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Interactive comment on "Direct and semi-direct radiative forcing of smoke aerosols over clouds" *by* E. M. Wilcox

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I thank Dr. García for thoughtful comments on this paper. Both reviewers expressed concern that uncertainties in the OMI aerosol index as a proxy for aerosols above clouds may be too great to accomplish the goal of the paper. First, let me clarify that the main purpose of the paper is to compare the magnitude of the radiative effect of semi-direct cloud thickening to that of the direct effect above overcast scenes for the same level of aerosol absorption. The uncertainties in the OMI AI discussed in greater detail in the review by Dr. Torres do prevent an empirical determination of the radiative forcing efficiency (forcing per unit aerosol optical thickness) using the methods outlined in the paper. However, I have added a quantitative uncertainty analysis to the paper based on results from the Torres et al. paper now in press (mentioned in his review)

that shows, together with results from Wilcox et al. (2009), that the OMI AI is sufficient to accomplish the goal stated above and in the abstract of the paper. The results of the paper are robust to the uncertainty in the interpretation of the OMI AI quantity in this study. Detailed responses to the comments from the review are included below.

Comment: Nonetheless, the estimates of radiative forcing based on OMI Aerosol Index may completely be not robust. This parameter may be interpreted as a proxy of absorbing aerosol presence, but given its uncertainties cannot be used to distinguish clearly situations with aerosols. To this aim, other parameter, like the POLDER aerosol optical depth, may be used as recommended by the other referee. Other possibility is to increase the OMI AI reference, guarantying absorbing aerosol conditions and including the AI uncertainties (for example, AI>2). Besides the author should include an error estimation more detailed, analyzing how the AI uncertainties affect the direct and semi-direct radiative forcing estimations.

Response: Motivated by this comment and the more specific comments (and paper) of Dr. Torres, I have completed a quantitative uncertainty estimate for the application of the OMI AI. Further details are included in the response to Dr. Torres' review. The results show that the uncertainty in the interpretation of OMI AI as a proxy for aerosol amount above cloud over the southeast Atlantic Ocean is +/- 0.46, which is less than half of the difference in OMI AI used to discriminate scenes impacted by absorbing smoke aerosol.

Comment: On the other hand, normally the radiative forcing is defined by the difference between conditions with and without atmospheric aerosols. Although in this work only the radiative effect of absorbing aerosols is estimated, including the aerosol scattering effects in the clear estimation of solar fluxes (AIï′C ËĞc0 [sic.]) may introduce significant errors in the estimation of radiative forcing.

Response: First, it is important to note that, consistent with the title of the paper, the goal of the paper is to estimate the magnitude of the forcing attributable to smoke above the cloud, not that due to aerosols generally. Thus the radiative transfer calculations that appear in the last two figures of the paper show the forcing efficiency of smoke using the optical properties measured during SAFARI2000, rather than trying to account for the full range of aerosol types that might be present. Under the assumption that the absorbing component is mainly contributed by the smoke, then using the OMI AI (cognizant of the uncertainties discussed above) is sufficient to compare the magnitudes of the direct and semi-direct radiative effects of the smoke for the same amount of smoke absorption above the cloud, which is the quantitative result of the paper.

Nevertheless, a separate set of radiative transfer calculations have been performed to explore the magnitude of forcing attributable to a hypothetical scattering component (single-scattering albedo = 0.99) of aerosol optical thickness. If indeed the samples with OMI AI <= 0 are more likely to coincide with a scattering aerosol layer above than are the OMI AI > 0 samples, this could introduce a bias into the reference value for the forcing calculations in the paper. This bias is negligible for the brightest clouds in the sample. For clouds at the median value of LWP, the presence of a scattering aerosol layer above cloud produces a forcing efficiency of -12 W m-2 per unit AOD at 550nm. The true bias will be substantially smaller because it seems unlikely that the difference in the fraction of optical thickness contributed by purely scattering aerosol between the smoke-contaminated scenes and the smoke-free scenes is anywhere near 1. Unfortunately, we cannot know this fraction. Perhaps with a combination of OMI absorption optical thickness and CALIOP or POLDER scattering optical thickness, one could try to determine this quantity, but that would be a substantial research effort.

The potential for this bias is noted in the manuscript, however I reiterate that resolving this potential bias in determining the aerosol radiative forcing efficiency above clouds is not essential to the reaching the goal of this paper, which is to compare the direct and semi-direct radiative forcing for the same amount of absorbing aerosol above the cloud.

Comment: A short description of the region analyzed in terms of cloud albedo, LWP

and OMI AI would be useful to complete the study. For example, the table 2 could be replaced by plots of frequency of occurrence of these parameters.

Response: Table 2 remains has it appeared before because the numbers in that table are the factor by which the instantaneous local radiative forcing is divided in order to estimate the regional forcing (i.e. the difference between figure 3a and 3b in the discussion paper). However, a new figure (figure 2 in revised manuscript) has been added showing histograms of OMI AI, AMSR-E LWP, MODIS cloud optical thickness, and CERES cloud albedo. Some discussion of these histograms has been added to section 2 in the revised manuscript.

Comment: A figure showing the semi-direct radiative forcing, like figure 3, would support the discussion of the semi-direct effect. Furthermore, a plot comparing the direct and semi-direct effect would help readers.

Response: The suggested figure has been added to the revised manuscript. Initially, I was concerned that random variability among the samples would be too large for this quantity to be evaluated for the highest OMI AI values. However, further analysis indicates that uncertainty is dominated by the measurement uncertainty up to the average forcing for samples with OMI AI greater than 4. Therefore, the figure has been generated and shows robust results even for a conservative estimate of forcing uncertainty.

Comment: The aerosol optical depth is a spectral magnitude, so author must include the wavelength at which AOD is given (figure 4 and section 3). Furthermore this information should be includes in the definition of aerosol forcing efficiency (section 3). Please, include the error of these latter values in the manuscript.

Response: The aerosol optical thickness values included in the manuscript text and shown in the figures are the values at 550 nanometer wavelength. Likewise, the radiative forcing efficiency discussed in section 3 and shown in figure 4 of the discussion paper are referenced to the optical thickness at 550 nanometer. The spectral dependence of the optical thickness was estimated based on values in the literature as described in section 3. However, the reviewer is correct that the wavelength of the optical thickness values was not properly indicated. Both the text and the figures have been amended in the revised manuscript to indicate the wavelength of the optical thickness.

Comment: Some details along the manuscript should be checked: the units of the AOD in the figure 5.b (this magnitude is dimensionless like the OMI AI, so the units of AI must be changed in table 1), the figure 1 was not referenced in the text.

Response: The units for AOD in figure 5b was a mistake that has been corrected. The units for OMI AI were assigned "n/a", which is common short hand for "not applicable". To avoid confusion, I have change the entry in the units column to "non-dimensional" for AI and cloud cover. Uncertainties in AI are now reported in table 1 and discussed in the text. The uncertainty in cloud cover is now also listed as "conservative overcast" to indicate that the data are carefully screened for cases that are overcast. Figure 1 is now referenced.

References:

Torres, O., H. Jethva, and P.K. Bhartia: Retrieval of aerosol optical depth above clouds from OMI observations: Sensitivity analysis and case studies, J. Atmos. Sci, in press, 2011.

Wilcox, E. M., Harshvardhan, and S. Platnick: Estimate of the impact of absorbing aerosol over cloud on the MODIS retrievals of cloud optical thickness and effective radius using two independent retrievals of liquid water path, J. Geophys. Res., 114, D05210, doi:10.1029/2008JD010589, 2009.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 20947, 2011.