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Atmospheric Chemistry and Physics Discussions

Interactive comment on "A six year satellite-based assessment of the regional variations in aerosol indirect effects" *by* T. A. Jones et al.

T. A. Jones et al.

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Response to Referee #1:

Summary: We appreciate the reviewers’ comments and criticisms and have revised the manuscript to address these concerns. Several major changes have been made based on your and the other reviewer’s comments and include a major rewrite of the Introduction to provide more focus to this research, more discussion concerning uncertainties involving (near) coincident aerosol and cloud property retrievals, and the addition of several additional quantitative assessments of aerosol – cloud – vertical motion interactions. To keep the manuscript length manageable, the discussion concerning 2 regions (Western Pacific and South Pacific) was removed. Both these regions had similar characteristics to the Western Atlantic and South Indian Ocean regions, which remain in the discussion. During the revision process, additional time and effort were spent addressing grammar issues present in the text.

Major Comments:

References and Limitations Additional discussion of the references you suggested (and others) has been added to the introductory portion of the text. Specifically, additional discussion on the importance of aerosol type to AIE [e.g. Breon et al. 2002] and especially the uncertainties inherent in satellite based retrievals of aerosol properties in the vicinity of clouds [Feingold et al. 2001, Bulgin et al. 2008, Koren et al. 2008]. To address readability concerns, the Introduction has been revised to separate model, satellite, and in situ analyses of AIEs into sub-sections to highlight the importance of each in a clear and concise manner. Greater emphasis has been places on addressing the limitations of satellite-based aerosol retrievals near clouds in this research. These uncertainties were broken down into three basic categories which include the lack of coincident aerosol and cloud property retrievals, photons escaping from the side of clouds being scattered back towards the satellite, and hygroscopic aerosols growing in size in the high humidity environments near clouds. We agree that there is no substitute for the lack of coincident aerosol – cloud observations. However, Bulgin et al. [2008], Quaas et al. [2008], and others have determined that for spatial scales on the order of 1° (or ~100 km) aerosol concentrations, on average, do not vary significantly. Thus, aerosol concentrations in the “clear” portion of a 1° box are assumed to be representative for those in the "cloudy" portion of the box. More specifically, the CCN concentration at cloud base is assumed to scale linearly with the AOT retrieved in the nearby clear-sky areas, an assumption which has been supported recently by the study of Andreae [2009]. As a result, we also make use of this assumption while noting that it is not perfect. Photon scattering has been observed to increase AOT values (for a given aerosol concentration) within 3 km of a cloud edge [Wen et al., 2006; Mauger and Norris, 2007; Marshak et al., 2008]. However, MODIS retrieves AOT at a 10 km resolution, and even that is convolved to a 20 km resolution in the CERES-

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SSF product. Over these larger spatial domains, the impacts of photon scattering to AOT are considered to be small. The most important uncertainty, and the most difficult to address, is the growth of aerosols in the high-humidity conditions near clouds. Unlike photon scattering, this effect may occur on the order of 10s of km; thus, having significant impacts on AOT retrievals. The end result is a false correlation between increases in AOT and cloud parameters such as droplet effective radius and cloud fraction. To quantify and partially address this uncertainty, we compare MODIS fine mode fraction (FMF) with cloud fraction. If aerosols are increasing in size near clouds, the resulting FMF should decrease. A decrease in FMF on the order of 15% from clear to cloudy conditions was observed in all regions where substantial anthropogenic (hygroscopic) aerosol concentrations existed. In the Eastern Atlantic, no changes was observed (non – hygroscopic dust) and in the southern Indian Ocean FMF actually increased as a function of cloud fraction indicating something else is occurring here. At least for the non-maritime case (IO), we can assume that hygroscopic growth of aerosols accounts for up to approximately 15% of the difference between aerosol properties from clear to cloudy conditions. Thus, AIE is only considered significant if this difference over a one month period is actually greater than 15%. If it is not, then AIE is not computed and included in the final results. Fortunately, this difference generally ranges between 20 and 45% indicating that at least some of the changes in cloud properties relative to AOT are due to actual microphysical interactions, and not observational artifacts. We concede that this test is not perfect, but given the data at had, no better method to quantify this uncertainty could be derived. We chose not to include additional atmospheric – cloud parameter plots for the examples, but we did add a histogram plot of MISR stereo heights for each example. This plot clearly shows the location of the primary aerosol and cloud layers and also shows the lack of either in the Bay of Bengal example, leading to the observation of negligible AIE.

Specific Comments:

Abstract: The abstract has been revised to improve clarity and highlight key findings.

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The revised averaged total AIE for the Arabian Sea is –0.27 Wm-2. In the results section, we also describe in detail how average AIE was calculated and note that the average value derived from the 70 month data set may not exactly equal the average value of either seasonal and/or cloud property sub-samples. (This is a result of the data being non-normally distributed). We also hypothesize that dust aerosols that acquire a hygroscopic coating are a key component to AIE in these region, which is a finding consistent with Levin et al. 1996 and Satheesh et al. 2006.

P 20351, line 6: We now note that aerosols from biomass burning are a result of both anthropogenic and natural causes.

P 20351, line 18: The term “fine mode” aerosols has been selected for this study to highlight primarily anthropogenic aerosols.

P 20352, line 15: The importance of aerosol size distribution to AIE has been added.

P 20355, line 5: High dust aerosol concentrations in NE Atlantic during DJF are now noted.

P 20355, line 8: Additional references to variability of dust aerosols in NW Atlantic have also been added. However, in our region of study, these variations are relatively small.

P 20357, line 3: The cloud property retrieval algorithm used here is capable of reporting 2 liquid water cloud layers. We use the lower of the 2 layers, and ignore the second, as it is only present for less than 5% of all data points. For the low-level cloud layer the average CTP is 837 hPa when averaged over all 6 regions.

P 20357, line 25: As part of the effort to address possible uncertainties, the sample was split into thin (LWP $<$ 20 gm-2) and thick (LWP $>$ 20 gm-2) clouds and AIE values examined [Lohmann et al. 2000]. With the exception of EA and BB, AIE cooling was greater for thick clouds when upward vertical motion was maximized.

P 20258, line 21: We agree that the true lack of independent and coincident measurements of aerosol and clouds properties is the greatest limitation to this and any satellite

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based analysis of AIE. A 10 km MODIS level 2 AOT retrieval is retrieved from a set of four hundred 0.5 km resolution pixels. After various reflectance and cloud testing has been performed, an AOT values can be reported when as few as ten 0.5 km pixels remain, though in practice the number is generally somewhat higher. We chose not to remove AOT values with cloud fractions of 80 or 90% since they account for a large portion of the data (see Figure 2a) and it is under these conditions that AIEs are most likely to be occurring. Instead, we developed a test using the change in FMF as a function of cloud fraction to determine impact of hygroscopic aerosol growth on the relationship between aerosol and cloud properties. The result of these tests was that in environments where large concentrations of anthropogenic and hygroscopic aerosols exists, FMF decreases approximately 15% from completely clear to almost completely cloudy pixels. Thus, we conclude that for the relationships between aerosol and cloud properties to be significant if the differences are greater than 15% over the given range of values. Fortunately, this threshold is generally exceeded.

P 20358, line 28: The uncertainty in FMF is 30% [Kleidmann et al., 2006].

P 20359, line 19: We were primarily referencing increased black carbon production from biomass burning, but have elected to remove this statement.

P 20360, line 4: The NCEP product contains data at levels from 1000 to 10 hPa with vertical resolution decreasing with height.

P 20360, line 15 Monthly averaged atmospheric parameters have been replaces by daily parameters to better sample the relationships between these conditions and AIE. Specifically, we now focus on vertical velocity as being key to the magnitude of AIE while also alluding to other atmospheric conditions where necessary. Standard errors are now reported for anthropogenic and dust AIE values in Tables 1 and 2, but adding these errors for all parameters makes the plots too noisy to interpret. Thus, we elected not to add them and mention variability where necessary throughout the text.

P 20360, line 26: Additional description on the mathematical methods developed by

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Kaufman et al. [2005] and used here for aerosol classification are given.

P 20362, line 6: Not sure what you were referring to here “does not appear to be defined in the text”.

P 20365, line 14: This has been reworded to reflect that CTP is lower, but that altitude is higher

P 20365, line 27: Number concentration (N) is derived from satellite retrieved droplet effective radius (Rc) using Eq. 6 and is used to calculate AIE for all regions.

P 20366, line 25: Statements implying that “aerosols ability to act as CCN determines AOT in non-cloudy pixels” have been revised, with a much greater emphasis placed on the uncertainties of aerosol retrievals near clouds and how we conclude that these artifacts are not the sole reason for the AIE results presented here. Refer to the major comment section above.

P 20367, line 17: Seasonal aerosol layer heights are now estimated using CALIPSO data from 2006 and 2007. While the uncertainties in this product remain large, they do give an important information for the differences in aerosol layers from region to region. For the summer season (JJA) in the Arabian Sea, the mean aerosol layer height is 3.3 km. Values for other regions are given in Table 1b.

P 20371, line 13: Yes, convective uplift is present along the ITCZ; however, the poor spatial resolution of the NCEP product fails to resolve convective updrafts. As a result, the vertical velocities within the NCEP product remain small for this region. This is now noted in the text.

P 20372, line 19: A greater emphasis on the potential for dust to obtain hygroscopic coating has been added throughout the text. In particular, we now compare AIE between the Arabian Sea where coated dust aerosols likely do exist, to AIT in the Eastern Atlantic where little potential for coating exists. In the latter case, AIE is small and weakly positive whereas in the Arabian Sea AIE is much more evident.

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P 20377, line 14: References to the impacts of aerosols on long-lived stratus sheets have been added to the text in both the introduction and results section [e.g. Nakajima et al., 1991; Feingold et al., 2003; Borg and Bennertz 2007].

P 20377, line 27: The conclusions have been heavily modified to better emphasize the important results of this paper. Specifically, we conclude that total AOT is a poor predictor of AIE alone, and that vertical velocity and aerosol layer heights are key to whether or not AIE is occurring, and finally that aerosol type is also important. We note that despite the uncertainties present, significant AIE values where observed in all regions except EA and BB, where aerosol and atmospheric properties do not lend themselves to AIEs occurring.

Figures and Tables:

A new table (Table 2) has been added that contains total AIE for thin vs. thick cloud samples and upward vs. downward motion samples. Also included in this table is the number of months where the relationship between AOT and Rc is statistically significant. What was Table 2 is now Table 3, and MISR aerosol height statistics are now present. To better expand on the importance of the MISR aerosol height product, a figure showing the frequency of heights for each case study is now shown (Fig. 9). What was Figure 2 is now Figure 3 and correlation is more clearly defined on the second y-axis. The label “Radius” actually referred to the correlation between AOT and Rc, and this label has been revised to better reflect this. For this figure “AOT” referred to total column AOT (not just fine mode). The addition of error bars to these figures makes them unreadable. Instead, we note the variability in terms of percent change at appropriate points throughout the text.

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