Mapping Aerosol Optical Depth over Europe using ATSR-2 data.

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ABSTRACT: Algorithms have been developed to retrieve aerosol optical depth over sea and over land, using data from ATSR-2, GOME and AVHRR. Over land, the dual view capability of ATSR-2, combined with the spectral information in the visible and near-infrared bands, is used to eliminate the influence of surface reflections on the radiance received by the radiometer. The GOME algorithm uses only wavelengths in the UV. With the present algorithms developed by TNO-FEL, aerosol optical depth can only be retrieved in cloud-free conditions. To ensure that the pixels are not cloud-contaminated, a semi-automatic cloud-screening algorithm is applied. The results were validated by comparison with sun-photometer data. The dual view algorithm was, among others, applied to map aerosol optical depth over Europe in August 1997. The maps are used together with data obtained from aerosol-transport-chemistry models. For easy comparison, the original optical depth results on a 1x1 km^2 grid were re-sampled on the model grid size. Results show large gradients in the aerosol optical depth over Europe, and regions with high pollution levels are clearly visible.

Introduction

Aerosols have been identified as an important factor in the regulation of the Earth' climate. The incoming solar radiation is scattered by aerosols, which induces a negative (cooling) effect on the atmospheric radiation balance. The magnitude of this direct aerosol effect is a major uncertainty in climate models [IPCC, 1995], and may be similar to that of the warming effect of greenhouse gases. It is noted that certain types of aerosols also absorb radiation. This property has often been used to identify aerosols by satellite remote sensing and providing an aerosol index. However, the absorption of many anthropogenic aerosol types that are important for climate, such as ammonium sulphate and ammonium nitrate, is negligible at wavelengths in the visible.

Apart from their effects on climate, aerosols are important for a variety of other processes and effects. Examples are health-related problems such as the amount of UV radiation reaching ground level and the concentration of respirable dust in our living environment. The effect on UV radiation is similar to the effect on climate; i.e. the particles scatter and absorb UV radiation, thus reducing the intensity of the radiation reaching ground level. Hence, to estimate the effects of aerosols on UV radiation levels, their column-integrated concentrations need to be known locally. The problem of respirable dust is different in the sense that only aerosols near ground level are important. Generally is assumed that the aerosol is mainly confined to the boundary layer. However, there is evidence that significant concentrations often occur in elevated layers. At present information on the height dependence of aerosol concentrations cannot be obtained from satellite retrievals with sufficient vertical resolution.

The concentrations and occurrence of aerosols are highly variable in both space and time, due to the presence of many direct sources with strongly different source strengths, atmospheric residence times of several days, and a variety of transport mechanisms that disperse the aerosol throughout the troposphere. The latter depends on the meteorological situation. In addition, many gaseous precursors are emitted which constitute secondary aerosol sources that are spread in space and time.

To obtain information on the regional and global distributions of aerosols, and thus on their effects on climate and other important issues such as health and environmental effects, satellite remote sensing is a very promising tool. Different satellite instruments are nowadays (becoming) available that have been designed to yield specific information that can also be used for aerosol retrieval.

Aerosol retrieval from satellite data

Algorithms for the retrieval of aerosol properties were developed at the TNO Physics and Electronics Laboratory (TNO-FEL) for application over land and over water [Veefkind, 1999]. These algorithms can only be applied when there are no clouds. In that case, the radiance received by satellites at the top of the atmosphere (TOA) is composed of contributions due to scattering by gases and aerosols, and reflection at the surface. Absorption by molecular species and aerosols further modify the TOA radiance. Hence the signal received by electro-optical instrumentation on satellites in principle contains information on the surface properties and on the atmospheric composition. The problem is to separate the various contributions.

Until recently it was thought that aerosol retrieval was only possible over water, i.e. dark surfaces with very low reflection. For this application, several algorithms were developed at TNO-FEL using data from AVHRR, ATSR-2 and GOME [Veefkind, 1999; Veefkind and De Leeuw, 1998; Veefkind et al., 1999a; De Leeuw and Veefkind, 1999].

However, at TNO-FEL also algorithms have been developed that can be applied over land with data from ATSR-2 and GOME [Veefkind, 1999; Veefkind et al., 1998; 1999b; De Leeuw and Veefkind, 1999]. For future application, these algorithms will be adapted for use with AATSR and SCIAMACHY on ENVISAT.

Retrieval over land using the dual view algorithm

Over land the surface albedo in the visible and near-infrared is often relatively high and variable. Because the contribution of the surface reflection to the TOA is not accurately known, it cannot be corrected for in a simple way. Therefore, the dual view algorithm was developed for the retrieval of aerosol optical depth over land [Veefkind et al., 1998]. It uses the unique dual view capability of the ATSR-2 sensor, which provides a forward view and a nadir view for the same pixel, separated by only two minutes.

The dual view algorithm uses both the spectral and directional information to eliminate the surface contribution from the TOA in the visible. It is based on the assumption that the shape of the bi-directional surface reflectance is independent of the wavelength, and that the effect of aerosols on the optical depth at 1.6 µm is small. The algorithm was developed with data from the TARFOX experiment at the US eastcoast[Russell et al., 1999], and further validated with results from experiments over NW Europe [Veefkind et al., 1999a]. An example of the validation with TARFOX data is shown in Figure 1, where optical depth retrieved from ATSR-2 data is compared with optical depth measured with co-located airborne sun-photometers, both plotted as a function of wavelength. Other results are presented in Veefkind et al. [1999b], where a comparison is made between data in a relatively clean air mass over De Bilt (NL) (AOD < 0.1 at 0.55 µm) and a more polluted air mass over Lille (F) (AOD ≅ 0.25 at 0.55 µm). Even for very small optical depth, the satellite derived data and the sun photometer data compare favourably.

An aerosol optical depth image for the TARFOX area is shown in Figure 2 [Veefkind et al., 1999a]. The aerosol optical depths over the North Atlantic and over the North American continent were both derived with the dual view algorithm. The results blend smoothly across the coastline. Over the North Atlantic, the results from the dual view algorithm compare favourably with those from the over-water algorithm. It is noted that this is not always the case.

In other areas the dual view algorithm sometimes yields high AODs over water [Veefkind et al., 1999b]. Likely this is due to the assumption that the contribution of aerosols to the AOD at 1.6 µm is negligible. In marine air masses the concentrations of continental aerosol particles (usually smaller than 1µm) are often low. In that case the contribution of sea spray particles, with diameters larger than 1 µm, to the radiation at 1.6 µm can be relatively high, especially in high winds. This is a point of further investigation.

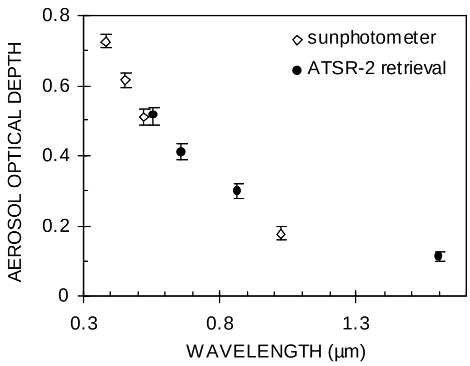

Figure 1. Aerosol optical depth retrieved from ATSR-2 data, and aerosol optical depth from co-located airborne sun photometer measurements. Error bars indicate the standard deviation.

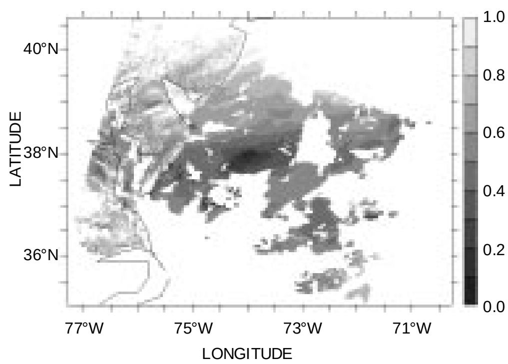

Figure 2. Aerosol optical depth image derived from application of the dual view algorithm to ATSR-2 data obtained during the ERS-2 overpass over the TARFOX area on July 25, 1996, 15:52 UTC.

Sensor synergy
The algorithms developed for application with GOME andATSR-2 were applied to retrieve the AOD over Europe [Veefkind, 1999; Veefkind et al., 1999b; Robles-Gonzalez et al., 1999]. A case for 25 July 1995 is presented in Veefkind et al. [1999b]. As an example for the good comparison between the results from both sensors, the spatial variation of the aerosol optical depth is shown in Figure 3. A problem for such comparison is the large difference in pixel size, 1x1 km^2 for the ATSR-2 data, and 320x40 km^2 for the GOME data in 'default' operation mode, and the different wavelengths at which the retrievals are made. ATSR-2 has fixed bands, and retrievals can be made in the 0.55, 0.659 and 1.6 µm bands, whereas for the retrieval from GOME only the UV data up to 0.4 µm can be used with the present algorithm. For the comparison in Figure 3, the ATSR-2 AOD results were averaged over the GOME pixel size and converted to 0.4 µm.

On the other hand, the different wavelengths also have an advantage, since information is obtained over a wider spectral regime. For the GOME/ATSR-2 combination this implies that information is available form circa 0.34 µm to 1.6 µm, which allows for accurate determination of the spectral shape of the aerosol size distribution, expressed as the Ångström coefficient. This is a very powerful option for the GOME/ATSR-2 combination (and in the future for SCIAMACHY/AATSR) because the sensors are based on the same satellite and thus measure simultaneously.

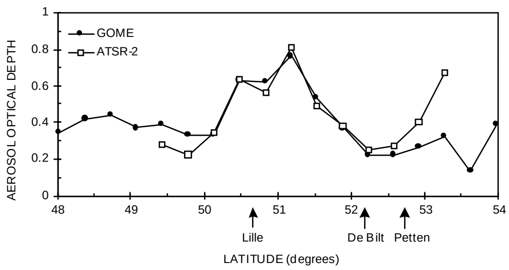

Figure 3. Spatial variation of aerosol optical depth at 0.400 µm, as determined from GOME and ATSR-2 data on 25 July 1995, 10:50 UTC. ATSR-2 data were averaged over GOME pixels and converted to 0.4 µm.

An example is presented in Figure 4, where information from ATSR-2 and GOME is combined to yield the spectral optical depth from 0.34 µm to 1.6 µm. A power law fit through these data yields values for the Ångstrom coefficients of 0.7±0.1 for De Bilt (Figure 4a) and 1.6±0.1 for Lille (Figure 4b). The latter value is in good agreement with the Ångstrom coefficient derived from sun photometer data in Lille, i.e. 1.8±0.2, in particular when it is realised that a sun photometer point measurement is compared with a GOME result averaged over a large area of 320x40 km^2. The higher value of the Ångstrom coefficient in Lille indicates a more polluted air mass with relatively high concentrations of small continental aerosol particles, as compared to those in De Bilt. This result is supported by the analysis of the aerosol optical depth over NW Europe for that day, which indicates that the air mass over The Netherlands was relatively clean while the air mass over Belgium and northern France had been transported over polluted industrial areas in the UK and Germany [Veefkind et al., 1999b]. Continental sources usually contribute most to the fine aerosol fraction (particles smaller than 1 µm).

Data such as presented in Figures. 2 and 4 can be used to derive aerosol properties in more detail. The Ångstrom coefficient yields information on the shape of the aerosol size distribution, which, combined with the optical depth, can be used to estimate the mean size distribution in the column. Combination of retrieved aerosol optical depth images with aerosol-chemistry transport models is a promising tool to derive more detailed information on the aerosol properties, i.e. their sources, transformation and composition. A first example of such an application is presented in Veefkind [1999], where data from GOME retrievals over Western Europe are compared with initial results from an aerosol chemistry transport model that predicts sulphate aerosol concentration based on sulphur dioxide (SO_2) emissions. Many assumptions had to be made in this comparison, leaving room for major improvement. The power of such combination of aerosol retrieval with modelling is both in the model development and validation, as well as in the interpretation of the retrieved aerosol fields.

Mapping aerosol optical depth using ATRS-2 data

Studies such as those presented above for 25 July 1995 are now carried out for the whole month of August 1997. Results from aerosol retrievals for this month and results from aerosol chemistry transport models are combined in a study on the effects of aerosol on health.

A problem in such studies with radiometers or spectrometers on ERS-2 is the spatial coverage. With an overpass once every three days, large

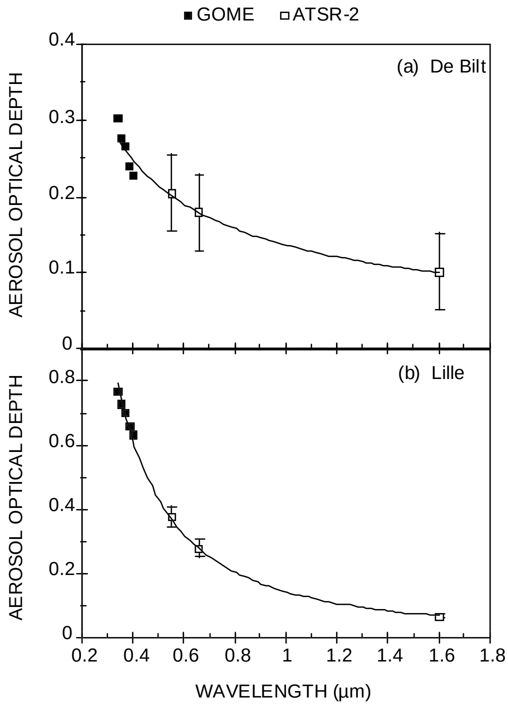

Figure 4. Aerosol optical depth versus wavelength as retrieved from ATSR-2 and GOME data on 25 July 1995, 10:50 UTC. Figure 4a shows data for the GOME pixel covering De Bilt (The Netherlands), in Figure 4b data are presented from the GOME pixel nearest to Lille. Lines are power fits to the combined ATSR-2 and GOME data, yielding the Ångstrom coefficient.

gaps result in the data which hamper the interpretation as regards the spatial coverage of the aerosol optical depth. This is illustrated in Figure 5, where aerosol maps of AOD are shown for four consecutive days, 7, 8, 9 and 10 August 1997. The coloured areas indicate AOD on the scale given on the rhs of each map. Grey areas indicate cloud coverage. The blue arrows indicate the analysed wind fields overlaid on the same maps. The latter show the circulation pattern with an easterly flow over Central Europe during all four days. The pressure systems responsible for this flow pattern gradually moved east.

The interpretation of the aerosol data in Figure 5 as regards the variation from one day to another, or in connection with the flow pattern is not easy. Also the presence of clouds, apparently moving with the pressure system, does not facilitate the interpretation. Areas with very high AOD of 0.6 and more are observed, but also areas where the AOD is smaller than 0.1. Individual results were validated with sun photometer data across Europe, with generally good agreement [Robles-Gonzalez et al., 1999].

To obtain a homogeneous picture of the distribution of the AOD over Europe, maps such as reproduced in Figure 5 were averaged into a composite map for the whole month of August. Data were averaged over pixels of 0.1^{o}x0.1^{o} (circa 10x10 km^2), which also facilitates comparison with model results on a similar grid scale, while at the same time the amount of data is significantly reduced (initially over 4 GB of data were obtained for August 1997). The result is a map of mean AOD for Europe for August 1997 [Robles-Gonzalez, et al., 1999] that shows the industrialised and polluted areas such as those in west and central Europe, northern Italy, etc., with a mean optical depth of circa 0.6. Other areas such as Scandinavia, south France, Spain, middle and south Italy and Russia are relatively clean with mean AOD of circa 0.1 or less. In these clean areas, some populated and/or industrialised areas can be identified by enhanced AOD, such as Tallin in Estonia, and Göthenburg and Stockholm in Sweden.

Discussion and conclusion

This is the first time that such a map for AOD over land was produced from satellite observations. The data will be used in studies on aerosol effects, as indicated in the introduction. In particular, they will be used in studies on the effect of aerosol and ozone on UV levels, and on the concentrations of respirable dust at ground level.

Other maps are produced for different regions, such as west of Africa, where the ACE-2 (Aerosol Characterisation Experiment) [IGAC, 1995] took place in the summer of 1997. These studies are aimed at the determination of the effects of aerosols on climate, through studies with different degree of detail of aerosol dynamics and transport. Hence the interaction between observations of different types, from very local micro-scale measurements to large-scale airplane measurements and satellite observations with model studies is expected to yield better insight into the aerosol dynamics and transport processes and their effects on a variety of issues.

For direct application of the results in climate studies, the aerosol effects on the incoming and outgoing radiation are most important. This information can be directly obtained from the retrieval. However, extension to larger wavelengths is required to fully take into account the effects of aerosols on outgoing thermal radiation.

Future application to SCIAMACHY will extend the wavelength range further into the IR. The developed algorithms are generic and will be further developed for application to instruments on future missions. Both polar orbiting and geostationary satellites will be needed for different applications related to, e.g., climate, air pollution and health problems on local, regional and global scales.

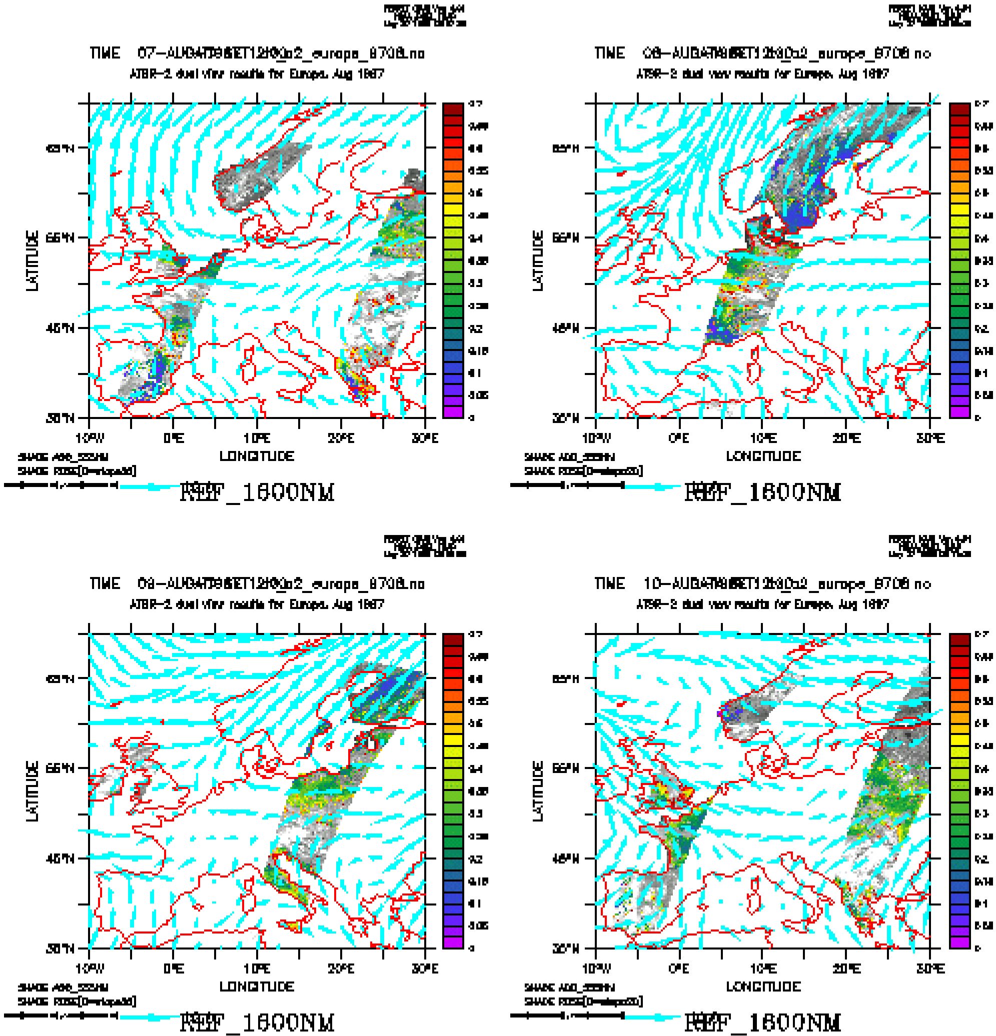

Figure 5. Maps of AOD for 7, 8, 9 and 10 August 1997 retrieved from ATSR-2 data over Europe. The AOD values are given in the colour scale on the rhs of each Figure. Grey areas indicate cloud contaminated pixels, and the blue arrows indicate the analysed wind fields.

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