Aerosol optical thickness from GOME data. Methodological approach and preliminary results.

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Abstract

A suitable methodological approach to retrieve the radiatively equivalent aerosol optical thickness from GOME data has been developed. The approach consists in having built up an algorithm based on a spectral radiative transfer model able to simulate the multilayer aerosol atmosphere seen by GOME over the sea. The aerosol optical properties needed for radiative transfer computations are taken from a complete data base of components and classes based on the most widely known and used models. The spectral reflectivities obtained by the model using different aerosol classes are compared with those one obtained by GOME data. The paper presents the algorithm approach together with a brief overview about the radiative transfer model, the aerosol optical properties data base and the first results obtained by applying the outlined algorithm to GOME data.
Keywords: Aerosol retrieval, GOME instrument

Introduction

Models and analyses of global warming agree that most long-lived gases that human activity add to the atmosphere make the Earth warmer than it would otherwise be. Anthropogenic (linked to fossil fuel and biomass burning) and natural aerosols act in the opposite direction on the temperature distribution on the Earth, by reflecting the sunlight back into the space before it reaches the surface and by absorbing the infrared radiation. Even though the cooling effect is mainly caused by anthropogenic aerosols, other kind of aerosols, like volcanic aerosols can contribute to short term variations.

In the last two decades satellite measurements (for instance the METEOSAT visible channel, AVHRR and TOMS data) have been extensively used to detect airborne particulate matter and to retrieve the main aerosol properties as for instance the optical thickness or the total mass loading. The remote sensing technique guarantees in fact a reliable, global scale and long-term record of aerosol properties needed to asses the aerosol impact on climate.

The presented approach aims to exploit the spectral coverage and resolution of the GOME instrument to retrieve, at least over oceanic, low reflecting areas, the vertical aerosol optical thickness and the aerosol class present on the footprint of the instrument. GOME (Global Ozone Monitoring Experiment) is a spectrometer measuring the radiance reflected from the Earth's atmosphere in the UV-Visible spectral range (from 240 to 790 nm) with a moderately high resolution (about 0.3 nm in the Visible and NIR) currently flying on the ERS2 satellite.

The ability of GOME in detecting smoke, soot and biomass burning (i.e. absorbing aerosols) using the index first proposed by Hsu et al. (1996) for TOMS has already been explored (J. Gleason, private communication) and a good correlation with TOMS results has been found. So the ability of GOME in detecting tropospheric absorbing particles seems demonstrated: in the absence of any other information the reflectivity difference between 340 and 380 nm can be used as a smoke index for studies of biomass burning.

Here we present a completely independent method in which the aerosol optical thickness is derived at several wavelengths by comparing GOME measured reflectances with reflectance values computed by means of a suitable radiative transfer model for several selected aerosol classes and for aerosol extinction optical thicknesses ranging from 0.01 to 1.

The comparison is carried out at a set of wavelengths selected to avoid the main gas absorption features. Then the Angstrom coefficient α is derived by linearly fitting the spectral aerosol optical thickness $\tau(\lambda)$ values (α is the slope of the graph of $\log \tau(\lambda)$ versus $\log \lambda$) for each class. Finally the slopes derived this way are compared with the theoretical slopes pre-computed for each tested class. Assuming that the aerosol present on the measured scenario is giving rise to the smallest difference between the theoretical and the retrieved slope, the aerosol class and the spectral optical thickness are determined.

In the next section a detailed description of the method is given and the aerosol classes used in the comparison are briefly presented. Then the results of an analysis of the method carried out using synthetic spectra obtained from MODTRAN instead of GOME measurements are presented, to show the performances of the method in well defined situations. Finally the method is applied to several real GOME measurements.

Aerosol spectral optical thickness retrieval: methodology

The synthetic reflectance spectra to be compared with GOME measurements are obtained from the radiative transfer code GOMESIM.

GOMESIM is based on a solution of the monochromatic Radiative Transfer Equation for a plane-parallel, homogeneous atmosphere first proposed by Sobolev (1963) and then adapted to a three layer atmosphere (Guzzi et al., 1996). The three layers have the following features: i) the aerosol is imbedded into a single layer, having a constant mixing ratio by density with scattering molecules, ii) the others two layers are formed only by molecules. The atmosphere is bounded at the bottom by a Lambertian reflecting surface.

GOMESIM computes the single scattering radiation correctly, taking into account the vertical variation of single scattering albedo and phase function. The solution for the higher order of scattering was found by setting a radiatively equivalent, vertically homogeneous, pure-scattering atmosphere, with ìeffectiveî and simplified phase function and scattering optical depth. The aerosol absorption is approximately described by means of transmittance factors.

The radiative transfer computations are carried out at a set of wavelengths selected to avoid the main gaseous absorption features. These wavelengths are reported in Tab. 1. Selecting wavelengths in atmospheric windows greatly simplifies the radiative transfer computations and allows to detect aerosols with a minimum of interfering effects.

Wavelengths (nm) considered free of molecular absorption for aerosol optical depth determination					
361 427 each 3nm	752.9	755.9	777	780	783

Tab. 1

The interaction between aerosol and solar radiation is described by the extinction coefficients, the single scattering phase function and single scattering albedo. These spectral properties are obtained by means of an Aerosol Data Base (ADB) (Levoni et. al., 1997) which, taking physical and chemical properties of basic components, allows to obtain optical properties of default as well as user-defined aerosol classes. An aerosol class is defined as a mixture of aerosol components by assessing the mixing ratio.

In this work only the aerosol optical properties of those classes defined by authoritative sources, such as WMO-112 (World Climate Research Program, 1986), WCP-55 (World Climate Research Program, 1983), LOWTRAN (Shettle et al., 1979), díAlmeida (díAlmeida et al., 1991), have been computed. These classes are reported in Tab. 2 along with the Angstrom coefficient (see below).

Class number	Class	$-\tilde{\alpha}$
1	Clean continental (díAlmeida)	1.048
2	Average continental (díAlmeida)	1.142
3	Urban (díAlmeida)	1.152
4	Clean maritime (díAlmeida)	0.1142
5	Maritime/polluted (díAlmeida)	0.7132
6	Desert background (díAlmeida)	0.05804
7	Desert wind-carry (díAlmeida)	- 0.06259
8	Maritime (WMO-112)	0.2522
9	Continental (WMO-112)	1.082
10	Urban/industrial (WMO-112)	1.233
11	Rural (LOWTRAN)	1.073
12	Urban (LOWTRAN)	0.9411
13	Maritime (LOWTRAN)	0.4987
14	Volcanic 1 (WCP-55)	- 0.02865
15	Volcanic 2 (WMO-112)	0.4950

Tab. 2

The spectral variability of atmospheric aerosol optical thickness $\tau(\lambda)$ can be described by a quantity α through the well known Angstrom relationship (Shifrin,1995):

$$\tau(\lambda) = \beta(\lambda/\lambda_0)^{-\alpha} \quad (1).$$

This formula shows that the spectral dependence of optical thickness becomes linear in a logarithmic plane, in fact:

$$\log \tau(\lambda) = -\alpha \log(\lambda/\lambda_0) + \log \beta \quad (2)$$

where α represents the angular coefficient of the straight line (2) and can be regarded as a spectral signature of the aerosol class.

For each class shown in Tab. 2 the spectral dependence of the extinction coefficient and therefore the parameter α has been computed by fitting with a straight line the extinction coefficients extracted from the ADB. Letís call $\tilde{\alpha}_{i=1,\ldots,15}$ these computed values relative to each class in the ADB, then the retrieval algorithm is based on comparison between $\tilde{\alpha}$ values and the α retrieved with the following procedure: the GOME reflectances at each wavelength are compared with the ones simulated with the forward model previously described, GOMESIM, by

$$\left| \frac{R_{Gome}(\lambda) - R_{Gomesim}(\lambda, \tau_{500}, class)}{R_{Gome}(\lambda)} \right| < \varepsilon \quad (3).$$

For a fixed $\bar{\lambda}$ and for each aerosol class, letís call $\tau_{min}(\bar{\lambda})$ and $\tau_{max}(\bar{\lambda})$ the smallest and the greatest values of $\tau(\bar{\lambda})$ that generated a $R_{Gomesim}(\lambda)$ that satisfies the (3), with $\varepsilon = 0.025$. A weighted linear fit (Press et al., 1992) is carried out, using $(\log \lambda_i, \log \tau_{med,i})$ as points and $(\sigma(\lambda_i) \cdot \log e / \tau_{med,i})$ (Bevington, 1969) as weights, where

$$\tau_{med}(\lambda_i) = \frac{\tau_{max}(\lambda_i) + \tau_{min}(\lambda_i)}{2}$$

$$\sigma(\lambda_i) = \frac{\tau_{max}(\lambda_i) - \tau_{min}(\lambda_i)}{2}$$

and $i = 1,\ldots,28$ is the number of wavelengths used.

If only one value of $\tau(\lambda)$ is found then:

$$\tau_{med}(\lambda) = \tau_{found}(\lambda)$$

$$\sigma(\lambda) = \frac{1}{2} \cdot 0.01$$

where 0.01 is the step used for the variation of τ at 500 nm, given in input to GOMESIM.

As a result of the fit, we obtain for each tested class the angular coefficient α_{retriv} and the $\log \beta$ (see eq. (2)). The goodness of the fit is evaluated by testing the probability Q that the observed χ^2 will exceed the value χ^2 by chance even for a correct model.

The fit is considered successful when $Q > 10^{-3}$ and $\sigma_{\alpha\, retriv} < 0.1$, where $\sigma_{\alpha\, retriv}$ is the uncertainty in the angular coefficient retrieved.

The ranking among the classes, whose fit has been considered successful, is made by:

$$\min_{class=1,\dots,15} \left| \alpha_{retriv} - \tilde{\alpha} \right|$$

i.e. the class that leads to the minimum difference between the retrieved and the theoretical slope is assumed present on the target.

Finally the spectral optical thickness is computed using the

$$\tau(\lambda) = 10^{\left(-\alpha_{retriv} \cdot \log(\lambda) + \log \beta\right)} \quad (4)$$

where α_{retriv} is provided by the ranking procedure.

Application of the method to controlled scenarios

Before applying this retrieval method to real GOME data, some tests have been performed using MODTRAN3 (Berk et al., 1989) to reproduce a few controlled scenarios.

MODTRAN3 is a well-known and widely used computer code based on AFGLís code designed to determine atmospheric transmission and radiance at moderate resolution from 0 to 50000 cm^{-1}.

MODTRAN3 and GOMESIM differ from each other for the atmosphere vertical structure (MODTRAN3 is representative of a plane parallel atmosphere divided into four height regions each having a different aerosol type, while in GOMESIM the aerosol is imbedded into a single region), for the treatment of multiple scattering (MODTRAN3 runs with a multiple stream DISORT algorithm), as well as for the classes of aerosol available (MODTRAN3 runs with LOTRAN classes while GOMESIM uses 15 aerosol classes presented in Tab. 2).

Four reflectance spectra have been generated using MODTRAN3 to act as pseudo-measured spectra: three with boundary layer aerosols (Maritime, Rural and Urban) and one with a stratospheric aerosol (Volcanic with extreme volcanic profile and Fresh volcanic extinction). The surface albedo has been considered constant and equal to 0.01 with Maritime and Volcanic and 0.3 with Rural and Urban aerosol.

The application of the method described in the previous section to the four test scenarios produced the following results:

- the Maritime (LOWTRAN) has been matched by a Maritime (WMO-112) with a relative error in the total aerosol optical thickness of 2.8% at 550 nm. Maritime (LOWTRAN) was the second in the ranking with an error in the total aerosol optical thickness of 8% at 550 nm;
- the Rural (LOWTRAN) has been matched by Average continental aerosol with an error in the total AOT of 11% at 550 nm;
- the retrieval of Urban and Volcanic aerosol has been unsuccessful.

Results indicate that over maritime surface the proposed method is able to retrieve a maritime aerosol class. However the Maritime WMO-112 class is retrieved instead of the LOWTRAN maritime class present on the target scenario: indeed, the two aerosol classes produce reflectance spectra very similar, so the error in retrieving the class is considered of minor importance.

Preprocessing of GOME data

GOME radiance and irradiance (level 1) data have been extracted in ASCII format from the DLR product; data have been obtained from 14 orbits, starting from 022, Oct.22, 1996 and ending with 000 Oct.23, 1996. Reflectances have been then computed, for ground central pixels lying between 70 deg. Lat. N 70 deg. Lat. S, and only at wavelengths satisfying the following conditions: a) radiance and irradiance spectra presented matching calibration wavelengths; b) wavelengths were lying within absorbing gas-free windows (see Tab. 1). Instrumental noises at the beginning of Band 3 have been noticed and automatically avoided.

Since spectral reflectance jumps between the GOME Bands 2b and 3 occurred, they have been automatically detected and flagged, and corresponding spectra have been discarded. Jumps and offsets prevent to use at least 40% of the pixels at our disposal. Since those spectra had been correlated with non homogeneous targets, this seems a self-consistent way to avoid ground pixels for which the homogeneity hypothesis do not hold. The spectral resolution of GOME data has been lowered by means of a box average process over selected wavelengths, with a width of 6 nm (first window) or 4 nm (second and third windows). The aim of such a choice was twofold: to reduce the noise and to filter the Ring signature from data, especially within the first window where the effect of the presence of Fraunhofer lines is largely clear, e.g. around 395 nm. Wavelengths whose average process has been successful have been selected and used in the retrieval as well as those that showed a Ring Effect residual smaller than 1%.

Application of the method to real cases

The retrieval procedure presented has been applied to the GOME data described in the previous section. A sample of the result of the retrieval is shown in Fig. 1.

In the figure the retrieved optical thickness over the GOME pixels for several orbits is shown. Holes between adjacent pixels in an orbit represent situations in which the data have been discarded due to the reasons seen in the previous section or to the fact that none class led to a successful fit. In a first approximation these pixels are suspected to be cloud contaminated.

Analyzing all the processed data respect the aerosol classes we found that 84 % of the data are related to Maritime (LOWTRAN) aerosol class, 3 % are Clear maritime, 4 % of Maritime/polluted, 2 % Maritime (WMO-112), 2 % Continental and 1.8 % Average continental.

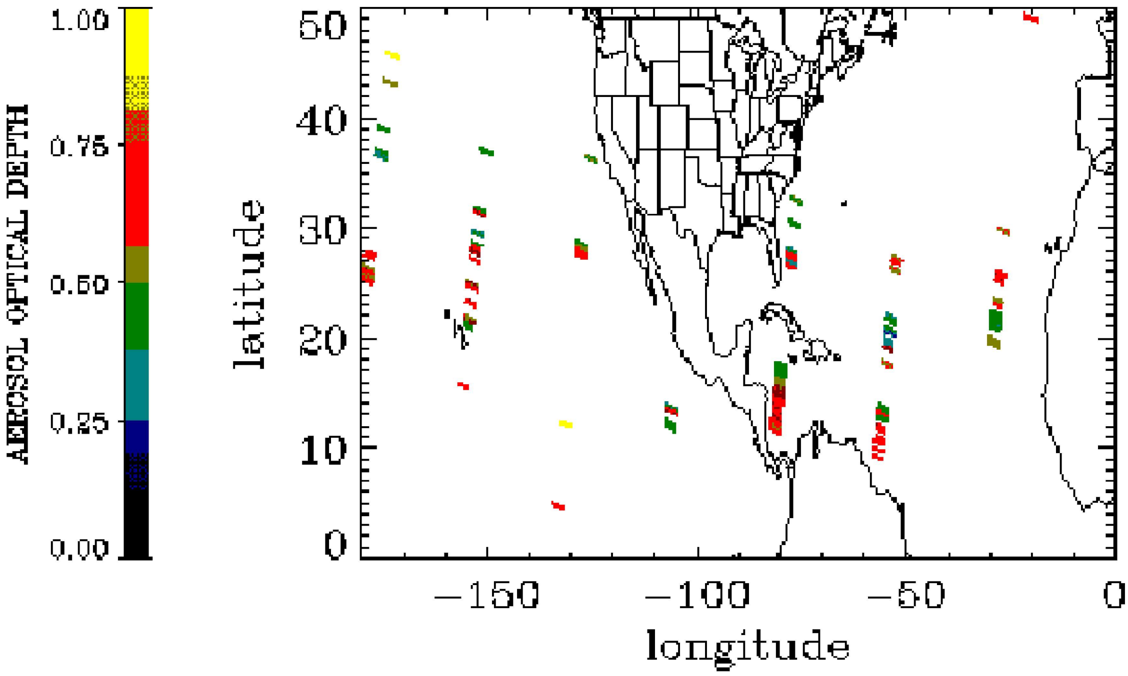

Fig. 1

Conclusions

From the simulation over controlled scenarios is evident that our algorithm is able to retrieve the aerosol optical thickness over the sea. The retrieval of the aerosol class needs more tests and investigations before to be considered fully reliable. Particular attention will be put on the selection of the optical thickness to be linearly fitted: the present choice can be considered precise only if the reflectance linearly depends on $(\tau(\lambda))$, and this assumption, even if adopted by other retrieval methods, can become critical at the wavelengths where strong aerosol absorption is active.

The correlation between the failure of the retrieval method and the presence of clouds detected by using METEOSAT images has been devised.

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