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Using Space-Borne Lidar to Identify Tropospheric Aerosols

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SUMMARY

An important contemporary problem is the identification of aerosols from space. Ground based lidar systems can use correlative measurements to determine aerosol types but spaceborne lidar systems (such as CALIPSO) rely on models for this identification. Most spaceborne systems (including CALIPSO, MODIS, and OMI) use models based on observations by AERONET, a world-wide network of ground based sun photometers. The aerosol parameters determined by AERONET include the real and imaginary refractive indices, the single scattering albedo and the extinction and absorption Angstrom coefficients. We compare the predictions of the satellite models with AERONET measurements by evaluating the Mahalonibis distances from the model prediction to clusters of aerosols of specific types (such as Urban-Industrial, Biomass Burning, and Dust). We show that some regions do not fit any of the traditional categories; consequently, aerosol identification is problematic. We discuss some of the difficulties associated with aerosol identification from space, specifically considering the CALIPSO system

Key words: Aerosols, Lidar, Aeronet, Modis, Omi, Calipso.

STATEMENT OF THE PROBLEM

It is well known that tropospheric aerosols are an important factor affecting climate change. The Intergovernmental Panel on Climate Change (IPCC) states that the aerosol contribution to anthropogenic climate change has a large degree of uncertainty. Consequently, it is of particular interest to be able to give a quantitative accounting of the amount and type of aerosols on a global basis. Only satellite borne sensors (such as the CALIOPE lidar or the OMI or MODIS sensors) can generate the density of measurements on a global scale that is required to understand the role of aerosols.

In this paper we describe the models used by three satellite groups (CALIPSO, MODIS, OMI) to identify aerosols, and we compare the results obtained from these models with the data obtained by AERONET. We find that in general there is a weak agreement between models and observations, as quantified by the Mahalanobis distances from known aerosol types.

Although it is not discussed in this extended abstract, we have found that the degree of linear polarization (a quantity that can be obtained from other aerosol parameters) can also be used as a means of aerosol identification.

AERONET

AERONET (AErosol RObotic NETwork) is an aerosol monitoring network consisting of about 200 solar-powered CIMEL Electronique spectral radiometers that measure sun and sky radiances at several different wavelengths (normally 440, 670, 870 and 1020 nm). The data obtained are inverted to give aerosol optical depths, size distributions, and diverse optical parameters such as refractive index, single scattering albedo and phase function at several different wavelengths. (Holben et al., 1998)

The AERONET archive is a valuable resource for determining properties of aerosols. Cattrall *et al.* (2005) in a preliminary study for CALIPSO used the AERONET archive to define a number of different types of aerosols, based on location and time of year. For example, measurements made at the NASA Goddard Space Flight Center (GSFC) during the period June through September were classified as “Urban Industrial”. (We have modified the Cattrall categorization somewhat because we are using Version 2 of the AERONET data and some of the types based on the earlier version are not appropriate.)

In Figure 1 we show scatterplots of extinction angstrom exponent (EAE) *vs.* single scattering albedo (SSA) for the Aeronet data from a number of different sites characterized as urban-industrial, biomass burning, dust, and a “mixed-industrial” category which was observed in Mexico City and Beijing. There are two distinct types of biomass burning aerosols, those found in Africa and those found in South America. In this analysis we used five different parameters (single scattering albedo, extinction angstrom exponent, absorption angstrom exponent, real index of refraction and imaginary index of refraction) at four different wavelengths. Plots such as Figure 1 show that different aerosol types are reasonably well differentiated, and suggests that these parameters could be used to identify aerosols from space.

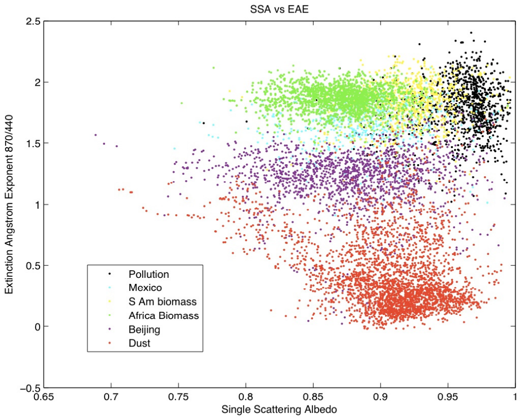

Figure 1. Scatterplot of extinction angstrom exponent (EAE) *vs.* single scattering albedo (SSA) for various aerosol types.

MAHALANOBIS DISTANCE

The Mahalanobis "distance" (which is measured in terms of the standard deviation of a data set) is an efficient and reasonable measure of the probability that a specific measurement belongs to that data set. Consequently, we evaluated the Mahalanobis distances from a set of selected measurements to the various clusters that we consider as "canonical" aerosol types, namely, Urban-Industrial, Biomass-South America, Biomass-Africa, Dust, and Mixed-Industrial. We determined which cluster is "closest" to the selected measurement and as long as it is less than 3 standard deviations from the cluster, we assume the aerosol is of that type.

The Mahalanobis distance can be evaluated using any number of parameters. We normally used five parameters at a single wavelength, but we have carried out calculations using 26 parameters, including values from four different wavelengths. The results are not significantly different from what is presented here.

The Mahalanobis distance is defined as follows: Let $\mathbf{x}=(x_1,x_2,\ldots,x_N)^T$ be an N dimensional vector representing the values of N parameters for a "test point" x. Consider a cluster of values with means given by the vector $\mathbf{m}=(m_1,m_2,\ldots,m_N)^T$. The Mahalanobis distance from the test point to the cluster is

$$D_M=[(\mathbf{x-m})^T\, S^{-1}(\mathbf{x-m})]^{1/2}$$

Where $S=\mathrm{cov}(x_i,x_j)$ is the covariance matrix whose elements are defined by $S=E[(\mathbf{x-m})(\mathbf{x-m})^T]$. Here E is the "expectation" which in our case is just the mean value.

THE SATELLITE MODELS

MODIS, OMI and CALIPSO scientists identify aerosol types based on models involving parameters obtained from their measurements. These differ for different sensors. For example, the CALIPSO instrument measures backscatter whereas MODIS and OMI are spectral radiometers. It should be kept in mind that these instruments are extremely good at carrying out their principle tasks; the identification of tropospheric aerosols is not their main purpose. Nevertheless, it is of interest to determine how well one can determine aerosol type from satellite data, so we have carried out an analysis of the models used by the three satellite groups to see how they compare with the AERONET data.

The MODIS models are divided into models for aerosols observed over land and aerosols observed over oceans. We only used AERONET data from land based photometers, so we present here the MODIS land models for comparison with AERONET retrieved quantities. The parameters used in the MODIS models were taken from the MODIS ATBD (Remer, 2004). These parameters (indices of refraction, mode radius, standard deviation, etc.) are presented as functions of the optical depth. In the figures, the nine heavy diamonds represent MODIS model results for optical depths ranging from 0.1 to 5.0 for dust and to 3.0 for other models. For example, in the EAE *vs.* SSA plot, the dust models are represented by red diamonds for τ ranging from τ= 0.1 (at the lower end of the red diamonds) to τ = 5 (at the upper end).

The parameters for our evaluations of the OMI models are taken from the OMI ATBD and Curier (2008). The OMI models do not include variations in size distribution or index of refraction with wavelength except for desert dust. As shown in the plots below, the

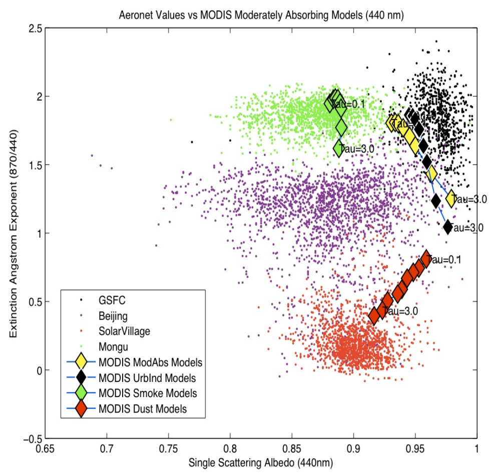

Figure 2. EAE *vs.* SSA for four characteristic aerosol types compared to MODIS models

agreement between OMI models and AERONET retrieved values is reasonable. We did not use all the OMI dust models, only those assuming spherical particles. The imaginary indices of refraction used in our calculations for dust were obtained by a large extrapolation from the UV values of Colarco (2002) and of Sinyuk (2002).

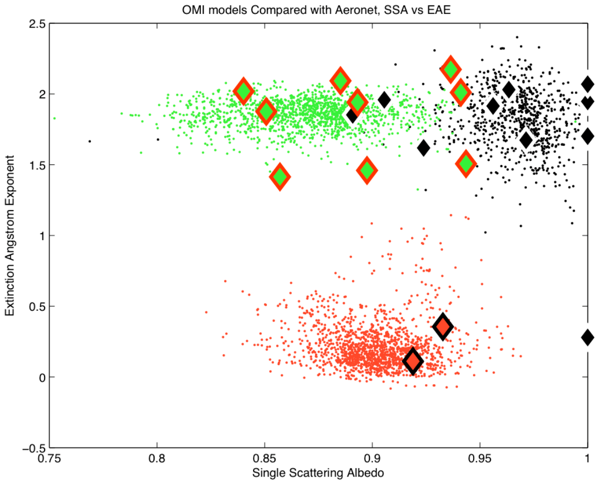

Figure 3. EAE *vs.* SSA for four characteristic aerosol types compared to OMI models.

The AERONET retrieved quantities are reported at 440, 630, 870 and 1020 nm. The CALIPSO models are for 532 and 1064 nm. Thus we can either interpolate and extrapolate the CALIPSO values to the AERONET wavelengths, or interpolate and extrapolate the AERONET retrieved values to the CALIPSO wavelengths. We chose to do the latter. The lack of agreement between the models and AERONET might be a consequence of these interpolations and extrapolations. Parameters for the CALIPSO models are from Omar (2009).

CONCLUSIONS

The Mahalanobis distance is a useful quantity for identifying aerosol types by determining its value from clusters of aerosols whose type is known with some degree of certainty. Using the Mahalanobis distance we can identify regions of parameter space for different types of aerosols and the boundaries between one type of aerosol and another. Our analysis demonstrated that Mexico City and Beijing aerosols are not similar to the Urban Industrial aerosols of Eastern USA and France. Mexico City and Beijing aerosols have properties lying between biomass burning and dust. Models used to identify aerosols from MODIS, CALIPSO and OMI are not always nearest (in terms of Mahalanobis distance) to the aerosol types they represent.

The Mahalanobis distances for the various satellite models compared to the aeronet clusters are given in the following tables.

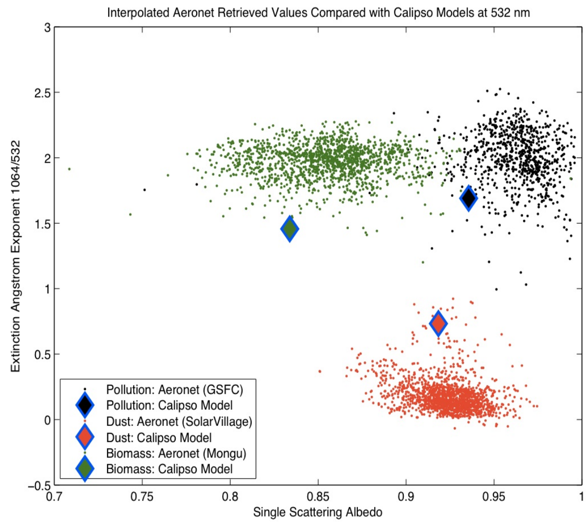

Figure 4. EAE *vs.* SSA for four characteristic aerosol types compared to CALIPSO models.

MODIS MODELS						
	Urb/Ind	Mex	S.Am	Afr	Beij	Dust
Urb/Ind	2.67	2.29	2.03	4.75	2.71	5.87
Biomass	3.89	2.62	2.00	1.74	4.15	6.24
Dust	9.06	7.05	8.07	14.9	2.65	1.95

OMI MODELS (τ=0.5)						
	Urb/Ind	Mex	S.Am	Afr	Beij	Dust
Pol1101	2.07	3.94	3.71	7.27	4.32	6.85
Biomass	2.80	3.80	2.99	4.07	5.76	7.07
Dust	16.5	15.6	14.7	28.2	6.51	3.46

CALIPSO MODELS						
	Urb/Ind	Mex	S.Am	Afr	Beij	Dust
Urb/Ind	0.81	1.93	1.54	4.21	3.09	5.37
Biomass	5.65	2.75	3.36	4.74	2.45	5.40
Dust	8.62	4.76	5.55	10.1	3.09	2.55

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