in the manuscript. We modified the text to more fully describe our preliminary findings:

'Total carbon emissions in equatorial Asia (90^{o}E–120^{o}E, 5^{o}S–5^{o}N) were 821 Tg C yr^{-1} in 1997 and 47 Tg C yr^{-1} in 2000. During 1997, black carbon (BC) aerosol emissions were 1.2 Tg yr^{-1} and organic carbon (OC) aerosol emissions were 9.5 Tg yr-1. These emissions corresponded to emissions factors of 0.63 g kg^{-1} for BC and 5.2 g kg^{-1} for OC which are almost the same as emission factors reported by Andrea and Merlet (2001) for tropical forests–implying that almost all fire emissions in equatorial Asia from GFEDv2 were from this biome. Monthly GFEDv2 emissions were interpolated to match the time-step resolution of the model and injected into the surface layer (Rasch et al., 2001; Collins et al., 2002). We injected emissions into the surface layer because many of the fires occur in peatlands (Page et al., 2002) and are thus are expected to have a strong smoldering phase. A preliminary examination of nine years of MISR observations using the MISR INteractive eXplorer (MINX) software (Nelson et al., 2009) confirmed that almost all of the observed fire plumes were injected within the atmospheric boundary layer (ABL) as defined by an interpolation of 6-hourly Goddard Earth

Observing System Model–version 4 (GEOS-4) reanalysis estimates.'

Section 3.1, Page 23327, Line 17: Why not give ASO precip anomaly for 2006 so I can compare it to the ASO precip anomaly for 1997 as 'apples to apples'? Also, comment on the similarity between 1997 (strong El Niño) and 2006 (moderate El Niño) year precipitation anomalies.

Although the negative precipitation anomaly for the study region was larger during the strong El Niño of 1997 (by about a third), the temporal pattern between 1997 and 2006 was similar. In both years the strongest precipitation anomalies occurred in the fall (October and November). This observed delay in monsoonal onset is a common effect of El Niño. The sentence has been amended in the text to provide the full ASO anomaly, instead of just the October anomaly. Because TRMM data before 1998 was not available, we are unable to comment on the similarity between 1997 and 2000 for southern Borneo as shown in Fig. 1 in the text:

'The moderate El Niño was associated with an August–October precipitation anomaly of -2.8 mm d^{-1} (Fig. 1b).'

Section 3.1, Page 23327, Line 25: This whole paragraph is discussing observational precipitation anomalies, right? Please make this clear.

Yes, the precipitation anomalies discussed in Section 3.1 were from GPCP and TRMM observations. We have changed the first sentence to make this clearer:

'GPCP precipitationhad a clear annual cycle and substantial interannual variability within our study region (90^{o}E–120^{o}E, 5^{o}S–5^{o}N).'

Section 3.1, Line 16: define PPT acronym (first use).

This is the only instance where 'PPT' is used in the text. We have therefore changed it to 'precipitation.' (see following changed sentence):

'As a consequence, AOD showed a significant, inverse relationship with precipitation in the region (Fig. 2c; MISR r^2=0.93, MODIS r^2=0.92, p=0.01).'

Section 3.2: Page 23329, First Paragraph: You discuss in detail your simulated AODs, but what

about your simulated AAODs (or, alternatively, aerosol single scattering albedo)? The effects of these aerosols on the regional climate are primarily sensitive to their aerosol absorption (AAOD) [see, e.g. Randles and Ramaswamy, 2008].

We observed a substantial area-wide increase (+0.03) in aerosol absorption optical depth (Fig. R2). The largest reductions occurred in areas of highest AOD, suggesting that smoke emitted in the high-emission scenario was highly absorptive. Fig. 6 (in the manuscript) depicts positive shortwave radiative forcing anomalies for the atmospheric column resulting from increased absorption. Combined, these figures suggest that, in addition to increased AOD, aerosols were more absorptive in the high fire scenario. The total percent contribution to aerosol optical depth from absorbing aerosols was 7%. We have added this information to our discussion of AOD (paragraph 2, section 3):

'The maximum AOD simulated by CAM occurred at the same time as the maximum in fire emissions (Fig. 3b). This timing is consistent with observed AODs that showed no lag relative to emissions (Fig. 1c, d). The higher emissions increased the aerosol absorption optical depth, which constituted 7% (and as much as 10%) of the total increase in regional aerosol optical depth for the August–October period.'

Section 3.2, Page 23329, Paragraph 2: Can you comment on the lag of the SST response to aerosol forcing. How does this affect your results when you consider ASO averages rather than considering the three months separately? I ask this because other studies have shown, over south Asia, that aerosol absorption contributes to increased precip over south Asia in May and June but decreased precip in July and August [e.g. Ramanathan and Carmichael, 2008].

Toward the end of Section 3.2, we discuss month-by-month precipitation anomalies for southern Borneo and Sumatra. On each island, surface shortwave cooling occurred almost in tandem with increased optical depth, with both reaching a maximum in September (Fig 3). However, both land and ocean temperatures lagged the forcing by about a month–decreasing in August in tandem with increased AOD, but not reaching a maximum anomaly until October. Some of this lag can be explained by heat storage. Both land and ocean do not respond instantaneously to radiative forcing. For example, in the northern hemisphere, diurnally-averaged solar radiation reaches a maximum in June, but land surface temperatures do not reach a maximum until July, and ocean temperatures not until August (Hansen, et al., 2010). In this study surface cooling reaches a maximum in September but surface temperatures lag a month behind. Despite not reaching a maximum anomaly until October, surface temperatures are decreasing throughout the period of high aerosol forcing. Likewise, the precipitation response is always negative during the period of high AOD, despite also not reaching a maximum until October. Unlike the Ramanathan and Carmichael (2008) study, we did not find a period of increased precipitation corresponding to increased AOD. This suggests that the precipitation response is a local climate phenomenon, rather than the result of a larger-scale circulation change. We have added several clarifying sentences to the last paragraph on page 23331:

'Precipitation response to the enhanced aerosol forcing was larger over the southern parts of Borneo and Sumatra (south of 1^{o}S) where most fire emissions originated. Similar to the region as a whole, the precipitation response in southern Borneo lagged the aerosol forcing by one month, with the largest negative precipitation anomalies occurring in October (1.6±0.3 mm d^{-1}; 17%) and November (1.4±0.5 mm d^{-1}; 16%). Averaged over the fire season during August–October, the precipitation reduction was 1.1±0.5 mm d^{-1} (13%). Precipitation anomalies in southern Sumatra were even larger, in terms of both absolute changes and relative differences. Decreases during September and October were 3.1±0.7 and -3.1±0.5 mm d^{-1}, respectively, corresponding to relative changes of 31% and 28%. In contrast with earlier work showing that in South Asia aerosols caused increases in precipitation in some months but decreases in others (Ramanathan and Carmichael, 2008), we did not observe any months in which precipitation increased significantly.'

Section 3.2, Page 23331, Line 5: Can you comment (here or in discussion) about the contrasting result you have with other studies like Menon et. al. [2002] that found increased rising motion (and convection) with increased aerosol absorption?

Both Menon et al. (2002) and Chung and Ramanathan (2002) assess the impact of absorbing

aerosols on precipitation in Asia. Menon et al. (2002) find increased rising motion corresponding to increased BC radiative absorption. The introduction of absorbing aerosols to the atmosphere at relatively low altitudes could create instability through the mid-troposphere, especially if the column was previously stable. This is consistent with peak vertical velocity anomalies occurring at relatively high altitudes, as presented in Menon et al. (2002). This middle to upper tropospheric instability could overcome any near-surface stability caused by aerosol cooling. Similarly, Chung and Ramanathan (2002) find increased monsoonal precipitation in India resulting from enhanced BC absorption. As we discussed in our manuscript, Chung and Ramanathan (2002) find that BC tropospheric heating in India modifies the north-south temperature gradient in the Indian Ocean such that the ITCZ shifts northward and enhances precipitation over the Indian subcontinent. Similar to the response observed in the mid-latitude continental atmosphere, low-level warming causes mid-tropospheric instability.

Compared to the subtropical areas discussed in Menon et al. (2002) and Chung and Ramanathan (2002), our study region is generally unstable throughout the entire column. Unlike the previous studies mentioned, this instability allows for aerosols introduced at relatively low altitudes to disperse throughout the entire column, thus preventing any middle or upper tropospheric instability to persist. This, combined with strong surface cooling would stabilize the column, therefore inhibiting precipitation.

The following paragraph has been added to the Discussion:

'There are other pathways by which absorbing aerosols might enhance precipitation. Menon et al. (2002), for example, suggest that increased BC absorption enhances convection over mid-latitude China. Results from a similar study by Chung et al. (2002) show that the introduction of absorbing aerosols into a relatively stable atmosphere heats the troposphere at low levels but that widespread heating does not extend above 700mb. This low-altitude heating destabilizes the atmosphere above as shown by peak vertical velocities occurring above 700mb in both studies. In contrast, our study region was initially unstable through the column, allowing aerosols introduced at the surface to disperse throughout the entire troposphere, not just at lower altitudes. Widespread heating was simulated well above 700mb and ultimately prevented the development of mid-tropospheric instability.'

Section 3.2, Page 23331, Line 26: Since your precip lags the aerosol forcing a month like your SSTs, can you comment on the linkage between SSTs and precip in this region?

In this paper (specifically in the Discussion), we acknowledge that the lag in precipitation suggests a link with SSTs. Numerous studies, including those we cite in the manuscript (e.g. Chelton et al., 2004; Raymond, 1995; Graham and Barnett, 1987; Hackert and Hastenrath, 1986), connect SST cooling with reduced convection in the tropical Pacific. Our study region is a mix of unconnected islands and ocean. It is thus reasonable to conclude that ocean temperatures do influence large-scale convection in the region. This may explain why both precipitation and SSTs lag the aerosol forcing.

However, the size of the largest negative precipitation anomaly is not substantially larger than the one during the previous month, when the shortwave tropospheric warming was highest. As we note: 'multiple mechanisms probably contributed to the precipitation reduction, including increased atmospheric stability from absorbing aerosols in the mid troposphere and decreased sea surface temperatures.' We do not feel we are in a position to comment with our current study on which forcing is stronger, or what portion of the precipitation response can be attributed to SSTs.

Section 4, Page 23335: Can you speculate what your results may have been if your AODs were higher and actually more representative of a high 1997-like El Niño year?

In the manuscript we referenced a figure from van der Werf et al. (2008) illustrating a nonlinear relationship between fire emissions and precipitation. A large portion of this nonlinear relationship results from fire's response to drought. However, our study suggests a possible feedback between fire and drought. If our simulations had better estimated AODs from fire emissions, we might expect the impact on drought to have been stronger. The nonlinear relationship between emissions and precipitation presented in van der Werf et al. (2008) suggests that AODs representative of a 1997-like El Niño year could have produced a substantially more negative

precipitation response. One way to test this would be to force CAM3 with AOD directly, but this may not represent large-scale mixing processes as accurately as forcing CAM3 with emissions.

The following sentence was added to the Discussion to address this reviewer suggestion:

'Given that our model substantially underestimated fire-induced changes in AOD, it is likely that our simulations did not represent the full atmospheric response to fires during the 1997 El Niño.'

Section 4, Page 23334, Paragraph 1: This is a very important point! Most models really underestimate biomass burning AODs! I wonder how they do on the absorption then!

We have modified the text (above) to address the underestimation of AOD in the model. Additionally, we have explicitly quantified the contribution to optical depth of absorbing aerosols (also above). We define aerosol absorption properties according to Flanner et al. (2007) as described in the Methods (Section 2). Single scattering albedos for both BC and OC are prescribed in SNICAR, and vary for hydrophobic and hydrophilic aerosols. The median visible single scattering albedo was set at 0.52 for hydrophilic (aged) BC and 0.3 for hydrophobic (new) BC. However, because GCMs (in particular, CAM3) underestimate total AOD, we expect them to also underestimate total absorbed and scattered shortwave radiation. This might introduce a low bias to the simulated precipitation decrease.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 23319, 2009.

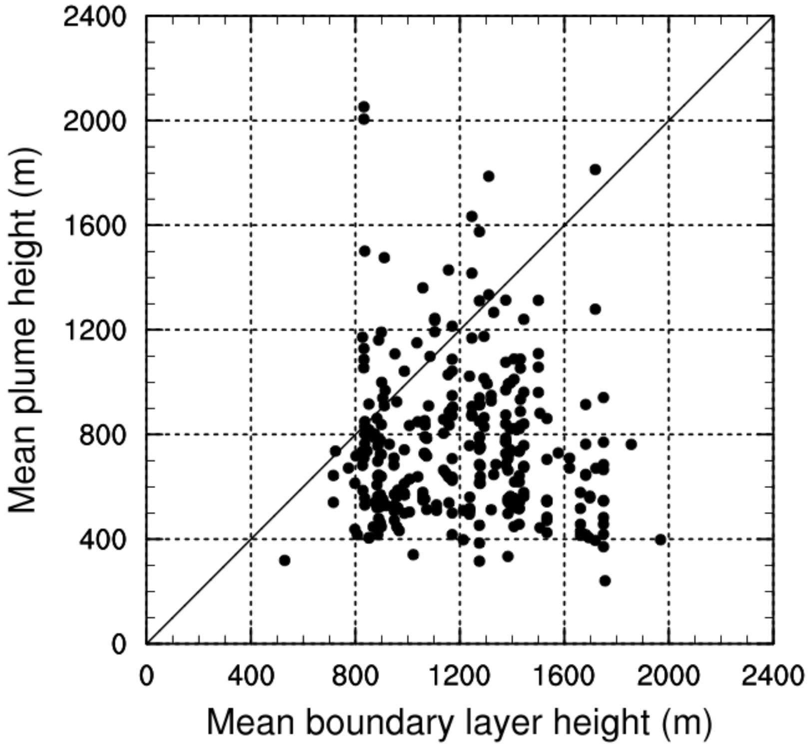

Fig. 1. (Figure R1): Observed mean plume heights (MISR) v. mean boundary layer heights (GEOS) for Borneo 2001–2006.

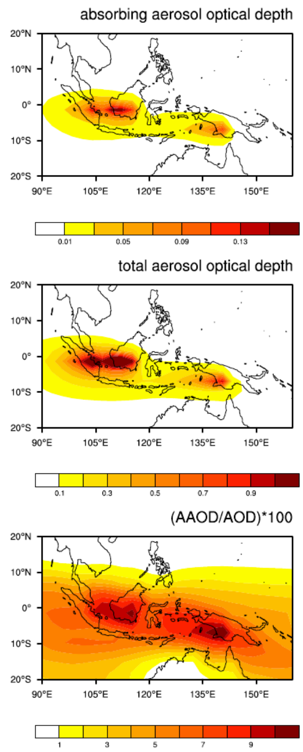

Fig. 2. (Figure R2): Simulated high fire minus low fire absorbing aerosol optical depth (top), total aerosol optical depth (middle) and percent increase in optical depth due to absorbing aerosols (bottom).