Global Aerosol Climatology Project

Cloudless scene identification for aerosol retrieval from TOMS measurements
(NAG5-7774)
Final Report

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1. Introduction

The general objective of this research project was the development of a multi-year record of aerosol optical depth from space observations of back-scattered near UV radiances by the TOMS (Total Ozone Mapping Spectrometer) family of instruments. The application of a retrieval algorithm to derive aerosol optical depth using measurements of backscattered radiances in the near UV (330-380 nm) was proposed.

The main difficulty in the retrieval of aerosol optical depth from TOMS observations is the identification of cloud-free pixels. The main advantage of the near UV approach to characterize aerosols is its applicability over all surfaces types (land and oceans).

The proposed work included the development of a method to identify clear scenes, extending the application of TOMS retrieval to non-absorbing aerosols, and validation of TOMS derived aerosol optical depth using ground-based observations.

2. The near UV method of aerosol characterization

2.1 TOMS Record

The record of backscattered UV radiances started in October 1978 with measurements by the TOMS sensor onboard the Nimbus7 satellite and extended continuously until April 1993. A second sensor on the Russian Meteor3 spacecraft operated between August 1991 and December 1994. After an 18-month gap, the TOMS record continued with the launch of two new sensors onboard the Earth Probe (EP) and ADEOS satellites (7 months of operation until the spacecraft failure in 1997). The EP-TOMS sensor is currently operating. The Nimbus7 and Meteor3 TOMS sensors measured backscattered radiances at six wavelengths in the range 312-380 nm while the newer instruments make measurements in the 308-360 nm range.

2.2 Aerosol detection with TOMS

In the last few years, a method of aerosol detection and characterization using near UV measurements by the TOMS instruments has been developed. The aerosol detection capability in the near UV first became apparent with the development of the TOMS Aerosol Index (AI), as a by-product of the TOMS version 7 ozone algorithm *[McPeters et al*., 1996]. The AI is a measure of the change of spectral contrast in the

near ultraviolet (with respect to a purely molecular atmosphere) brought about by the radiative transfer effects of UV-absorbing aerosols such as smoke [*Hsu et al* 1996], volcanic ash [*Seftor et al,*1997, *Krotkov et al,*1999] and desert dust in a Rayleigh scattering atmosphere. The AI is a very useful qualitative indicator to identify aerosol sources and transport patterns. An inversion procedure is required to interpret the measured near UV radiances in terms of quantitatively useful parameters such as optical depth, τ, and single scattering albedo, ω_0 [*Torres et al.*, 1998].

2.3 Inversion Algorithm

Measurements in the 331-380 range, where gaseous absorption is negligible are used to derive aerosol properties. In the near-UV method, measurements of the backscattered radiance (I_δ) at two wavelengths λ_1 and λ_2, ($\lambda_2 > \lambda_1$) are used. Aerosol particles are characterized by examining the variability of the relationship between the spectral contrast ($I_{\lambda 1}/I_{\lambda 2}$) and the radiance at the longer wavelength ($I_{\lambda 2}$) , by means of an inversion algorithm that makes use of a set a pre-computed look up tables (LUT) of radiances emerging at the top of an aerosol-laden atmosphere.

The retrieved quantities are aerosol extinction optical depth and a microphysical aerosol property. When it is assumed that the aerosol type is mineral dust, the second retrieved parameter is the effective particle size. On the other hand, if a carbonaceous aerosol type is assumed, the second retrieved parameter is the imaginary component of the refractive index [*Torres et al.*,1998]. The single-scattering albedo associated with the retrieved microphysical property (and the assumed values for the others) is calculated.

Dependence on aerosol layer height and sub-pixel cloud contamination are the two major limitations of the TOMS method of aerosol retrieval.

3. Accomplished work

3.1 Algorithm Improvement

Cloud Screening

Sub-pixel cloud contamination is a major source of uncertainty in the application of the near-UV algorithm to the TOMS data. Since the TOMS family of sensors was not designed to measure aerosols, the large field of view (FOV of 40X40 km^2 at nadir and as large as 200 X200 km^2 at extreme off-nadir viewing geometry) is clearly not optimized for aerosol sensing.

A two-step cloud mask was developed. To exclude pixel-size clouds as well as obvious cloud contamination cases, a pixel reflectivity, R_{pix}, cut-off of 0.25 was applied. In the second step, the measured reflectivity and the aerosol index , AI, are combined in the quantity CM,

$$CM = \frac{R_{pix} - R_{sfc}}{AI}$$

where R_{sfc} is the surface reflectivity as given by the global climatology [*Herman and Celarier*, 1997]. The optical depth error due to cloud contamination is minimum when the quantity CM lies between zero and 20 for biomass burning aerosols, and between zero and 5 for desert dust aerosols. These threshold values were empirically derived by

systematic comparison of TOMS retrievals to ground-based measurements. For non-absorbing aerosols, the cloud screening is simply based on a maximum allowed reflectivity increase above the surface value.

Other cloud screening methods based on the use of other sensors, collocated in time and in space with TOMS, were considered. Particular attention was given to the combined use of the TOMS and THIR (Temperature Humidity Infrared Radiometer) sensors. THIR operated on the same platform as TOMS from 1979 to 1985, with a spatial resolution of 7X7 km^2. The spatial homogeneity method was applied to the THIR measurements by examining the spatial variability of the 11.5 μm radiances over a TOMS pixel. Over the oceans the spatial homogeneity analysis clearly identified the presence of cold (i.e., high altitude) sub-pixel clouds. The presence of low lying (i.e., warm) clouds, however, was not clearly detected due to the lack of thermal contrast between the clouds and the underlying surface. In addition to the difficulty of detecting warm clouds, the spatial homogeneity analysis over land is also complicated by the natural variability of surface skin temperature of terrain features.

Height of absorbing aerosol layer

The characterization of UV-absorbing aerosols is sensitive the height of the absorbing aerosol layer. This sensitivity is largest for strongly UV-absorbing aerosols and decreases rapidly with decreasing absorption [*Torres et al*., 1998]. For non-absorbing aerosols, the dependence on aerosol layer height is negligible.

In the retrieval algorithm, the height of the absorbing aerosol layer is assumed to be 3 km for carbonaceous aerosols. For mineral dust, the aerosol layer height has been taken from a climatology of monthly mean values using calculations from the chemical transport model of *Ginoux et al* (2001). The use of monthly mean values is based on the assumption that the interannual variability of aerosol height is of secondary importance. The aerosol layer height on a given day is estimated by linear interpolation using the corresponding two monthly mean values. Since the daily variability of the aerosol vertical distribution is not accurately accounted for, the aerosol layer height assumption remains a source of uncertainty in the TOMS aerosol products.

3.2 Validation Analysis

A comparison of aerosol optical depth derived from Earth Probe (EP) TOMS observations to AERONET sun-photometer measurements, was carried out at a variety of sites characterized by different types of atmospheric aerosols. In order to validate the TOMS retrieval under different aerosol load conditions we have selected six sites in regions, each characterized by one of the three most predominant tropospheric aerosol types: sulfate, carbonaceous and mineral aerosols, and with long enough records to allow comparisons along the seasonal aerosol cycle. Table 1 lists the AERONET sites used in the analysis. Except for the Banizoumbou and Bidi-Bahn sites, the satellite-ground comparisons were made at 380 nm. At the dust sites the comparison was made at 440 nm, which is the shortest wavelength available. The average of the EP-TOMS measurements within a 1°x1° box centered at the AERONET site, are compared to the average of the sun-photometer observations within 30 minutes of the satellite overpass. Correlation coefficients and the parameters of the resulting AERONET-TOMS linear fit are shown in Table 2.

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Table 1. *AERONET sun-photometer sites used in this study*

AERONET site	Lat.	Lon.	Location	Aerosol type	Period
GSFC	39N	77W	Maryland, US	Industrial	1996-2000
CART	37N	97W	Oklahoma, US	Industrial	1996-2000
Bondville	40N	88W	Illinois, US	Industrial	1996-2000
Mongu	15S	23E	Zambia, Africa	Smoke	1996-2000
Banizoumbou	14N	3E	Niger, Africa	Dust/smoke	1996-2000
Bidi-Bahn	14N	2W	Niger, Africa	Dust/smoke	1996

The AERONET database

AERONET, a federated network of CIMEL sun-photometers [*Holben et al*, 1998], measures spectral aerosol optical depths [*Eck et al*, 1999] every fifteen minutes from direct sun measurements at 8 wavelengths (340, 380, 440,500, 670, 870, 940 and 1020 nm), except for a few sites in Northern Africa where the shortest wavelength available is 440 nm. These measurements are carried out at a large number of sites around the world. Because of the availability of aerosol optical depths at near UV wavelengths, and the diversity of environments covered which allows the ground-satellite comparisons for different conditions of atmospheric aerosol load, this is a valuable data set for the validation of the TOMS aerosol optical depth.

Non-absorbing aerosols

A comparison of satellite derived optical depths of non-absorbing aerosols to AERONET observations at three locations in the continental United States (GSFC, Cart site and Bondville) are shown in Figure 1. The dotted lines above and below the one-to-one line in Figures 1a, 1b and 1c, indicate the largest of 0.1 optical depth, or 20% departure from the ground-based measurement. The resulting linear fit between the AERONET and TOMS observations is also shown. Largest EP-TOMS over-estimations occur at optical depth values lower than about $\tau = 0.2$. This over-estimation underscores the disadvantage of the large EP-TOMS FOV that prevents the separation of aerosol effects from those of optically thin clouds. For sun-photometer measured values larger than about $\tau = 0.2$, the level of agreement is within the predicted accuracy based on the uncertainties associated with the prescribed values of surface albedo and sub-pixel cloud contamination. The resulting correlation between the ground and space measurements (0.70 at GSFC, 0.84 at the Cart site, and 0.58 at Bondville) is mainly driven by those retrievals larger than $\tau = 0.3$. If only retrieved values lower than $\tau = 0.3$ are used, the resulting correlation loses statistical significance.

Absorbing Aerosols

EP-TOMS retrieved values of UV-absorbing aerosol optical depths are compared to ground based measurements at three AERONET sites: Mongu, Banizoumbou and Bidi-Bahn. The comparison in Mongu is done at 380 nm. For the Banizoumbou and Bidi-

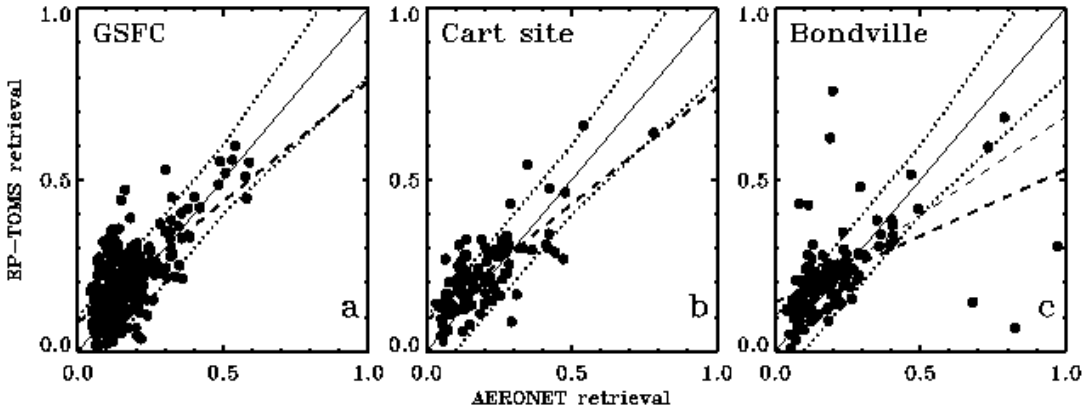

Figure 1. *Comparison of EP-TOMS retrieved optical depth for non-absorbing aerosols, to AERONET measurements at a)GSFC, b)Cart site, and c)Bondville. The one-to-one agreement is indicated by the solid line. Dashed lines represent the predicted uncertainty of the satellite retrieval (see text). The thick dashed line is the resulting linear fit.*

Bahn comparisons, measurements at the shortest wavelength available, 440 nm, were used. Scatter plots in Figures 2a, 2b and 2c depict the level of agreement between the two data sets. Dashed lines indicate the expected uncertainty associated with prescribed values of surface albedo, aerosol layer height and sub-pixel cloud contamination [*Torres et al.*, 1998]. Carbonaceous particles produced by intense biomass burning are the predominant aerosol type in Southern Africa (Zambia) where Mongu is situated. As shown in the corresponding scatter plots (Figures 2b and 2c), the EP-TOMS retrieved optical depth compares reasonably well to the AERONET measurements with most of the data within the theoretically predicted uncertainty. The resulting correlation coefficients are 0.97 (at Mongu), 0.82 (at Bidi-Bahn), and 0.83 (at Banizoumbou).

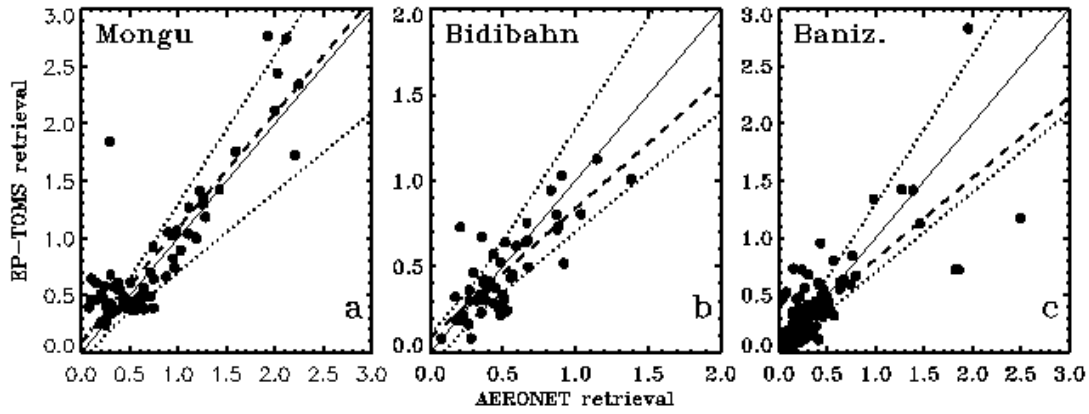

Figure 2*. As in Figure 1, for absorbing aerosols at a)Mongu, b) Bidi-Bahn. and, c) Banizoumbou*

3.3 Global Climatology

The near UV aerosol retrieval method has been applied to the multi-year record of backscattered ultraviolet radiance observations. Although the retrieval is done using two different pairs of wavelengths depending on the instrument (i.e., 340-380 for Nimbus7 and Meteor3 and 331-360 for the others) , the results are reported at 380 nm for continuity of the longer (1978-1993) Nimbus7 TOMS record. The retrieval algorithm is applied to the orbital or level-2 TOMS data. Retrieved products are gridded at a 1°X1° resolution to produce daily, weekly and monthly averages. To facilitate the inter-comparison with other global aerosol products (i.e., AVHRR, MODIS), visible optical depth and single scattering albedo products are created by converting the derived near UV parameters to 550 nm. The conversion is carried out using the theoretically established spectral dependence associated with the adopted aerosol models optical properties.

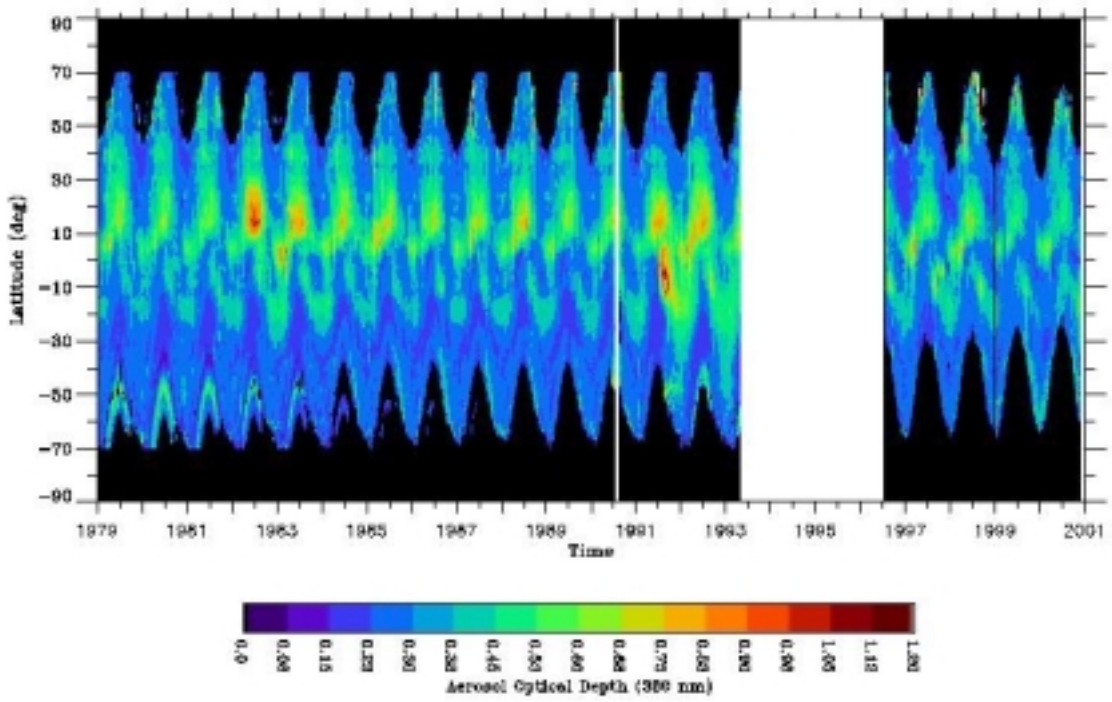

Figure 3 *Time series of the zonally averaged 380 nm aerosol optical depth over the period of operation of the TOMS instruments onboard the Nimbus-7 (1979-1992) and Earth Probe satellites (1996-present). Weekly averages over a 1°x1° geographical grid are plotted.*

Figure 3 shows the time series of global zonally and weekly averaged near UV optical depths over the years of operation of the two sensors. The one-degree longitudinal average was done requiring that at least 10% of zonal coverage was available per week. The obtained time series shows the seasonal cycle of mineral dust aerosols in the northern hemisphere and carbonaceous aerosols in the southern hemisphere. The effects of the two major volcanic eruptions of the last twenty years (El Chichon, 1982; Pinatubo, 1991) clearly show in the TOMS aerosol optical depth record.

The TOMS aerosol optical depth data is available at the TOMS homepage http://toms.gsfc.nasa.gov.

4. Publications

Results of the research activity under the Global Aerosol Climatology Project were summarized in the following publications:

Aerosol properties from EP-TOMS near UV observations, Torres, O, J.R. Herman, P.K. Bhartia, and A. Sinyuk, accepted for publication in Advances in Space Research, 2001.

A long term record of aerosol optical thickness from TOMS observations and commparison to AERONET measurements, Torres, O., J.R. Herman, P.K. Bhartia, A. Sinyuk, P. Ginoux and B. Holben, accepted for publication in the Journal of the Atmospheric Sciences, special GACP issue, 2001

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