THE COMBINED USE OF CALIPSO, MODIS AND OMI LEVEL 2 AEROSOL PRODUCTS FOR CALCULATING DIRECT AEROSOL RADIATIVE EFFECTS

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ABSTRACT

We describe a technique for combining CALIPSO aerosol extinction and backscatter, MODIS spectral AOD (aerosol optical depth), and OMI AAOD (absorption aerosol optical depth) measurements for the purpose of calculating direct aerosol radiative effects. We show sensitivity studies and first results of the methodology applied to airborne observations collected in the ARCTAS field campaign. Radiative fluxes modeled based on the multi-sensor aerosol retrievals compare reasonably well with radiative fluxes measured by an airborne spectral flux radiometer aboard the same aircraft.

1. INTRODUCTION

Aerosols introduce a major uncertainty in predictions of possible future changes to the Earth system in general, and its climate in particular, owing to the incomplete knowledge of aerosol physicochemical properties and their spatial distribution. The IPCC-2007 estimates of the direct aerosol radiative forcing (DARF) of climate are largely based on climate model simulations. Observationally-based estimates are sparse, and their mean result for DARF is about a factor of two larger than the mean of the model-based estimates [1]. A recent study [2] suggests that the differences between model- and observation-based estimates is to a large extent due to a change in aerosol optical properties attributable to anthropogenic activity (i.e., a stronger increase in soot aerosols by comparison to purely scattering aerosols since pre-industrial times) not accounted for in the observation-based estimates. The authors of [2] conclude that "remaining uncertainty (in DARF) is probably related to the vertical profiles of the aerosols and their location in relation to clouds".

With the addition of designated aerosol satellite sensors such as MODIS, MISR, CALIOP and OMI the study of aerosols from space has become more quantitative [3-7]. These sensors each provide important contributions to our understanding of the effects of aerosols on climate. MODIS and MISR provide reliable measurements of spectral AOD with reasonably well known uncertainties under most conditions [8, 3, 9]. OMI has begun to investigate aerosol absorption, although extensive validation of the absorption optical depth product is still to be undertaken [6, 10]. CALIOP has been providing vertical profiles of aerosol properties along the satellite ground track [7]. Studies of aerosol DARF depend critically on the vertical profile of radiative properties, yet CALIOP only provides aerosol extinction at two wavelengths, with the maturity of these products still low. It is paramount for the community to develop techniques to combine the A-Train aerosol observations with each other and with auxiliary suborbital observations to improve the estimates of the specific aerosol properties relevant for the various processes governing aerosol-climate interactions. In this paper, we describe a methodology for the combination of aerosol observations from MODIS, CALIOP, and OMI, with the goal of improving estimates of the three-dimensional structure of aerosol radiative properties and hence estimates of the direct and semi-direct effect of aerosols on climate.

2. PRELIMINARY STUDIES

As a prerequisite for the application of our methodology to the actual satellite observations, we assessed the consistency between comparable measurement quantities from the different A-Train sensors. For four months in 2007, comparisons of the standard MODIS-Aqua level-2 spectral AOD data to the AOD calculated from the initial and the latest release of the CALIOP level-2 aerosol extinction profile data set show how the use of appropriate quality flags in the CALIOP product and a restriction to scenes with cloud fractions below 1% (as defined in the MODIS aerosol retrievals) results in generally good correlation between the two data sets and rms differences in AOD of 0.1 or less.

3. METHODOLOGY FOR MULTI-SENSOR RETRIEVAL OF AEROSOL RADIATIVE PROPERTIES

In the first step of our strategy for combining A-Train aerosol data sets we seek to find all combinations of MODIS microphysical aerosol particle models (one fine + one coarse mode) that are reconcilable with the OMI and CALIOP observations within the uncertainties of their respective retrievals (each MODIS particle mode consists of a geometric mean radius and standard deviation, along with a prescribed spectral complex index of refraction). Subsequently, we use the mode combinations that provide the best match with the observations to forward calculate aerosol radiative properties required for a full assessment of aerosol DARF, i.e., spectral extinction, single scattering albedo (ssa) and asymmetry parameter. In the final step, we use a radiative transfer model to determine how the range of microphysical retrievals translates into a range of radiative forcing estimates. Figure 1 illustrates our basic approach.

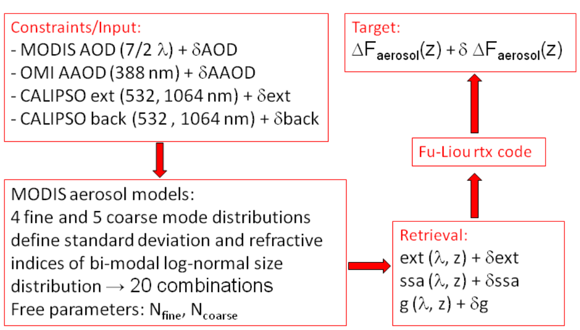

Figure 1. Schematic representation for the inversion of MODIS, OMI and CALIOP data to aerosol radiative properties and radiative forcing estimates, including respective uncertainties.

The different fine/coarse mode combinations define different wedges (e.g., fine #1, coarse #5 in Figure 2, top). The totality of all wedges defines the solution space of possible fine and coarse mode concentrations that are consistent with the observables, with each color in Figure 2 (bottom) representing a different fine/coarse mode combination. Finally, our methodology evaluates the goodness of a solution thus derived by only accepting the top 10% of all solutions in the context of the metric:

$$X = \left(\sum_i \log^2 \left(x_i / \hat{x}_i \right) \right)^{1/2} , \qquad (1)$$

where $\hat{x}_i$ are the input observables and x_i their corresponding values forward calculated from the combination of fine and coarse mode aerosol model being tested.

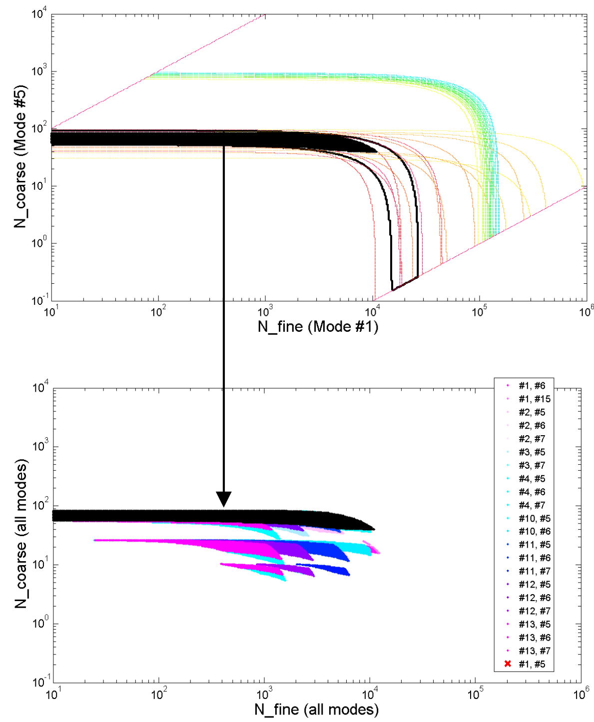

Figure 2. Illustration of inversion method. Top: each observable, in this case MODIS AOD at 550nm, defines a wedge in N_fine/N_coarse space for a given fine and coarse mode combination (here fine #1, coarse #5). ALL observables define a smaller wedge again for the fine #1 and coarse #5 combination. Bottom: Different fine/coarse mode combinations define different wedges. All wedges define the solution space of possible fine and coarse mode concentrations that are consistent with the observables – each color represents a different fine/coarse mode combination.

The range of N_fine/N_coarse solutions provides a range of aerosol radiative properties (spectral extinction, ssa and asymmetry parameter) that is consistent with the observables. We tested the inversion by forward calculating sets of MODIS, CALIOP and OMI observations (hereafter referred to as synthesized data) for light, medium and heavy aerosol loadings (midvisible AOD = 0.05, 0.2, 0.7), each for different levels of aerosol absorption (midvisible ssa = 0.8, 0.9, 0.98). It was noteworthy that for AOD greater than 0.2, the mean radiative properties retrieved were very near the values forward calculated from the synthesized data.

To illustrate the usefulness of aerosol backscatter in constraining the aerosol radiative properties required for radiative transfer calculations, Figure 3 shows two sets of inversions for an initial synthesized set of aerosol observations with a mid-visible AOD of 0.2 and ssa of 0.9. The upper panel of plots shows the inversion that is only constrained by MODIS spectral AOD and OMI absorption AOD. The lower panel of plots shows the inversion with an additional constraint of aerosol backscatter. The three black lines in each of the right hand plots show the mean plus and minus one standard deviation of the best 10% of all inversions. The grey areas show the minimum and maximum values of radiative properties for the same best 10% of all inversions. We assumed that aerosols were confined in a 1000-m layer (in translating the column integral AOD and AAOD into local extinction and absorption coefficients).

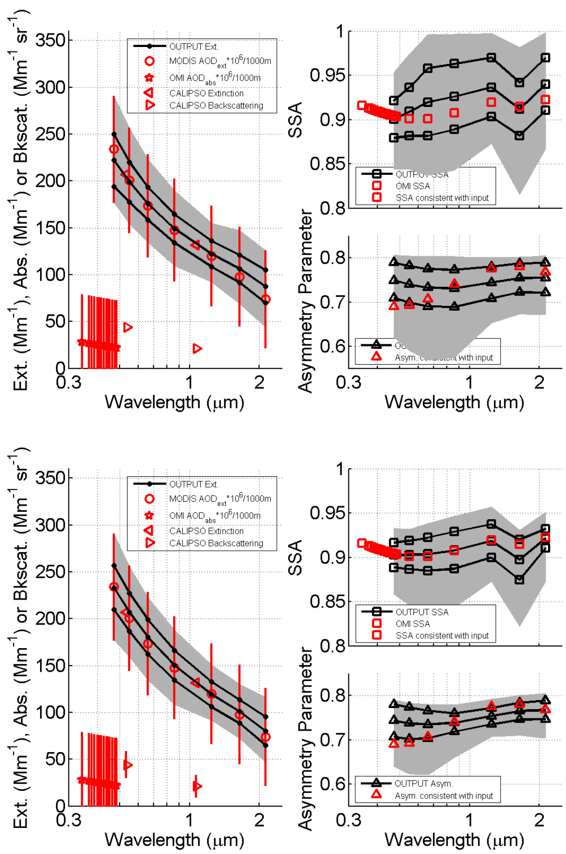

Figure 3. An illustration of the usefulness of lidar-derived aerosol backscatter to constraining inversions for retrieving aerosol radiative properties: upper panel of plots shows the inversion that is only constrained by MODIS spectral AOD and OMI absorption AOD. The lower panel of plots shows the inversion with an additional constraint of aerosol back-scatter (see text).

It can be seen that the grey areas and the areas bounded by the standard deviations (black lines) are considerably smaller for the inversion that is constrained by the CALIOP backscatter observations. These inversions assumed an uncertainty of 10%±10Mm^{-1}sr^{-1} on the CALIOP-derived layer-averaged aerosol backscatter. A loosening of these requirements to 10%±20Mm^{-1}sr^{-1} resulted in less useful constraints of this particular inversion. These comparisons illustrate how measurement uncertainties propagate into uncertainties in radiative effect estimates.

4. TESTING THE METHODOLOGY WITH SUBORBITAL OBSERVATIONS

As a test, we applied our methodology for multi-sensor retrievals of aerosol radiative properties to airborne HSRL (High Spectral Resolution Lidar) data [11] from a high-flying NASA B-200 aircraft, and airborne sunphotometer (AATS) [9] derived AOD and in situ aerosol absorption measurements from the NASA P-3 aircraft flying in direct formation underneath the B-200, in a fire plume study during the ARCTAS (Arctic Research of the Composition of the Troposphere from Aircraft and Satellites) field campaign in 2008. Figure 4 shows the airborne HSRL data for layer-integrated aerosol backscatter and sunphotometer derived AOD.

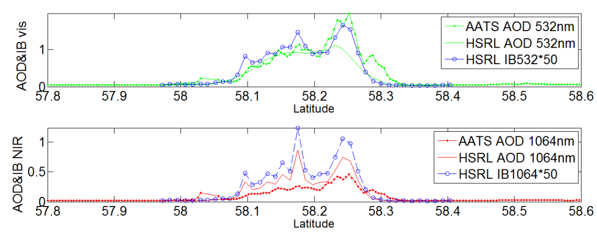

Figure 4. Airborne testbed data for the retrieval methodology, taken from observations on June 30th, 2008 in ARCTAS as a function of aircraft latitude.

The AATS AOD and HSRL-derived integrated backscatter (IB532 and IB1064) data in Figure 4 along with in situ measured aerosol absorption were used as an input to our newly-devised methodology for retrieving spectral aerosol radiative properties.

Figure 5 (top) shows the aerosol single scattering albedo (ssa) as retrieved by our multi-sensor technique for the first three bands of the Fu-Liou radiative transfer model. The bottom panel of Figure 5 shows the comparison of broadband radiative fluxes in two spectral ranges, 350-700nm in green, and 350-2150nm in red. The circles represent the radiative fluxes measured with a set of solar spectral flux radiometers (SSFR) on the low-flying aircraft, and the solid lines represent fluxes as computed with the Fu-Liou radiative transfer model with the aerosol radiative properties derived from the multi-sensor retrieval technique described above. It can be seen that the radiative fluxes compare well for the broader wavelength range of 350-2150nm, but not as well for the shorter wavelength range. This points to the possibility that differences in various spectral bands offset each other to result in a reasonable comparison in the entire wavelength range of 350-2150 nm.

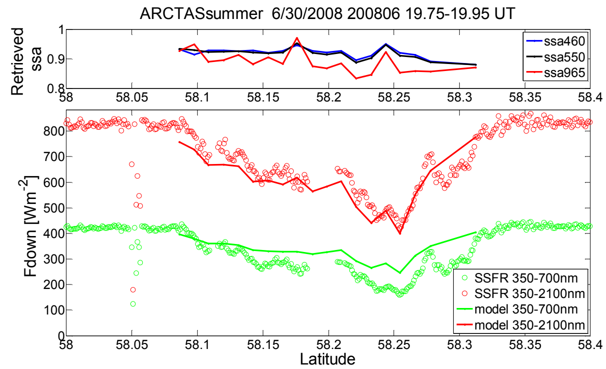

Figure 5. Top: Retrieved aerosol single scattering albedo in the first three bands of the Fu-Liou model. Bottom: Comparison of measured and modeled broadband radiative fluxes.

5. CONCLUSIONS

We have developed a methodology for the retrieval of a full set of spectral aerosol radiative properties from collocated AOD, AAOD and aerosol backscatter and extinction data as provided by the formation flying of the CALIPSO, MODIS and OMI instruments in the A-Train constellation of satellites.

In a first application of our methodology to airborne testbed data, radiative fluxes modeled based on the multi-sensor aerosol retrievals compare reasonably well with radiative fluxes measured by an airborne spectral flux radiometer aboard the same aircraft.

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