High resolution 3D-mapping of urban air pollution using EO data

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ABSTRACT: This study deals with the original combination of a digital elevation model (DEM) with satellite-based information on the spatial distribution of air pollution over a large urban area namely, the Greater Athens Area in Greece. At a first stage high spatial resolution imaging data acquired by the TM and ETM+ sensors on board the Landsat satellite series were carefully selected so that they are representative for air pollution conditions over Athens. At a second stage the satellite data were processed by applying in-house developed algorithms allowing assessing and mapping the aerosol optical thickness (AOT) over the entire examined area. The AOT values retrieved using the second spectral band of TM/ETM+ correlate with fine particle concentrations (i.e., with a diameter smaller than 2.5 μm), which are considered amongst the most hazardous to human health; therefore the information depicted by AOT maps is potentially related to the air quality situation over the examined area during satellite image acquisition. At a third stage, the use of a DEM derived by ASTER satellite data optimised the satellite-based AOT information in two ways: (i) the pollution cloud was represented in 3D maps over the Greater Athens Area, and (ii) the upper limit of the cloud was delineated so as to allow to approximate the atmosphere’s mixing height and to convert AOT values to air quality related information.

1 INTRODUCTION

Air pollution has been considerably interfering with visibility since the beginning of the industrial era. Visibility impairment is due to the emission of atmospheric aerosols, which are liquid and solid particles suspended in the air from natural or man-made sources (Kaufman et al. 1997a). Man-made aerosols can be sulphates, nitrates, organic, ash etc. (Seinfeld and Pandis 1998), and naturally generated aerosols can be produced by soil erosion or biomass burning (Tegen et al. 1996). Aerosols of small diameter (fine particles) have been linked to pollution impact on the health of citizens (Pope et al. 1991, Swartz et al. 1996, Samet et al. 2000, Brunekreef and Holgate 2002). Increased aerosol concentrations are encountered usually in urban areas, where pollution is monitored by ground based instruments but mapping its distribution is a highly uncertain task mainly due to the large spatial and temporal variability of the aerosols.

Satellite remote sensing, now known as Earth observation (EO) is likely to be a valuable tool for assessing and mapping aerosols (e.g., King and Greenstone 1999) due to its major benefit of providing complete and synoptic views of large areas in single snapshot. Despite this fact a review of published literature revealed relatively few applications of EO data for urban and regional air quality. As reported by Engel-Cox (2004) the causes of this scientific “delay” appear to be related to a series of obstacles; among that the poor collaboration between air quality and satellite scientists, the limited resources both financially and in trained personnel of the urban air quality
sector, and the priority given to “global change” vs. local environmental applications by the EO scientific community in the last decade. We could add to these the natural advantage of satellites for global observations along with their ability to provide data “easier” for the higher than the lower atmosphere and, finally, the technical complexity in discerning the tenuous signal of urban pollution sources from the embedded signal of larger polluted air masses.

As a consequence urban air quality has been so far monitored by networks of ground monitoring stations and/or by models evaluating emissions and predicting changes in air quality. The limitations of using these approaches became gradually evident: on the one hand, ground-based stations can monitor conditions only at isolated points so they provide an accurate but limited geographic picture of the pollution trajectory from the sources to the receptor; on the other hand models provide “simulated” instead of “real” information on pollution phenomena, and heavily depend on the initial conditions.

Currently the use of EO to assess and eventually to map aerosol loading over cities where most anthropogenic pollutant emissions arise and the human population lives received considerable attention from researchers who have developed a variety of techniques using EO data with spatial resolutions varying from low such as, Meteosat or AVHRR (Kaufman et al. 1990, Holben et al. 1992, Costa et al. 2002, Ignatov and Stowe 2002, Retalis et al. 2003) to high such as, SPOT or Landsat) (Sifakis and Deschamps 1992, Sifakis et al. 1998, Retalis et al. 1999, Wald and Balleynaud 1999).

The current research work used high spatial resolution EO data to assess and map the aerosol distribution over a highly polluted urban area that is, the Greater Athens Area, not only horizontally but also to represent it in 3D. The optical indicators used to express the aerosol load were here the optical thickness and the scattering coefficient, which are key parameters for satellite-based aerosol assessments (Kaufman et al. 1990), and are directly linked to the visibility (Aranuvachapun 1983).

2 METHODOLOGY

2.1 What does the satellite observe?

The Landsat satellite system with its TM and ETM+ sensors was chosen for this study for the following reasons: (i) it has the wider swath (dimension of the area covered by a single scene) from all high spatial resolution EO sensors, that is, 185 km by 185 km, (ii) it has a relatively low data purchase cost (less than 0.5 € per sq. km), and (iii) it is one of the first EO satellites launched with the oldest image archive.

Landsat, just like any other high spatial resolution EO sensor, is destined to observe the Earth’s surface not its atmosphere. The latter, however, even when it looks limpid, affects both the downwelling solar and the upwelling emitted or reflected by the Earth energy. Therefore, any change in the composition of the atmosphere such as, by the presence of pollution, modifies the electromagnetic signal received by the satellite sensor through interaction mechanisms that take place between radiation and the atmospheric components. The most common of these interaction mechanisms are light absorption, scattering and backscattering caused by atmospheric molecules (gases) and by particles (aerosols). Scattering, for example, by high concentrations of aerosols is accounted for visibility reduction while absorption by nitrogen dioxide is accounted for the yellow-brownish coloration of the urban pollution cloud (Waggoner and Weiss 1985). These phenomena are translated into the optical atmospheric effects (OAE) on the satellite images:

(a) The “blurring” OAE degrades the image texture by making dark targets to appear brighter and bright targets to appear darker due to contrast reduction (Tanre et al. 1988), and is present mainly in the visible and near infrared spectral bands; it is due to the scattering and backscattering induced by fine particles.

(b) The “screening” OAE obscures the image in the visible wavelengths by making all targets to appear darker, and is due to absorption by black particles such as, soot.

(c) The “opacity” OAE veils the image in the thermal infrared due to the attenuation of upwelling radiative temperature by particles (Sifakis et al. 1992).
EO sensors generally use the so-called “atmospheric windows”, that are parts of the electromagnetic spectrum where absorption by gases is negligible, on the other hand absorption by particles depends on black particles such as soot, rarely found isolated in the atmosphere. High spatial resolution satellite-based pollution observations are therefore primarily linked to elastic scattering resulting in an angular redistribution of the photons after their interaction with molecules or particles. Non-elastic scattering mechanism does not concern this category of satellite sensors because it can only be observed in very narrow spectral bands such as the ones used by very low spatial resolution sensors (e.g., TOMS). Elastic scattering can be broken down into the factors of molecular or Rayleigh scattering and of particulate or Mie scattering. Both these mechanisms are wavelength dependent (selective); Mie scattering can be non-selective when particles are too large compared to the observed wavelength (this is the case of cloud particles). The first of these two scattering mechanisms (i.e., Rayleigh) is strongly present in the unpolluted atmosphere, and is not sensitive enough to detect pollution variations. Finally, the mechanism used to assess pollution by high spatial resolution satellites is the aerosol (or particulate) scattering, and the satellite-based surrogate used for pollution quantification is the aerosol optical thickness (AOT) of aerosol scattering. AOT is the integral from the ground to the satellite (z) of the extinction coefficient due to scattering by aerosols \( k_{\text{scat}} \) at a given wavelength \( \lambda \) and its magnitude is directly connected to the columnar concentration of optically effective particles:

\[
AOT(z, \lambda) = \int_0^z k_{\text{scat}}(z', \lambda) dz' 
\]

These optically effective particles that affect the satellite signal over urban areas may consist by primary (i.e., directly emanated) or secondary particles (i.e., formed in-situ); their chemical composition is expected to correspond to the dominant scattering species typically associated to \( \text{SO}_4^{2-} \), occurring both in acid and neutral salt forms, and to \( \text{NH}_4^- \) that is found in secondary particulate pollutants. It should be noted here that as this kind of satellite measurement is based on the quantification of the scattering efficient particles, exclusively absorbing particles, though rarely found isolated, could be underestimated.

2.2 How is air pollution assessed?

Since high spatial resolution EO systems do not allow a direct retrieval of atmospheric parameters, the quantification of pollution is attained differentially as follows: comparative radiometric measurements taken on EO images acquired under clear (reference) and under characteristic pollution conditions allow to quantify the OAE due to pollutants. Resolving the radiative transfer equation allows the retrieval of AOT values. Extracted AOT values are thus relative to the reference satellite data used (i.e., acquired under atmospheric conditions when AOT is nearly zero).

More specifically AOT can be quantified by means of the SMA code (Sifakis et al. 1998), which is applicable to high spatial resolution EO data containing information from the visible and thermal infrared spectral regions. This code assumes a uniform particle size distribution and composition over the examined area and neglects bidirectional reflectance. The second spectral band of Landsat TM/ETM+ is used to retrieve AOT values in the visible spectrum, in particular at 0.55 \( \mu m \) where, according to Mie’s law, the scattering coefficient depends on optically effective particles with diameters between 0.1 and 3 \( \mu m \) (Van de Hulst 1957). The SMA code also uses information from the thermal infrared band to distinguish between real OAE due to pollution and apparent OAE due to ground temporal variations that may exist in the compared images. AOT is then calculated for each cell of the domain of interest and represented in maps with a spatial resolution of the same order of the spatial resolution of the EO sensor used; in the case of Landsat: 30 metres by 30 metres.

Since AOT is the integral of the extinction coefficient due to scattering from the ground to the height of the satellite orbit the AOT profiles derived by EO refer to the total atmospheric column. In order to calculate the scattering coefficient, which is directly linked to the concentration of
particles, AOT has to be divided by the appropriate scale length under well-mixed conditions. As almost 90% of fine aerosols stay within the so-called mixing layer of the atmosphere, which spans from the ground up to the mixing height \( h_{\text{mix}} \), a reliable approximation would be to consider that the correct scaling height for the scattering coefficient is the mixing height (Sarigiannis et al. 2005a). This height is so far calculated from meteorological data, based either on in situ observations, or on meteorological models. The innovative part of the current study is that the mixing height is approximated with the use of a digital elevation model (DEM) combined with the AOT maps without involving any other external meteorological information or measurement. By dividing the value of AOT with the mixing height, the scattering coefficient of the aerosol within the lower section of the troposphere (the mixing layer) is reckoned. The satellite-based information is thus normalised to reflect air quality in terms of ground level aerosol load.

3 RESULTS

3.1 The study area

The area tested by this study was the Greater Athens Area, an urban region well known for its air quality degradation due to emissions from transport, industry and domestic heating. The local pollution monitoring network of EARTH carries out systematic measurements of the important gaseous and particulate pollutants in the area. Nonetheless, due to the complex terrain and dispersed pollution sources there are difficulties in mapping the air pollution dispersion over Athens, especially when monitoring is based on a sparse network with stations disputable for their representative location; the location of the stations has been based on empirical criteria rather than an independent and objective means that could give a synoptic view of the pollution distribution over the entire area.

The air pollution phenomenon in Athens-Greece is known as “the nephos” (the cloud, in Greek) a name that underlines its visible character. Visibility impairment during pollution episodes is due to high burden of aerosol particles in the atmosphere while the yellowish-brown colour of the cloud is due to high NO\(_2\) concentrations. In Athens, as in most densely populated urban areas, aerosol particles are formed in the lowest part of the atmosphere as secondary aerosols (ammonium sulphates or nitrates and organic particles rather than soot).

3.2 Satellite data selection

The first step in this study was the selection of the high spatial resolution EO data acquired by the TM and ETM+ sensors on board the Landsat satellite series. This selection was a critical phase as it could directly affect the reliability of the results; one satellite image (reference image) had to be as clean as possible in terms of pollution load, and the others should be representative in terms of pollution conditions. The selection of the reference image determines the reliability of the results as during this day the atmosphere should be homogeneous and if possible totally un-polluted. The selection of this key-day requires the consultation of existing ground-based measurements; in our case it was based on the data made available from the EARTH monitoring network.

Twenty-two satellite images in total covering the study area had already been selected in the framework of the RETROPOLIS and ICAROS NET projects, covering the time period of the last twenty years. The following two spring-time images were chosen as “pollution images” for the purposes of the current study: 26 April 1994 and 13 June 1994. The image acquired on 16 August 2000 was used as “reference image”.

3.3 Derivation of AOT maps

The initial step in satellite image analysis was a geometric pre-processing consisting in an absolute rectification (geo-referencing). The images, when necessary, were corrected applying a least-square regression, and the values of the pixels were resampled using the nearest-neighbour algorithm in order to maintain intact the pixels distribution pattern and avoid any alteration of the raw radiometric
values (digital numbers). For the same reason, no stretching or any other contrast enhancement techniques were applied to the histograms of the images prior to the main processing.

The SMA code was subsequently applied allowing to assess AOT values over the entire examined area. This code has been developed “in-house” and is applicable to Landsat two-image data sets composed by one “pollution image” and one “reference image”. The code initially calibrates the images aiming to render them radiometrically comparable; this includes transformation of the digital numbers to apparent (at-satellite) radiance values and then to apparent reflectance values. Digital numbers of the thermal infrared band were converted to radiative temperatures. Finally the code carried out a precise radiometric comparison based on the evaluation of the OAE as previously described allowing to produce “AOT maps” at urban scale.

The derived AOT maps of Figure 1 were interpreted in conjunction with modelling and ground measurements, which allowed to explain how pollution spreads over the Athens basin at single representative moments such as, on these two polluted days corresponding to spring and early summer episode conditions respectively; the first day is characterised by the presence of a pollution shroud over and around the centre of Athens while is the second day pollution becomes denser from west to east and from south to north inside the basin but not particularly in the city centre.

Figure 1. AOT mapping over the Greater Athens Area on 26 April and on 13 June 1994. AOT values increase from transparency to light blue, then green, yellow, orange and red.

3.4 3D Air pollution projection

At this stage, a digital elevation model (DEM) derived from ASTER satellite data was used to further optimise the AOT maps. The DEM extraction was based on the principle of automatic stereo correlation, and its accuracy in elevation was approximately ± 26 metres.

First, the satellite-based AOT maps were overlaid to this DEM so that the pollution cloud would be projected in 3D over the Greater Athens Area (Figure 2). 3D-viewing was attained by the ER-Mapper image processing software (ER Mapper 6.0 User guide”, 1998), which allowed to “stuck” two surfaces: (i) a Landsat 5 pseudo-natural colour composite (i.e., spectral band 5-4-3 combination in R-G-B) of the “reference image” represented with height information (DEM) of the Greater Athens Area, (ii) ten AOT value classes displayed through a standard legend.

DEM was projected with a 50% scaling height while AOT values were projected with a 200% scaling in height in order to amplify the 3rd dimension of the pollution cloud upper surface. No transparency was applied to the projected layers. The use of the “3D Perspective” tool allowed to view the final image in an orthographic projection and to manipulate it from a fixed view point.

In Figure 2 the well known “horse-shoe” shape of the pollution cloud becomes obvious during a typical springtime episode when the main pollution burden is confined to the basin with higher AOT levels (depicted in red) above and around the Athens city centre. The cloud is expanded, according to the wind regime, to the north-northeast (Mt. Pendeli) and east of the basin (Mt. Ymittos).

Second, the upper limit of the pollution cloud was delineated so as to allow to approximate the
atmosphere’s mixing height and to pass from AOT values to air quality related information, in terms of scattering coefficient. This calculation was made possible by the existence in the study area of significant relief composing the Athens basin; a west-east traverse (profile) along the basin was carried out for AOT values. The cloud’s higher limit was then approximated as that height at which AOT values dropped abruptly that is, as the highest value of the first derivative of AOT (Figure 3). AOT values profile data underwent a “thresholding” to reduce noise by replacing values above “2” by the average of the two neighboring values.

The satellite-based AOT values refer to columnar measurements in the atmosphere, which correspond to the integral of the scattering coefficient \( k_{\text{scat}} \) from the ground to the satellite. If the scattering coefficient, which is directly linked to the concentration of particles, has to be calculated AOT should be divided by the appropriate scale length. Assuming that all fine aerosols stay within a layer from the ground up to the mixing height \( h_{\text{mix}} \), it is reasonable to consider that the correct scaling height for the scattering coefficient is the cloud’s higher limit, which was reckoned directly by the satellite data. This allowed converting AOT values to \( k_{\text{scat}} \) values at every image pixel as follows:
Maps depicting the $k_{\text{scat}}$ horizontal distribution over the studied area for the previously examined dates were finally produced (Figure 4). The most interesting observation is that while the city centre seems to be more intensely polluted on the 26 of April than on the 13 June according to AOT mapping (Figure 1), the pollution intensity is comparable between the two days when mapping is based on $k_{\text{scat}}$ values. This can be explained by the 400 m approximated mixing height of the pollution on the second day compared to the 700 m on the first day, which vertically distributed the aerosols (AOT) in a much denser atmospheric layer.

Figure 4. Scattering coefficient in the Greater Athens Area on 26 April and on 13 June 1994.

4 CONCLUSIONS

A combination of a 3D digital terrain model with satellite-based aerosol optical thickness (AOT) maps over the Greater Athens Area provided two types of information:

(i) satellite-derived AOT maps projected in 3D over the study area with the help of a DEM, the interpretation and analysis of which allowed explaining how the pollutants spread over the Athens basin at single but representative points in time;

(ii) the approximation of the upper limit of the pollution cloud allowing to normalise the initially columnar AOT values to scattering coefficient values ($k_{\text{scat}}$), which is directly related to ground level air quality since it is well with fine particle concentrations measured at the ground level (Sarigiannis et al. 2004). Airborne particles of this size are considered amongst the most hazardous to human health. Therefore the scattering coefficient maps produced depict information potentially related to the air quality situation over Athens during the image acquisition.

The main drawback of the derived pollution maps is their discontinuity in time due to the low revisit period of the satellites. Therefore the selected images had to be chosen so that they are representative for air pollution conditions over Athens during the last twenty years (Sarigiannis et al. 2005b). Other assumptions considered during this study concern a vertically homogeneous and stable atmosphere and that there were no considerable emissions in the surrounding mountains. It should also be noted that the existence of an important topographic relief (i.e., the Athens basin is surrounded by relatively steep mountains) was determinant in approximating the cloud’s upper limit.

To date, the state-of-the-art in air quality assessment comprises information and data processing tools using data only from ground-based measurements (produced in the context of established monitoring network or ad hoc campaigns) and atmospheric modelling (i.e., models of meteorological...
parameters, transport and chemical transformation of pollutants in the atmosphere). The main weakness of these approaches are: (a) spatial discontinuity of the pollution information from ground-based data, that causes the need to introduce linearity assumptions in the spatial correlation of information from neighbouring data points, and (b) the fact that numerical modelling is based on operational assumptions concerning the initial composition of ambient air and the reliability of the actual emissions inventory. The introduction of another source of information derived from high spatial resolution EO satellite data can be used to bridge the gap between models simulating the transport and chemical transformation of ambient air pollutants on the one hand, and analytical observations to the other. Therefore the methodology used here represents an innovation in the assessment of air quality at urban and regional scales; through the integration of AOT measured by satellite with a DEM it can provide a more coherent depiction of air pollution over extended geographic areas and with high spatial resolution.

There is obviously a need for spatially resolved information on the mixing layer height as this would have been derived by atmospheric models, which are, however, cumbersome to run. A future direction of this study is, therefore, to attempt to approximate a spatially variable height of pollution cloud over the examined area by using a multiple traverse method across the basin’s surrounding watershed.

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