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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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Torres review:

I thank Dr. Torres 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 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.

Wilcox et al. (2009) show that increasing absorption by smoke aerosol with increasing OMI AI is evident in a linear reduction in upwelling visible reflectance measured by MODIS with increasing OMI AI from 0 to 5. Furthermore, the quantitative radiative effects of smoke aerosols reported in the abstract of the present paper are the difference between the average of all samples with OMI AI > 1 and all samples with OMI AI $\leq$ 0 (the figures include the values for wider differences of OMI AI). The error analysis of OMI AI as a proxy for aerosol amount (discussed in greater detail below) results in an uncertainty of +/- 0.46 in OMI AI, which is less than half the difference between the OMI AI values used to discriminate the samples influenced by absorbing smoke from the others. Thus the results of the paper are robust to the uncertainty in the interpretation of the OMI AI quantity in this study. The uncertainty analysis and responses to the other comments from the review are included below.

Comment: Although, as stated by the author, variations in aerosol altitude over a bright surface do not have a significant impact on ultraviolet radiance, the aerosol height above the cloud does have an important effect on the near-UV spectral dependence.

Response: The statement regarding the impact of aerosol height above a bright surface on UV radiance has been removed and replaced with a statement about the results for impact on OMI AI of aerosol height above clouds from the Torres et al. (2011) paper.

Comment: In addition to the dependence of the AI signal on the aerosol layer optical depth and the height above the cloud, the AI also depends on the optical depth of the cloud itself, and on the aerosols absorption angstrom exponent (AAE). The sensitivities of the AI to these parameters have been documented in a soon to be published peer-reviewed manuscript which is available to the author upon request. For the above stated reasons, the observed AI of aerosols above the cloud cannot be simply interpreted as a proxy of the aerosol optical depth without accounting for the uncertainty associated with the mentioned dependencies.

Response: I have been careful not to interpret the AI as an optical depth because of the uncertainties noted in the review. Nevertheless I have now incorporated the quantitative estimates of uncertainties in interpreting AI as a proxy for aerosol optical thickness described above, prior to the Torres et al. (2011) paper it was not possible to quantitatively factor the specific uncertainties mentioned above in the error budget for the study. This has now been accomplished and incorporated into the revised manuscript. The details of the error budget are as follows.

The dependence of OMI AI on the aerosol layer height is 0.55 kmˆ-1 in fig. 4 of Torres et al. (2011) for an absorbing aerosol layer above a cloud of optical thickness 10. Sixty seven percent of aerosol layers present above clouds in the Calipso lidar dataset reside between 2.8 and 3.7 km altitude (1-sigma variability derived from the histograms in fig. 1 of Wilcox 2010). Thus the uncertainty in OMI AI as a proxy for aerosol amount owing to this error is about +/- 0.25.

Sixty seven percent of the cloud samples in the present paper fall between cloud optical thickness values of 8 and 16 (1-sigma variability in optical thickness). The dependence of OMI AI on cloud optical thickness is less than 0.05 per unit cloud optical thickness for a layer of aerosol optical thickness 1, single-scattering albedo 0.85 and absorption Angstrom exponent 1.91 residing above a cloud of optical thickness 10 (fig. 3 in Torres et al., 2011). This is an uncertainty in OMI AI of +/- 0.2.

The dependence of OMI AI on the absorption angstrom exponent (AAE) is at most 1.31 per unit AAE in fig. 3 of Torres et al. (2011) for a layer of aerosol above a cloud of optical thickness 10. While I could not find a study of the variability of AAE for African smoke through the burning season, Russell et al. (2010) report on the global range of AAE values for biomass burning sources from 1.25 to 1.75. Using this as a plausible range of variability in smoke AAE implies an uncertainty in OMI AI of +/- 0.33.

Assuming these three sources of uncertainty in the interpretation of OMI AI as a measure of aerosol amount are uncorrelated, the total uncertainty in OMI AI as applied in this study is +/- 0.46.

Finally, I reiterate that the main point of the paper is to compare the magnitudes of the semi-direct and direct radiative forcing for the same amount of aerosol absorption above cloud, not to quantitatively determine the forcing efficiency of each of these processes per unit aerosol optical thickness. For the forcing efficiency to be determined empirically would require application of the POLDER retrieval mentioned by both of the reviewers. This is not necessary to achieve the goal of the present paper. Nevertheless, as was noted in the original submitted manuscript, the Wilcox et al. (2009) paper has already demonstrated that there is a linear reduction in visible reflectance with increasing OMI AI from 0 to 5 for overcast scenes. This is evident in a systematically increasing difference between the MODIS cloud liquid water path retrievals derived from visible reflectance, and the AMSR-E LWP retrieval based on microwave emission that is transparent to smoke aerosol. This is sufficient, I believe to make the case that higher OMI AI corresponds to greater visible absorption over the Southeast Atlantic Ocean during the July, August, September season. And this fact is sufficient to satisfy the principle goal of the paper stated at the top of this response.

Comment: The POLDER capability should be discussed in the literature review of this manuscript. It is also suggested that the use of the POLDER aerosol optical depth to characterize the above-cloud aerosol load be considered.

Response: It was an oversight not to include a reference to the Waquet et al. (2009) report of the POLDER retrievals of AOD above cloud. This has been corrected in the revised manuscript. I have chosen not to attempt to include the POLDER retrievals in the analysis at this time but will consider doing so in a future study. Furthermore, I have indicated in the revised manuscript that this would be a fruitful application of the POLDER data. As I have argued above, the present study provides sufficient evidence that increasing absorption above clouds leads to both a positive direct radiative forcing and a partly compensating negative semi-direct forcing. While the application of the OMI AI is not sufficient to quantify the forcing efficiency per unit AOD, the results of the paper are robust to the uncertainty estimated above in the interpretation of OMI AI as a proxy for aerosol amount.

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