The Relationship between Incident and Double-Way Transmittances: An Application for the Estimate of Surface Albedo from Satellites over the African Sahel

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ABSTRACT

The inference of surface reflectances from satellite observations requires the knowledge of the double-way transmittance through the atmosphere. Since the existing pyranometer networks routinely provide measurements of the incident transmittance over sensitive climatic regions, it would be useful for subsequent applications to relate this ground-based measurement to the corresponding double-way transmittance. A variety of satellite radiance simulations corresponding to clear sky conditions has been made in order to derive a suitable parameterized expression between the two quantities. The accuracy of this expression when making use of additional meteorological observations is shown and discussed. Finally, the derived expression is used to improve a method recently proposed by Pinty et al. for retrieving surface albedo over the African Sahel from METEOSAT radiances.

1. Introduction

Radiances measured by satellites constitute a unique and valuable means of monitoring land surface reflectances on a regional scale. However, insofar as surface reflectances are to be derived from satellite data, it is clear that the atmospheric contribution must be estimated and corrected. Because of its major influence on the accuracy of the derived surface reflectance, the double-way transmittance through the intervening atmosphere must be carefully determined and, consequently, concurrent observations of the atmospheric optical properties are required. From conventional meteorological surface networks, the dewpoint and the horizontal visibility are the only two parameters providing rather indirect information about the optical properties of a cloud-free atmosphere. More efficient information is routinely given by pyranometer networks designed for the assessments of solar energy resources. With regard to conventional meteorological measurements, pyranometers offer the advantage to deliver vertically and spectrally integrated data representative of a spatial scale convenient for regional climate studies (Bouka Biona and Boutin, 1985; Hay, 1984).

For the retrieval of surface albedo, Pinty et al. (1985) proposed to use surface radiation measurements as an input parameter of the satellite radiance equation. In the model they used, a rather crude approximation was made by replacing each spectral transmittance by an averaged value over the whole solar spectrum. However, the attenuation processes in the atmosphere are basically nonlinear and it becomes evident that a more physically realistic treatment is necessary. The purpose of this paper is to examine the relationship between the incident and the double-way transmittances over the solar spectral range, based on model calculation with respect to the relevant optically acting parameters for a cloudless atmosphere. In some ways, our approach is analogous to those previously used in studying a global relationship between planetary and surface albedos (Chen and Ohring, 1984; Preuss and Geleyn, 1980; Koepke and Kriebel, 1987).

2. Methodology

The relationship between the incident and the double-way transmittance is examined with the help of the factor a_T defined as follows:

$$a_T = \frac{T^{\downarrow\uparrow}}{T^{\downarrow}} \tag{1}$$

where $T^{\downarrow\uparrow}$ and $T^{\downarrow}$ are the double-way and the incident transmittance over the total solar spectrum, respectively. To estimate the a_T factor, we use a computational method which is based on the algorithm of the 5 S code (Simulation of the Satellite Signal in the Solar Spectrum) developed by Tanré et al. (1986) to calculate radiances at the surface and at the top of the atmosphere. A detailed description of the model formulation can be found in Tanré et al. (1979, 1981). According to this algorithm, $T^{\downarrow\uparrow}$ and $T^{\downarrow}$ are computed from

$$T^{\downarrow\uparrow} = \frac{\int_{0.3}^{3\,\mu\mathrm{m}} \mu_s E_s t\hat{g}_\lambda(\theta_s, \theta_v) T_\lambda(\theta_s) T_\lambda(\theta_v) \langle\alpha\rangle_\lambda d\lambda}{\int_{0.3}^{3\,\mu\mathrm{m}} \mu_s E_s \langle\alpha\rangle_\lambda d\lambda} \quad (2)$$

and

$$T^{\downarrow} = \frac{\int_{0.3}^{3\,\mu\mathrm{m}} \mu_s E_s t\hat{g}_\lambda(\theta_s) T_\lambda(\theta_s) d\lambda}{\int_{0.3}^{3\,\mu\mathrm{m}} \mu_s E_s d\lambda} \quad (3)$$

with

$$\mu_s = \cos\theta_s$$

where θ_s and θ_v are the solar zenith angle and the satellite viewing angle, respectively; E_s is the solar irradiance; $\langle\alpha\rangle$ the surface albedo; $T(\theta_s)$ the total (direct + diffuse) downward transmission factor of the scattering atmosphere along the direction of the incident sun's rays; $T(\theta_v)$ the total (direct + diffuse) upward transmission factor of the scattering atmosphere along the viewing direction of the satellite; $t\hat{g}(\theta_s, \theta_v)$ the total transmission factor for the effective gaseous absorption along the optical path from the sun to the satellite via the surface.

The calculation of the total transmission factors is made according to Zdunkowski et al. (1980) and in this study, the aerosols' type and concentration are taken from the Continental II Model of the Standard Radiation Atmosphere. The calculation for the gaseous transmission is based on statistical models proposed by Goody (1964) for water vapor and by Malkus (1967) for ozone, oxygen and carbon dioxide. As previously done by Stum et al. (1985), a step function is used to describe the dependency of the surface albedo with wavelength for the two spectral ranges located on both sides of 0.7 μm. In that way, an additional surface parameter called the spectral band ratio I is defined by

$$I = (\rho_2 - \rho_1)/(\rho_2 + \rho_1), \quad (4)$$

where ρ_1 is the value of the mean albedo over the spectral range 0.3–0.7 μm and ρ_2 is the value over the range 0.7–3.0 μm. The parameter I is analogous to the vegetation index available from AVHRR data.

3. A simple parameterization

With the previously described treatment, the a_T factor has been calculated for several values of the independent variables. As a first attempt, we have limited our investigation to cases where the sun and satellite zenith angles are less than 30° and we have excluded model conditions leading to large masking effects of the atmosphere. So, computations have been made with the following values: 1, 3, 5 cm in total water vapor content; 0.1, 0.3, 0.5 for the 0.55 μm total aerosol optical depth corresponding to ground visibility of 35, 19, and 11 km, respectively; 0.2, 0.25, 0.3 cm atm in ozone; 0.2, 0.3, 0.4 in surface albedo; and 0., 0.2, 0.4, 0.6 for the so-called spectral band ratio. The sun and satellite angles take the values 0, 15, and 30°, and the relative azimuth ψ is 0, 90 and 180°.

As examples of the a_T factor behavior, Figs. 1, 2, and 3 show the variations of a_T with the ground visibility, water vapor content and spectral band ratio, respectively. From Figs. 1 and 2, the increase (decrease) of a_T with an increasing visibility (water vapor content) is observed. In both cases, this behavior of a_T results from the well-known decrease of the transmission factor with an increasing optical air mass. The dependency of a_T on the spectral band ratio is illustrated in Fig. 3. The observed decrease of a_T with an increasing spectral band ratio is due to the shift of the radiance distribution reflected by the ground towards wavelengths where absorption by water vapor is stronger.

A simple parameterization of the relationship between a_T and the various independent variables has been sought for in the form of a polynomial expansion. From the total sample of computation we studied here, it appears that, for a given satellite angle, the visibility, total water vapor content and spectral band ratio are the most sensitive variables leading to significant changes of the a_T factor around a mean value. Finally, the following parameterized expression is proposed:

$$a_T = 0.8536 + f_1(\theta_v - 15) + f_2(\mathrm{vis} - 19) + f_3(U_{\mathrm{H_2O}} - 3) + f_4(I - 0.2). \quad (5)$$

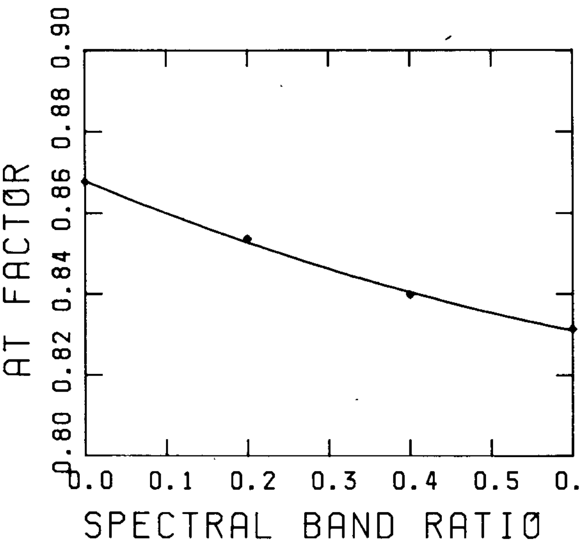

FIG. 1. The a_T factor as a function of the ground visibility. Points are calculated values and the curve is an adjusted relationship. The solar and satellite zenith angles are both 15°, the relative azimuth is 180°, the water vapor content is 3 cm, the total ozone amount is 0.247 cm atm, the surface albedo is 0.3 and the spectral band ratio is 0.2

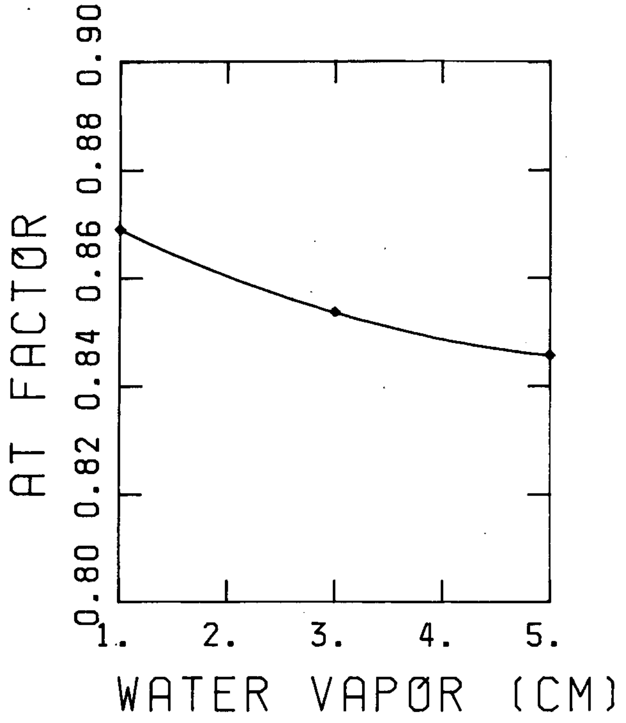

FIG. 2. As in Fig. 1 for the a_T factor as a function of water vapor content. The ground visibility is 19 km.

TABLE 1. Order and coefficients of polynomial expressions f_j appearing in Eq. (5).

Variable (x_j)	Order n^o of $f_j(x_j) = a_i X_j^i$	Coefficients (a_i)	Exponent (i)
vis—19	2	−0.77865E-04	2
		0.31521E-02	1
U_{H_2O}—3	2	0.91249E-03	2
		−0.58250E-02	1
I—0.2	2	0.35000E-01	2
		−0.68400E-01	1
θ_v—15	2	−0.22900E-04	2
		−0.65000E-03	1

In Eq. (5) vis denotes the horizontal visibility in kilometers, U_{H_2O} is the total water vapor content in centimeters, and I is the spectral band ratio. The degrees and the coefficients of the polynomial f_j are given in Table 1. The medium 0.8536 value is obtained for the following model conditions: $\theta_s = 15°$, $\theta_v = 15°$, $U_{H_2O} = 3$ cm, vis = 19 km, $\langle\alpha\rangle = 0.3$, $I = 0.2$, $U_{O_3} = 0.25$ and $\psi = 180°$. The dependency of the a_T factor with respect to θ_s, $\langle\alpha\rangle$, U_{O_3} and ψ, respectively, has been found weak enough to be neglected for the present purpose. It has been determined that in the proposed polynomial expansion, the contribution of terms of higher order than those appearing in (5) could actually be neglected. To estimate the relative errors arising from the parameterization itself and/or the lack of appropriate additional meteorological data we computed a_T factors for two extreme conditions which lead to the highest and lowest a_T values, respectively, and we compared these values with those obtained from Eq. (5). As shown in Table 2, the errors due to the parameterization are 0.5 and 0.1% for the highest and lowest conditions, respectively, and thus remain acceptable for subsequent uses of Eq. (5). For these two extreme conditions, Table 3 gives the relative errors corresponding to cases where additional information is partially or fully nonexistent. When this information is missing (cases figured by * in Table 3), the a_T factor is estimated with the mean values taken by the variables in the derivation of Eq. (5). The results clearly show the major dependence of the a_T factor with respect to the total aerosol optical depth. The lowering of the relative error associated with a good knowledge of the spectral band ratio is also noticeable and emphasizes the usefulness of the vegetation index currently produced from AVHRR data.

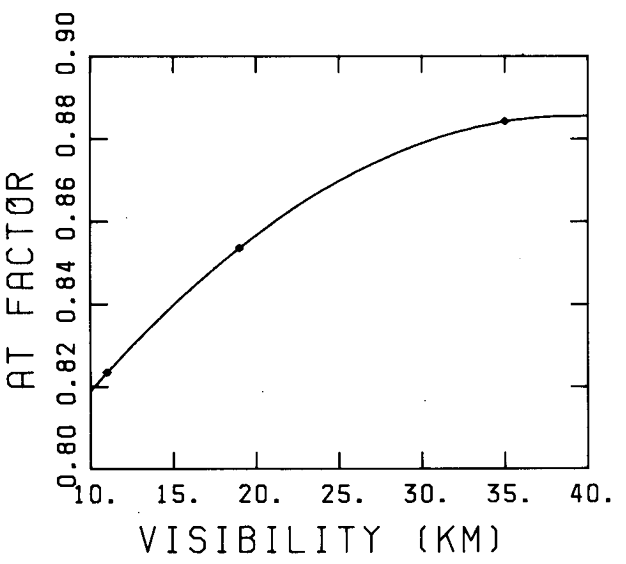

FIG. 3. As in Fig. 1 for the a_T factor as a function of the spectral band ratio. The ground visibility is 19 km and the water vapor content is 3 cm.

TABLE 2. Relative error in the a_T factor from the use of Eq. (5); a_{Tm} is the value from 5 S code and a_{Tc} is the value from Eq. (5).

vis	U_{H_2O}	I	θ_v	a_{Tm}	δa_T*
35	1	0	0	0.9140	0.5%
11	5	0.6	30	0.7776	0.1%

* $\delta a_T = \frac{a_{Tc} - a_{Tm}}{a_{Tm}}(100)$.

4. Application

In an earlier work, Pinty et al. (1985) proposed to use measurements of surface global radiation together with METEOSAT radiances in order to infer surface albedo values over some instrumented sites of the African Sahel. Starting from the monochromatic equation for the upwelling radiance to the satellite (Eq. 1 in Pinty et al., 1985) and introducing the a_T factor when performing the spectral integration over the solar spectrum leads to the following approximation for the radiance at the top of the atmosphere L_S:

$$\prod L_S \approx C + A\langle\alpha\rangle \qquad (6)$$

with

$$A = E_G a_T; \quad C = \mu_s E_s \alpha_a$$

where E_G is the surface global radiation and C the intrinsic atmospheric contribution which corresponds to the part of the atmospheric flux scattered above a nonreflecting surface.

The mean albedo values have been estimated with Eq. (7) on 2 July and 18 February 1979 over the sites of Dori (14.05°N, 0°), Ouagadougou (12.42°N, 1.5°W) and Fada-Ngourma (12.06°N, 0.4°E) in Burkina Faso where previous estimates are given in Pinty et al. (1985) and Pinty and Szejwach (1985). The broad band radiance L_S and the C term have been computed according to the procedure described in Pinty et al. (1985). The comparison of the results presented in Table 4 shows that the above updated method gives lower albedo values in all the studied cases. It can be seen that the albedo values shown in Table 4 are closer to those proposed by Deschamps and Dedieu (1986) than the albedo values given in Pinty et al. (1985). The significant departures between the successive estimates are explained by the fact that the assumption used in Pinty et al. in computing the parameter A leads to an overestimation of the masking effect of the atmosphere.

TABLE 3. Relative error in the a_T factor as computed by Eq. (5) when additional meteorological data are missing (*). Upper and lower lines (values in brackets) are for the highest and lowest a_T values, respectively.

vis	l	U_{H_2O}	δa_T
*	*	*	−6.1%
(*)	(*)	(*)	7.8%
*	*	1	−4.4%
(*)	(*)	(5)	6.8%
*	0	*	−4.3%
(*)	(0.6)	(*)	5.0%
35	*	*	−2.7%
(11)	(*)	(*)	3.9%
*	0	1	−2.8%
(*)	(0.6)	(5)	4.0%
35	*	1	−1.1%
(11)	(*)	(5)	2.9%
35	0	*	−1.1%
(11)	(0.6)	(*)	1.2%

TABLE 4. Comparison of albedo values obtained from Eq. (6) (upper line) and from previous studies by Pinty et al. (1985) and Pinty and Szejwach (1985) (lower line).

Sites	Feb	Jul
Ouagadougou	0.25 (0.31)	0.23 (0.28)
Dori	0.34 (0.38)	0.29 (0.37)
Fada-Ngourma	0.19 (0.22)	0.22 (0.28)

The sensitivity of the estimated surface albedo to uncertainty on the parameter A is given by

$$\frac{\delta\langle\alpha\rangle}{\langle\alpha\rangle} = -\frac{\delta A}{A} = -\left(\frac{\delta E_G}{E_G} + \frac{\delta a_T}{a_T}\right). \qquad (7)$$

From Eq. (7), the accuracy in surface albedo is determined by instrumental errors inherent to pyranometer measurements and by the error in the estimate of the a_T factor, which has been discussed in the previous section. It is noteworthy that the resulting error in albedo from the use of classical meteorological observations together with a standard model of the atmosphere concerns the a_T factor estimate only and not the estimate of the surface global radiation. In practice, one may expect that the final error in surface albedo will be less than the one coming from the direct calculation of the double-way transmittance when using the standard model and the same additional meteorological data.

5. Concluding remarks

A simple parameterized relationship between the incident and the double-way transmittance has been derived for clear sky conditions and for near-nadir sun and satellite angles. The limitations of this relationship are those arising from the use of a given standard atmosphere to simulate atmospheric radiances. It must be kept in mind, for instance, that the optical properties and the vertical profiles of aerosols vary with the geographical regions and periods of the year. Despite those limitations, it has been shown that this relationship can improve the assessment of surface albedo from satellite data.

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