Aerosol climatology using a tunable spectral variability cloud screening of AERONET data

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[1] Aerosols, humidity and clouds are often correlated. Therefore, rigorous cloud screening can systematically bias toward less cloudy and drier conditions, underestimating the average aerosol optical thickness (AOT). Here, using AERONET data we show that systematic rejection of variable atmospheric optical conditions can generate such bias in the average AOT. Therefore we recommend two approaches to deal with cloud contamination: (1) to introduce more powerful spectral variability cloud screening and (2) to retain most of the data despite cloud contamination, estimate average cloud contamination and to correct for it. Both methods are applied to aerosol with Ångström exponent > 0.3 and compared with the AERONET cloud screened level 1.5 data. The new methods do not apply for pure dust. Analysis for 10 AERONET stations with ~4 years of data, shows almost no change for Rome (Italy), but up to a change in AOT of 0.12 or +30% in Beijing (PRC).
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1. Introduction

[2] Evaluation of chemical transport models and introduction of aerosols into climate models is based on average aerosol properties measured from ground based or satellite platforms, over a given time and space interval [*Chin et al.*, 2002; *Menon et al.*, 2002]. AERONET cloud screening (http://aeronet.gsfc.nasa.gov/) is based on variability within 1 minute (triplet measurements) and variability of consecutive samples every 15 minutes (Level 1.5 cloud screening) [*Smirnov et al.*, 2000]. The basic assumption is that clouds vary more than aerosols and a given threshold of variability can separate clouds from aerosol. *Kaufman et al.* [2005a] introduced a new spectral variability cloud-screening algorithm (SVA) of AERONET optical thickness data [*Holben et al.*, 1998, 2001]. Application to one month of data collected in Lille, France indicates that the present L1.5 AERONET cloud screening rejects variable aerosol as clouds. Aerosols can vary due to variability in humidity, the presence of nearby sources or cloud processing. Due to the correlation between the aerosols and cloud cover [*Chou et al.*, 2002; *Sekiguchi et al.*, 2003; *Kaufman et al.*, 2005b; *Koren et al.*, 2005], time averaged values may be influenced by the particular use of cloud screening.

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2. Spectral Variability Cloud Screening Algorithm

[3] The SVA cloud screening method [*Kaufman et al.*, 2005a] increases available aerosol data-volume by keeping highly variable aerosol and therefore helps improve the statistics of aerosol climatology. The physical principle behind the SVA is shown in Figure 1. Quick observation shows that the main difference between the clouds and the aerosol in the MODIS image is the difference in color. We can also see that while the clouds are more variable than the aerosol, the heavy pollution aerosol is also highly variable. Elimination of the variable aerosol means elimination of the most concentrated aerosol. The SVA is designed to screen as clouds only measurements with significant spectrally neutral variability. Plot of the AERONET data using the SVA and L1.5 cloud screenings (Figure 1) shows under representation of the hazy conditions in the L1.5 data. There is no indication in the time dependence of the Ångström exponent for cloud contamination.

[4] Another demonstration of the need of spectral screening in more controlled conditions is shown in Figure 2. The measurements represent thin smoke plumes generated by numerous small fires in the Lag-Baomer holiday in Israel. The spectrally sensitive SVA detects most of the smoke plumes while AERONET L1.5 rejected 2/3 of them as clouds. We can see in the figure that the rejected data, though variable, have similar Ångström exponent, indicating variable aerosol rather than clouds. Similar rejection of smoke plumes was found by *O'Neill et al.* [2003].

[5] The SVA used in Figures 1–2 is applied to the level 1.0 AERONET data using the following criteria [after *Kaufman et al.*, 2005a]:

[6] Triplet screening (variation over 1 minute) using spectral neutral variability for aerosol with Å > 0.3:

$$\begin{aligned} &\text{It is a cloud if : } \delta\tau^{\text{cloud}} > 0.005 + 0.02\tau^{675} \\ &\text{With } \delta\tau^{\text{cloud}} = \delta\tau^{870} - \delta\tau^{440}(\tau^{870}/\tau^{440}) \end{aligned} \quad (1)$$

where $\delta\tau^{\lambda}$ is the spectral triplet value for wavelength λ, τ^{λ} is the measured optical thickness and $\delta\tau^{\text{cloud}}$ is the estimated variability of the cloud optical thickness. The threshold dependence on the AOT in equation (1) represents the effect of humidity on the spectral dependence of the AOT. The thresholds were selected based on detailed hands-on analysis of the data. The cloud variability $\delta\tau^{\text{cloud}}$ (equation (1)) is the spectrally neutral component of the triplet variability. Lets take an example of aerosol with Å = 1, constant τ^{440} = 0.2 and variable cloud optical thickness within the 1 minute measurements between 0 and 0.06. For the aerosol we get $\tau^{870} \sim 0.5\tau^{440} = 0.1$ and

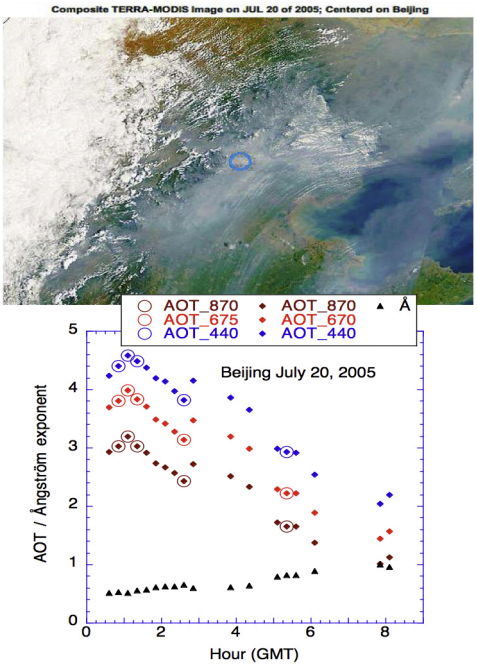

Figure 1. (top) MODIS image (July 20, 2005) of pollution in Beijing region (blue circle) observed from the TERRA satellite. The image shows the highly variable white clouds and still variable blue pollution aerosol with aerosol optical thickness as high as 5.0. (bottom) AERONET AOTs using SVA (diamonds) and L1.5 (circles) for this day and Ångström exponent (triangles).

$\delta\tau^{870} \sim \delta\tau^{440} = 0.06$ giving for clouds $\delta\tau^{cloud} = 0.03$, and rejection of the measurement as cloudy. In another example, of pure aerosol with Å = 1 but variable in time, we get $\tau^{870} \sim 0.5\tau^{440}$ and $\delta\tau^{870} \sim 0.5\delta\tau^{440}$ resulting in $\delta\tau^{cloud} = 0$ for any aerosol optical thickness and variability. This measurement is retained as cloud free. Note that the aerosol spectral measurements are taken within 10 seconds. For wind of 10 m/s it corresponds to 100m of the atmosphere. Aerosol correlation length is ~100 km [*Anderson et al.*, 2003], therefore 100 m corresponds to variability of ~0.1% in the AOT and a change in Å of only 0.002.

[7] Adjacent screening (variation over 15 minutes):

$$\text{It is a cloud if : } \Delta\tau^{cloud} > 0.0075 + 0.03\tau^{675}$$
$$\text{with } \Delta\tau^{cloud} = \Delta\tau^{870} - \Delta\tau^{440}(\tau^{870}/\tau^{440}) \quad (2)$$

where $\Delta\tau^{\lambda}$ is the maximum difference between the current AOT and the next or previous one. $\Delta\tau^{cloud}$ is the estimated variability of the cloud optical thickness. Only data with Ångström exponent, Å(440–870) > 0.3 are analyzed here (Å < 0.3 represents clouds or pure dust conditions). If the screened value is found later to be surrounded by values declared as cloud contaminated then the value is also eliminated. To be consistent with L1.5 data we screen out measurements for solar zenith angle > 78.5°.

[8] Application of the SVA is shown for 4 locations in Figure 3 and compared with the AERONET L1.5 algorithm. The SVA generates larger AOTs in Beijing and ISPRA for Å < 1. These were found to be the heavy pollution conditions of Figure 1. The density of measurements increases all along the Å axis, and is most pronounced in Beijing for Å~1.3 and in Alta Floresta in the presence of biomass burning smoke for Å~2.0.

3. Aerosol Climatology

[9] The density of measurements, the average AOT, and Å all depend on the threshold of the SVA (Figure 3). Therefore in the presence of cloud contamination the aerosol is still screened out with the clouds. Is there a way to avoid this trap of heavy aerosol being thrown away with the clouds? In Figure 4 we explore variations of the average AOT and Å with variations of the triplet cloud screening thresholds; namely for several values of the threshold in equations (1) and (2) from zero to infinity we recorded the average AOT and Å. The results are plotted as a function of the estimate of the cloud contamination optical thickness - $\delta\tau^{cloud}$. To estimate the cloud contamination we calculate the average cloud variability for all the measurements with positive $\delta\tau^{cloud}$ or $\Delta\tau^{cloud}$. The cloud variability is then converted into the cloud optical thickness using the relationship shown in Figure 4 (bottom), and subtracted from the AOT. Here the lidar measured variability of the thin cloud optical thickness is plotted as a function of the actual cloud optical thickness. This relationship basically suggests that the cloud optical thickness is on average twice

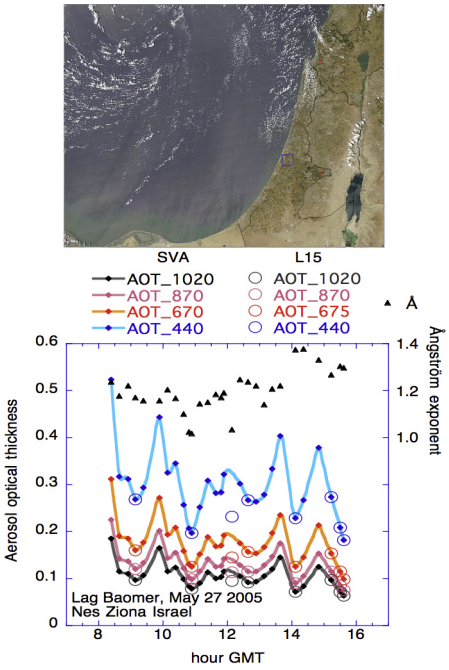

Figure 2. Time variability of the spectral optical thickness and Ångström exponent (triangles) in Nes Ziona, Israel, during the holiday of Lag-Baomer when fires are set and result in numerous thin smoke plumes. SVA (solid diamonds) detected most of the measurements as cloud free while less than 1/3 were detected as cloud free by AERONET L1.5. The L1.5 average AOT is about 25% smaller. (top) Aqua image from that day (~15 hr GMT) shows very little cloud cover in the area (the sunphotometer is in the blue box).

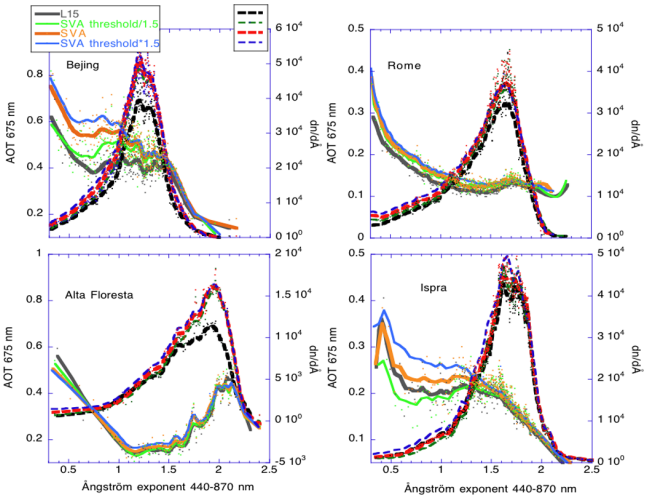

Figure 3. Aerosol optical thickness (light color solid lines) and density of measurements (strong color dashed lines), dn/dÅ, as a function of the Ångström exponent, Å. The data, from 2001–2005, are sorted by Å and averaged in groups of 100. dn/dÅ is the number of measurements, n, per unit Å. Black/gray – AERONET level 1.5 data; red/orange – spectral variability algorithm (SVA); green – SVA for thresholds reduced by 33%; blue/aqua – SVA with thresholds increased by 50%. The high AOTs with Å∼1.0 in Beijing, China and Ispra, Italy [*Mélin and Zibordi*, 2005] are due to accumulation of pollution over China and under the Alps respectively. Low Å values (∼0.5) are due to desert dust. Alta Floresta, Brazil represents an area with concentrated biomass burning aerosol. Rome represents mostly local pollution with dust intrusions for lower values of Å.

the variability of the cloud optical thickness across 1 minute for the 4 cases studied.

[10] As expected, increase in the SVA threshold increases the number of observations included, increases the average AOT and decreases Å (dashed lines in Figure 4 (top)), a clear evidence of the cloud contamination. The derived cloud optical depth estimates is subtracted from the total AOT. The correction removes most of the change in Å, leaving it practically constant. Note that the minimum value of the AOT indicates an optimum selection of the cloud-screening threshold with minimum contamination.

[11] Statistics of these data are compared in Table 1 to the statistics from the spectral variability method and from the standard L.15 operational AERONET retrieval. For some of the locations (Rome, Kanpur, Mongu) the SVA did not change significantly the average AOT but increased the data rate by 4–20%. For other sites SVA increased the average AOT by 0.02 or 9% for Alta Floresta up to 0.08 or 20% for Beijing. Relaxing the SVA threshold and correcting for the cloud contamination still did not make a significant difference for Rome, Kanpur & Mongu but increased the average AOT for other site with a maximum increase of 0.12 for Beijing. The large difference in Beijing between the L1.5 and the SVA algorithm can be traced back to Figure 1. The heavy aged pollution in Beijing with AOT values as high as 3.0 are sub-sampled in the L15 algorithm better represented by the SVA algorithm. In Table 1 we also show the annual cycle of the variation in the average AOT and Å for SVA and AERONET L1.5. The largest differences are for July–Aug with 28% additional points, or 50% more data and AOT higher by 0.16. Note that AERONET monthly climatology may correct for some of the sub-sampling of variable high AOT by giving equal weight to each day of measurements.

4. Discussion

[12] The proposed new cloud screening methods are based on the spectral differences between aerosols and clouds. Therefore we limited ourselves to Å > 0.3 and were not able to include pure dust such as observed in Capo Verde with Å < 0.3 in our analysis. Except for Capo Verde Å < 0.3 occurs only 5–10% of the AERONET measurements for the stations shown in Table 1 and Figure 4.

[13] Correction of the cloud contamination is based on a factor of 2 found to relate the cloud optical thickness and the variability of the cloud optical thickness across the 1 minute of AERONET observations. This was measured by lidar on stratocumuli in 4 different locations (maritime, rural, and semi-urban) and altitudes, 600, 2500 and 1000 m, respectively. This relationship should be established in more numerous cloud conditions. However, the fact that the corrected average value of Å is practically independent of

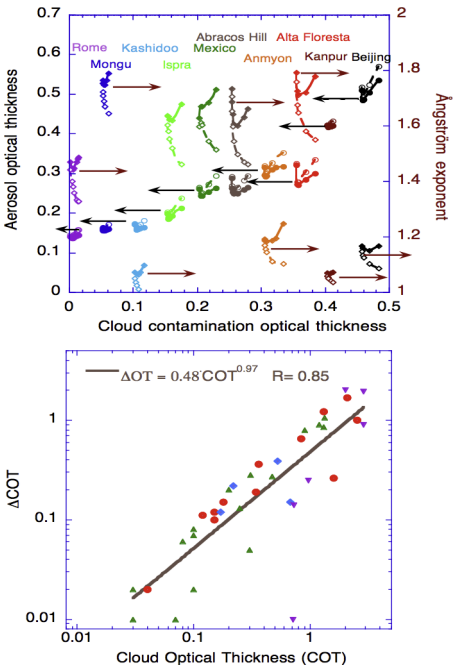

Figure 4. (top) Aerosol optical thickness (circles and arrows pointing to the left scale) and Ångström exponent (diamonds and arrows pointing to the right scale) calculated for a range of SVA cloud screening thresholds and plotted as a function of the average residual cloud contamination. Full symbols – corrected for clouds. The abscisa is shifted for each case by 0.05. Open symbols – no correction for clouds. Bottom - Lidar measurements of the 1 minute variability in the cloud optical thickness (ΔCOT) as a function of the actual COT (for ΔCOT < 1). Different symbols are for 4 different days and locations of measurements. The power law fit is for all the data.

Table 1. The Average Aerosol Optical Thickness at 550 nm (AOT), Ångström Exponent (Å), and % of Measurements for Å > 0.3[a]

	AERONET Level 1.5 for Å > 0.3			SVA Cloud Screening for Å > 0.3			Corrected for Cloud Contamination for Å > 0.3		
	AOT	Å	%	AOT	Å	%	AOT	Å	%
Rome	0.14	1.36	65	0.14	1.4	70	0.14	1.49	81
Ispra	0.18	1.56	63	0.19	1.58	67	0.21	1.68	85
Anmyon	0.26	1.15	56	0.3	1.15	65	0.32	1.25	80
Kanpur	0.42	1.02	54	0.42	1.05	74	0.42	1.07	80
Abracos Hill	0.24	1.57	51	0.26	1.6	59	0.26	1.66	76
Mongu	0.15	1.68	70	0.16	1.71	74	0.16	1.79	82
Alta Floresta	0.26	1.62	56	0.28	1.67	69	0.3	1.78	88
Kashidoo	0.18	0.92	50	0.16	1.02	54	0.16	1.1	66
Mexico City	0.22	1.44	45	0.25	1.61	71	0.26	1.73	90
Beijing - all	0.41	1.14	56	0.49	1.13	72	0.53	1.17	86
Jan–Feb	0.25	1.14	76	0.3	1.13	86			
Mar–Apr	0.46	0.98	60	0.5	0.97	77			
May–Jun	0.58	1.16	59	0.66	1.16	82			
Jul–Aug	0.47	1.31	55	0.63	1.28	83			
Sep–Oct	0.38	1.2	62	0.44	1.19	84			
Nov–Dec	0.28	1.09	35	0.32	1.09	38			

[a]Three estimates are made: (1) the AERONET L1.5 cloud screened data, (2) average after SVA screening, and (3) no cloud screening but corrected for the average cloud contamination.

the threshold of cloud screening indicates that the correction is performing well.

5. Summary

[14] The correlation among aerosol, the humidity field and clouds introduces errors into aerosol climatology derived using rigorous stringent cloud screening. Using AERONET data we show that screening algorithm that uses spectral variability is able to discriminate better between clouds and aerosol, but probably the least biased climatology can be achieved using a relaxed cloud screening and estimating statistically the cloud contamination, subtracting it later from the climatology. We showed that using this technique we derive higher aerosol average AOT in some polluted locations while keeping the same values in others. Much larger fractions of the data are retained in the process, while still maintaining fairly constant Ångström exponent.

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References

Anderson, T. L., R. J. Charlson, D. M. Winker, J. A. Ogren, and K. Holmen (2003), Mesoscale variations of tropospheric aerosols, *J. Atmos. Sci.*, *60*, 119–136.

Chin, M., et al. (2002), Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements, *J. Atmos. Sci.*, *59*, 461–483.

Chou, M.-D., P. K. Chan, and M. H. Wang (2002), Aerosol radiative forcing derived from SeaWIFS-Retrieved aerosol optical properties, *J. Atmos. Sci.*, *59*, 748–757.

Holben, B. N., et al. (1998), AERONET—A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, *66*, 1–16.

Holben, B. N., et al. (2001), An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET, *J. Geophys. Res.*, *106*, 12,067–12,098.

Kaufman, Y. J., et al. (2005a), A critical examination of the residual cloud contamination and diurnal sampling effects on MODIS estimates of aerosol over ocean, *IEEE Trans. Geosci. Remote Sens.*, *43*, 2886–2897.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich (2005b), The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proc. Natl. Acad. Sci.*, *102*, 11,207–11,212.

Koren, I., Y. J. Kaufman, D. Rosenfeld, L. A. Remer, and Y. Rudich (2005), Aerosol invigoration and restructuring of Atlantic convective clouds, *Geophys. Res. Lett.*, *32*, L14828, doi:10.1029/2005GL023187.

Mélin, F., and G. Zibordi (2005), Aerosol variability in the Po Valley analyzed from automated optical measurements, *Geophys. Res. Lett.*, *32*, L03810, doi:10.1029/2004GL021787.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo (2002), Climate effects of black carbon aerosols in China and India, *Science*, *297*, 2250–2253.

O'Neill, N. T., T. F. Eck, A. Smirnov, B. N. Holben, and S. Thulasiraman (2003), Spectral discrimination of coarse and fine mode optical depth, *J. Geophys. Res.*, *108*(D17), 4559, doi:10.1029/2002JD002975.

Sekiguchi, M., T. Nakajima, K. Suzuki, K. Kawamoto, A. Higurashi, D. Rosenfeld, I. Sano, and S. Mukai (2003), A study of the direct and indirect effects of aerosols using global satellite data sets of aerosol and cloud parameters, *J. Geophys. Res.*, *108*(D22), 4699, doi:10.1029/2002JD003359.

Smirnov, A., et al. (2000), Cloud screening and quality control algorithms for the AERONET database, *Remote Sens. Environ.*, *73*, 334–337.

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