A radiative model based on multispectral direct solar radiation measurements

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Abstract

This work estimates the total spectral atmospheric transmission in the urban environment of Athens on four selected days, one in each season, based on a radiative transfer model. With records of spectral direct solar irradiance measurements in the spectral range of 310-575 nm, the partial spectral atmospheric transmission functions due to Rayleigh and aerosol scattering, ozone, nitrogen oxide, mixed gases and water vapour absorption are provided. The results are discussed in view of the weather conditions prevailing during the selected days of measurements.

1 Introduction

The physical mechanisms of atmospheric attenuation as well as the chemistry behind the air composition are very complicated. Existing solar radiation codes, such as LOWTRAN, allow us to model atmospheric properties of the various atmospheric constituents assuming standard
atmospheric conditions. However, the rapid and great urbanisation, implying an increase in air pollution, has made atmospheric constituents very variable as far as their distribution, size and concentration are concerned. This causes a variable and unpredictable spectral atmospheric transmission if only standard atmospheric conditions are taken into account. Thus, knowledge of the real atmospheric conditions is required for many applications in air pollution and atmospheric chemistry studies, as well as climatic change research and remote sensing features, such as the atmospheric correction of satellite images.

In the past, Leckner\(^2\) modeled the attenuation of solar irradiance and the total atmospheric transmission was analysed as a product of partial transmission functions due to various atmospheric constituents (Rayleigh scattering, absorption by ozone, water vapour and mixed gases and aerosol scattering). Later on, Gueymard\(^3\) included one more term in this product, the transmission function due to atmospheric NO\(_x\), which in turn, can be separated in the stratospheric and/or the tropospheric counterpart. The NO\(_x\) absorption is significant and cannot be neglected especially in polluted urban or industrial areas.

2 Description of the apparatus

Direct solar irradiance was recorded under clear-sky conditions by the use of a Passive Pyrhieliometric Scanner (here-in-after PPS). In general, a pyrhieliometer is a solar radiation instrument that records direct component of the solar irradiance. The term ‘‘passive’’ indicates that no energy source is required for recording solar radiation, apart from the sun. The term ‘‘scanner’’ implies that PPS performs spectral measurements. A detailed description of the apparatus is given in Kambezidis et al.\(^4\).

3 Methodology

Based on the algorithms proposed by Gueymard\(^3\) in his SMARTS2 code, a new radiative transfer model was first developed by Kambezidis et al.\(^1\). This calculates spectral radiative properties, such as atmospheric optical thickness and transmission and also estimates atmospheric constituents, such as O\(_3\) and NO\(_x\), e.g. Kambezidis et al.\(^1\), Kambezidis et al.\(^5\). Ground-based multispectral measurements of direct solar irradiance are required as input values to the model; such measurements were carried out in the 310-575 nm spectral range with a resolution of about 0.5nm.

The total spectral atmospheric transmission, P(λ,z), (in the sun-sensor direction), considering single scattering, can be written as follows:
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\[ P(\lambda, z) = \frac{I(\lambda, z)}{I_0(\lambda)} D \] (1)

where \( I(\lambda, z) \) is the irradiance measured and calibrated in \( \text{Wm}^{-2} \) (a function of wavelength. \( \lambda \) and zenith angle, \( z \)), \( I_0(\lambda) \) the spectral extraterrestrial radiation after Gueymard\(^3\), and \( D \) is the correction factor for the earth-sun distance\(^1\).

The spectral optical thickness (towards zenith), \( \tau'(\lambda) \), is determined from the equation:

\[ \tau'(\lambda, z) = 1/m \ln \left[ \frac{1}{P(\lambda, z)} \right] \] (2)

where \( m \) stands for the atmospheric optical mass.

The total spectral transmission function (towards zenith), \( P' \), is given from the following equation:

\[ P'(\lambda, z) = \exp[-\tau'(\lambda, z)] \] (3)

To model the atmospheric transmission, six individual atmospheric processes are considered here: Rayleigh scattering, absorption by ozone, nitrogen dioxide, uniformly mixed gases (such as \( \text{CO}_2 \)), and water vapour, as well as aerosol extinction. Their respective spectral transmission functions are denoted \( P_R \), \( P_o \), \( P_n \), \( P_g \), \( P_w \), and \( P_a \). Within narrow spectral regions, these atmospheric processes can be considered independent of each other, so that the total transmission function can be derived as the product of these individual spectral transmission functions\(^1.3\). Thus:

\[ P(\lambda, z) = P_R(\lambda, z) \ P_o(\lambda, z) \ P_n(\lambda, z) \ P_g(\lambda, z) \ P_w(\lambda, z) \ P_a(\lambda, z) \] (4)

For each atmospheric extinction process \( (i^{th}) \) mentioned above, the transmission function, \( P_i \), can be written in terms of optical thickness, \( \tau_i \), and the optical mass, \( m_i \), as follows:

\[ P_i = \exp(-m_i \ \tau_i) \] (5)

The formulae for all the above-mentioned individual spectral optical thicknesses, spectral transmission functions and optical masses (functions of zenith angles) are given in Gueymard\(^3\) and Kambezidis et al.\(^1\). If the calculations are made for optical mass \( m_i = 1 \), the individual spectral transmission functions \( (P'_i) \) are derived in the direction towards
zenith, and therefore, are independent of the optical mass at the time of measurements. Thus, eqn (4) can also be written as follows:

$$P'(\lambda) = P'_R(\lambda) P'_o(\lambda) P'_n(\lambda) P'_g(\lambda) P'_w(\lambda)$$  \hspace{1cm} (6)

The transmission function due to aerosols is generally derived using Ångström’s turbidity formula. Since this model is applied in the urban environment of Athens, Greece, the actual wavelength exponent differs from the average value of 1.3 commonly employed for most natural atmospheres. The wavelength exponent, $\alpha$, is related to the size distribution of the aerosol particles the Ångström’s turbidity coefficient, $\beta$, is an index representing the amount of aerosols present in the atmosphere in the vertical direction. Although these two parameters can be estimated, the aerosols are very variable in space and time, so that it is considered more accurate to calculate the spectral transmission function due to aerosols via the following equation with all the rest functions estimated as in Kambezidis et al.:

$$P'_d(\lambda) = P'(\lambda)/ [P'_R(\lambda) P'_o(\lambda) P'_n(\lambda) P'_g(\lambda) P'_w(\lambda)]$$  \hspace{1cm} (7)

### 4 Results and discussion

Spectral measurements of beam solar irradiance were recorded on 4 selected days around midday, one in each season, in the period 1996-97, under clear-sky conditions. The measurements were performed on the roof of the Electrical Engineering Building of the National Technical University of Athens situated in the city centre of Athens. In addition, simultaneous observations of air temperature, relative humidity, atmospheric pressure and visibility were carried out at the measuring site. Substituting the data in the relevant formulae of the individual transmission functions presented in Kambezidis et al., the contribution of each atmospheric constituent to the solar irradiance attenuation at optical mass equal to unity is found. The spectral transmission function due to aerosols is calculated via eqn (7), as mentioned in the previous section. The spectral distributions of the extraterrestrial radiation as well as the absorption coefficients of the considered atmospheric constituents are those given in Gueymard. In addition, the absorption coefficients were corrected for the temperature effect. The results are illustrated in Figs 1-4, for the respective dates of 4th November 1996, 3rd February 1997, 20th May 1997, and 6th August 1997. Generally speaking, the spectral transmission function due to air molecules (Rayleigh scattering) rapidly
Figure 1. Partial atmospheric transmission functions for Athens on November 4, 1996.

Figure 2. Partial atmospheric transmission functions for Athens on February 3, 1997.
Figure 3. Partial atmospheric transmission functions for Athens on May 20, 1997.

Figure 4. Partial atmospheric transmission functions for Athens on August 6, 1997.
increases with wavelength: this happens because the scattering coefficients are inversely proportional to $\lambda^{-4}$ approximately. In all Figures, the atmospheric transmission due to ozone exhibits a well-known pattern with very low values in the considered UV spectral range. Moreover, the ozone transmission becomes unity in the atmospheric window 366-406 nm. On the other hand, water vapour shows only a weak absorption, while the uniformly mixed gases possess no absorption spectral lines in the range under consideration. In order to compare the four retrieved Figures, we must highlight the conditions of the day and time of each measurement first. On the 4th November 1996, the total ozone column was estimated to be $l_o=0.333$ atm-cm, while that of the total NO$_2$ column amount $l_n=0.017$ atm-cm. These calculations were obtained with the method illustrated in Kambezidis et al. In all, the visibility can be used as an index for the confirmation of the presence of particulate matter in the atmosphere. It was relatively good to about 10 km at the time of measurement (12:00 h LST); in the morning hours it was observed to be much lower (about 6 km at 9:00 h LST) and constantly got better till noon. Northern winds were prevailing at this time with an intensity of about 2 ms$^{-1}$. To knock out the impact of wind on air pollution, the second example was taken on 3rd February 1997, a day with exactly the same wind conditions. This day was characterised by roughly the same amounts of ozone ($l_o=0.339$ atm-cm) and NO$_2$ ($l_n=0.015$ atm-cm), while the visibility was excellent. The spectral total transmission calculated for this date, (Figure 2), exhibits higher values than the same parameter does on the 4th November 1996 (Figure 1). In addition, the aerosol transmission achieves higher levels on the same day. This is observed, line-by-line, throughout the spectral range under consideration in accordance with the observed visibility for these two days. Moreover, the function of total transmission and aerosol transmission, too, show a similar pattern throughout the spectral range for these two days and they differ only quantitatively. We can invoke as an explanation that the aerosols, present in the atmosphere, are of the same origin on both days.

Two more examples of analysis of total atmospheric transmission into the individual functions are taken into account. On the 20th of May 1997, an air-pollution episode took place in Athens, favoured by the development of the sea-breeze (SSW wind direction) coming inland from the Saronikos Gulf thus trapping air pollutants in the basin. At the time of the measurement, the visibility did not exceed 10 km, while it achieved very low values earlier in the morning. In sharp contrast, the visibility was very good and the atmosphere looked clear on the 6th August 1997.
This occurred because the Etesian winds (northerly flow streaming over Greece every summer) associated with cleansing the atmosphere of Athens, prevailed during that day with a daily mean intensity of about 4 ms\(^{-1}\). The calculated column amounts of ozone and NO\(_2\) which, in turn, constitute input values to the estimation of the transmission functions for these two days, were \(l_o=0.329\) atm-cm, \(l_n=0.020\) atm-cm and \(l_o=0.325\) atm-cm, \(l_n=0.028\) atm-cm, respectively. As a result, the total transmission and the aerosol transmission functions achieve much lower values on the polluted day, that is the 20\(^{th}\) of May (see Figs 3 and 4). Nevertheless, both functions exhibit a similar pattern in the considered range on these two days, indicating that the aerosols present in the atmosphere are coming from common sources.

However, comparing all four days together, it is concluded that aerosols observed on the two days of cold period (4\(^{th}\) November, 3\(^{rd}\) February, see Figs 1 and 2) and those on the days corresponding to warm period (20\(^{th}\) May and 6\(^{th}\) August-see Figs 3 and 4) may have different origin. In addition, it is obvious that a greater amount of aerosols are present in the atmosphere of Athens in the warm period resulting in much lower levels of transmission. This is consistent with the higher Unsworth-Monteith turbidity factors derived in the warm period for Athens by Kambezidis et al.\(^{12}\).

5 Conclusions

Based on a simple model and using spectral beam solar irradiance measurements, one can analyse the spectral total atmospheric transmission to individual components due to molecular scattering (Rayleigh), absorption by ozone, nitrogen dioxide, uniformly mixed gases, and water vapor, as well as aerosol extinction. The weather conditions and the observed visibility reflect the retrieved spectral total and aerosol transmission of the atmosphere. The results suggest that the origin of the aerosols in the cold period may be different from that corresponding to the warm period of the year in Athens. Additionally, the spectral total and aerosol transmission functions turn out to be much higher in the cold period. However, to prove these conclusions, much more measurements throughout a year are required.

References


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