Determination of fine particulate matter from MERIS and SeaWiFS aerosol data

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1 ABSTRACT
Over land, the Dense Dark Vegetation is used to derive in a first stage the aerosol path radiance and in a second stage to propose an aerosol product which consists of the aerosol optical thickness at 443 nm. Air quality monitoring of the particles is based on measurements of PM₁₀ and PM₂.₅, which are respectively the density of particles of diameter lesser than 10 µm, lesser than 2.5 µm, at the surface. The satellite aerosol product can be converted into PM₁₀ and PM₂.₅, based on different assumptions: particle density and vertical distribution mainly. This first attempt to monitor PM from space can be validated with in-situ data. Another approach will simply consist in using the in-situ PM measurements to calibrate the satellite imagery. Within the frame of a European project called EXPER-PF, we generated, over an area centred on Lille (50°36’ N, 3°08’ E, North of France), a data base with the SeaWiFS archive, and the PM data collected by the regional air quality network. The above technique will be applied and validate using this data base. MERIS data will be integrated in 2004. We show here the potential improvements on the aerosol product we can expect from MERIS

Keywords: Aerosol over land, Air quality, EXPER-PF project.

2 INTRODUCTION
The role of Earth Observation for monitoring the environment is a rapidly growing activity with important European projects emerging in 1990's and 2000's such as ENVISAT. There is a need for developing specific processing tools for these new observation capabilities in order to provide value-added products with regard to socio-economic aspects. This is particularly true for health management where little has been done previously and where the social demand is important. An important effort has been developed on the remote sensing of tropospheric aerosol from space¹. The new era of sensors have better characteristics for the aerosol remote sensing over land (MERIS, MODIS and MISR). The high resolution and narrow spectral bands of these sensors offer an accurate detection of aerosols from space. Here, we first aimed to use the MERIS sensor for which an atmospheric correction algorithm for the remote sensing of tropospheric aerosol over land has been developed². SeaWiFS sensor has been chosen because its spectral bands are very close to those of MERIS (visible and near infra red spectral bands) and we got a 6 year archive representing more than 3500 LAC Level 1B images.

Air quality is an environmental issue it is generally monitored from ground based networks. Because particle matter settles down into the breathing system with a risk of effect on health, particle matter density level is subject to new regulations and relevant ground based instrumentation is deployed on purpose. Because the new generation of Earth Observation sensors offers the opportunity to remote sense aerosol over land, we propose here to derive from SeaWiFS particle matter. First, based on a simple conversion of the retrieved aerosol optical thickness into PM with different assumptions. The first assumptions is the sphericity of aerosols, which significantly simplify the optical theory. The second is that aerosols are identical in the atmospheric column. This assumption is valid because this is the atmospheric column that is seen from space. There is also an assumption on the vertical profile of aerosol. The aerosol model is chosen to know the refractive index and the density. These assumptions allow to convert aerosol optical thickness into PM. Within the frame of a European project called EXPER-PF (see www.appanpc-asso.org/experpf/), we generated, over an area centred on Lille (50°36’ N, 3°08’ E) in the North of France, a data base with the SeaWiFS archive and the PM data collected by the regional air quality networks of Belgium and North of France. As for epidemiological studies, this data base aims at providing an estimation of the background exposure to fine particles and this for multi-year time series on a regional scale. This approach is very new but has a great potential. Unfortunately, assumptions made for the conversion from aerosol optical thickness into PM are too restrictive and we propose here, to use ground based measurements to calibrate the satellite data. Ground measurements allow to retrieve optical parameter, which validate the aerosol model.
3 THE MERIS-LIKE AEROSOL PRODUCT

3.1 Algorithm description

The usual strategy for the remote sensing of aerosol over land in the visible and NIR spectral range is the use of dark targets. There are several advantages of using the dark targets with low surface reflectances. First, the impact of the uncertainties in the estimated surface reflectances on the aerosol optical thickness estimates is smaller for lower surface reflectances because the atmosphere path radiance dominates in top of atmosphere (TOA) radiance. Second, the absorption effect of aerosol is small for low surface reflectances, but is significant for brighter targets. Thus, the impact of the uncertainties in the aerosol absorption, given by the single scattering albedo, on the aerosol optical thickness estimates is also smaller for lower surface reflectances. The dark vegetation was determined by high values of NDVI with low reflectance in the near-IR. DDV is dark in the spectral bands where the chlorophyll absorption is strong, in the blue (400-500nm) and in the red (600-700nm) spectral regions. These bands are always present in ocean colour mission.

We generate level 2 aerosol products on SeaWiFS images based on the atmospheric correction scheme developed for MERIS. SeaWiFS input images are L1B images. They consist of 8 calibrated radiances, the sun zenith angle, the view zenith angle and the relative sun-view azimuth. Here is a list of the successive steps that are performed on a pixel basis:

- Conversion from radiance to reflectance.
- Correction from the ozone absorption with ancillary data from TOMS.
- Computation of the barometric pressure from the GLOBE 1km Digital Elevation Model and assumption of an exponentially decreasing pressure vertical profile with an scale height of 8 km and actual pressure from meteorology data at z=0.
- Correction from the molecular scattering. This correction is applied for a better selection of the DDV pixel.
- Select a DDV model in auxiliary data base depending on location and date.
- Computation of the ARVI (Atmospheric Resistant Vegetation index) and selection of the DDV pixels. An ARVI threshold is computed for the selected DDV model.
- Aerosol inversion above DDV pixels in the chlorophyll absorption spectral region. From the blue and red top of aerosol reflectances, we can just expect to derive two pieces of information on the aerosol model: the abundance on the atmospheric column (or the aerosol optical thickness) and a parameter for the size distribution. Due to poor knowledge of aerosols, the simplest, though realistic, description for the size distribution by a Junge power law is assumed

\[ n(r) = r^{-\alpha - 3} \]

Where the Angström coefficient \( \alpha \) describes the wavelength dependency of the aerosol optical thickness \( \tau_a \).

The aerosol path radiance can be retrieved in these spectral bands over DDV and, for a given aerosol model, we obtain \( \tau_a \), the aerosol optical thickness (AOT). This retrieval is performed for four aerosol models (\( \alpha = 0, -0.5, -1, -1.5 \)). The model for which the Angström coefficient is the closest to that obtained from the \( \tau_a \) retrieval is then selected. The aerosol refractive index \( m \) has to be specified by the user among 1.33 (pure water), 1.44 (sulfate) and 1.55 (continentale dust) with a default option \( m = 1.44 \).

A sensitivity of this algorithm to the key selected parameters (ARVI threshold, aerosol refractive index \( m \)) indicated that \( m \) has a little impact on the aerosol product while the ARVI threshold driven the aerosol type more substantially. The validation of the algorithm products has also been done, comparing retrieved aerosol products with \textit{in situ} sunphotometer measurements of the AERosol RObotic NETwork (AERONET).

3.2 Example of AOT maps from SeaWiFS over North of France

In Figure 1 we show an example of two consecutive SeaWiFS aerosol maps obtained with this algorithm over North of France. Maps were generated within the European EXPER-PF project and are available online through the web server of the project for referenced users. The aerosol index of refraction was set to 1.44 and ARVI thresholds for the detection of vegetation have been lowered by 0.15 compared to what is used in the nominal MERIS ground segment. These thresholds allow a good spatial covere for the aerosol product over land, at least for June. Aerosol product over water is obtained from SeaDAS processing. There is a good consistency between AOTover land and ocean. The main limitation is the quality of the cloud mask. AOT are abnormally high in the vicinity of clouds. This problem is also encountered in MERIS level 2 nominal products. Along the coast we see also typical adjacency effects.
3.3 Aerosol Product Improvement with MERIS

Figure 2 shows the result of applying the same algorithm to MERIS level 1B images recently acquired over the same region on 16, 19 and 22 September 2003. On 16 and 22, the region was partly covered by cirrus clouds whereas on 19th the atmosphere was cloud free day. The spatial cover of the AOT is less important than in June because vegetation cover decreased. We also plotted $\Delta P$, the difference between surface pressure derived from the MERIS O$_2$ band (band 11) and barometric pressure, versus AOT in order to show the impact of thin clouds on the aerosol product. MERIS has the capability to improve the cloud mask over land and thus remove outliers in the aerosol product.
4 FROM AEROSOL PRODUCT TO PM

4.1 Formulation

Air quality monitoring is based on the measurements of PM$_{10}$ and PM$_{2.5}$, which are respectively the density of particles of diameter lesser than 10 $\mu$m and lesser than 2.5 $\mu$m at the surface. The satellite aerosol product can be converted into PM$_{10}$ and PM$_{2.5}$, based on different assumptions. The particle density has to be estimated and depends on the aerosol type. The vertical distribution of aerosol is a key parameter for the conversion. Validation activities conducted over land show that the most robust parameter retrieved was the aerosol optical thickness at 443 nm over dark vegetation. Once again, in order to perform the conversion from optical quantities to fine particles concentration, the aerosol model was fixed to the average continental model (ACM). The formulation of the PM$_{x}$ is:
Where $d$ is particle density ($\mu g.m^{-3}$), $H_a$ is the aerosols vertical scale height (km), $\tau_a$ is the aerosol optical thickness at 443 nm derived from the satellite data ($m^{-1}$), $\Sigma_{sca}$ is the aerosols scattering coefficient at 443 nm ($km^{-1}$) and $n_0(r)$ (resp. $n_1(r)$) is the aerosol size distribution for hydrated ambient particles (resp. dry particles). The first assumption for the inversion of the satellite product into PM was an averaged continental model composed of mineral, water soluble and soot. This aerosol model allows calculating the aerosol scattering coefficient with a relative humidity of 70% ($\Sigma_{sca} = 0.0577$). Relative humidity is taken into account because we are computing aerosol optical properties in the ambient conditions. This aerosol model also allows estimating the particle mass concentration for dry matter ($D = 16.6 \mu g.m^{-3}$). $H_a$ is the aerosol vertical scale height in the case of an exponentially decreasing aerosol vertical profile. For this study, the default value of 2 km has been applied.

4.2 First results

As for epidemiological studies dealing with gases, air quality ground networks bring most of the information concerning particles exposure. Nevertheless, whether their sampling is representative is still a matter of debate, the spatial coverage is sometimes very sparse, measurement accuracy is weak for PM$_{2.5}$ as several methods are currently used, and background exposure is badly known. Figure 3 shows the Region Of Interest of the EXPER-PF database along with the locations of the PM measurement stations.

![Figure 3. Area of interest and air quality networks measurement stations](image)

We reprocessed the whole SeaWiFS database according to Eqs. 2 in order to provide time series. On Figure 4 is represented the variation of the mean PM$_{10}$ from SeaWiFS data over a square area of 50 km around Lille. This figure shows that the significant seasonal variation is well reproduced but that there is an anomalous number of days with very high values of PM derived from SeaWiFS. Nevertheless the order of magnitude is reasonable with an overall overestimation of 100%. With a good cloud mask and a better estimation of the aerosol vertical profile we shall be able to start real correlation studies between space based and ground based PM measurements. There is a clear need for ancillary data and for a sensitivity study to the size of the averaging box. This will be possible online soon thanks to the interrogation and visualisation tool of the EXPER-PF Web site.
Figure 4: (Top) Correlation between SeaWiFS derived PM$_{10}$ ($\mu$g/m$^3$) and AERONET AOT at 440 nm. Satellite data were average over a 50x50 km box centred on the town of Lille (France, 50’36° N, 3’08 E); (Bottom) monthly average of ground based PM$_{10}$ (mg/m$^3$) for the same time interval for three representative measurements stations in the 50x50 km box.

4.3 Comparison between instantaneous satellite and ground based PM measurements

In Figure 5 is represented the comparison between the satellite and AERONET PM product versus the ground PM measurement for each coincidence within half an hour. For this comparison, we use the ground based measurement value closest to the satellite overpass. Contrarily to monthly average the scatter plot of instantaneous coincidence shows that satellite and ground dataset are uncorrelated whereas AERONET and PM are slightly correlated. That means that the assumptions were too restrictive and some improvements are needed. First of all, the aerosol product has to be improved.
and then the aerosol model has to be validated. Finally, the aerosol vertical profile, which is considered homogeneous in the atmosphere, play a key role in the aerosol scale height and can change the PM value two or three times. The variability of the relative humidity has also to be taken into account. At last, the distinction between rural and urban ground based measurement has to be done to avoid high source of aerosol.

4.4 Calibration using ground based optical data

The use of the satellite images can be improved by the calibration of satellite data using ground based optical measurements. In order to understand the relationship between in situ PM measurement and optical measurement, we can use the sun-photometer data from 3 sites in the region of interest. These three sites are Wimereux (51.78° N, 1.6° E), Oostende (51.13° N, 2.55° E) and Lille. The sun-photometer first measures sky the solar extinction in different wavelengths that can be reliable to the aerosol optical thickness and Angström coefficient \( \alpha \), defined as:

\[
\frac{\tau_\alpha(\lambda)}{\tau_\alpha(\lambda')} = \left( \frac{\lambda}{\lambda'} \right)^\alpha
\]

For a given type of aerosol, size distribution and refractive index, the abundance is proportional to the aerosol optical thickness. This value is more directly accessible from ground based measurements than from space. The correlation from optical and in situ measurements is possible. An example of such analysis is given in Figure 6. We plotted the dataset of Figure 5 for several classes of the Angström coefficient. For \( \alpha=1 \) sun-photometers and PM are well correlated but for other classes the correlation is weak. It is necessary to go further in the analysis with an integration of meteo data. From space, we do not have access to the solar extinction measurements but instead to the sky radiance. The aerosol remote sensing algorithm extracts the aerosol path radiance in primary scattering \( L^{(i)}_\alpha \):

\[
L^{(i)}_\alpha = \frac{\tau_\alpha(\theta)}{4\mu_v},
\]

where \( P_\alpha \) is the aerosol phase function, \( \Theta \), the scattering angle and \( \mu_v \), the view zenith angle. We will search for correlation between \( \mu_v, L^{(i)}_\alpha \) and PM in order to better calibrate our satellite data. The same approach can be used on the sky radiance from the optical ground measurements. It is more direct because of the absence of contamination of the optical signal by the ground surface.
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AERONET data and we want to thank all AERONET PI for the use of their data and specifically B. Holben, D. Tanré. NASA DAAC center and particularly to James Acker. The validation work took benefit of the good availability of tailored MERIS data. The feasibility study using SeaWiFS data has been possible due to the long term support of the 1. M. D. King, Y. J. Kaufman, D. Tanré, and T. Nakajima, “Remote sensing of tropospheric aerosols from space: Past, present and future.”, Bulletin of the American Meteorological Society, 80, no. 11, pp. 2229-2259, 1999.

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5 CONCLUSION

Remote sensing of particle matter from space is a challenging issue. To answer to this problem, we have to understand the relationship between the optical characteristic of aerosol and the in situ ground measurements of the PM. Different problems have been identified to improve the determination of particle matter from space. First of all, the aerosol product has to be corrected from cloud contamination. Then the climatology of the aerosol model can be improved by ground based optical measurement. The vertical profile of aerosol and the relative humidity can be improved with LIDAR or meteorological data. Another approach is to make a more direct correlation between aerosol path radiances and PM. A universal linear regression does not appear suitable. This calibration has to be conducted on radiance corrected from viewing angle, for defined scattering angle ranges and Angström coefficient classes and for various meteorological conditions.

Figure 6.: PM10 (µg.m⁻³) from in situ in Lille vs. AOT at 440 nm from the AERONET sun-photometer for various classes of Angström coefficient α.

y = 0.0041x ; R² = -0.6735

y = 0.0079x ; R² = 0.5395

y = 0.0069x ; R² = 0.172

y = 0.0071x ; R² = 0.0735

y = 0.0071x ; R² = 0.0735

y = 0.0069x ; R² = 0.172

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