Surface Albedo over the Sahel from METEOSAT Radiances

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ABSTRACT

A method to estimate surface albedo in the African Sahel is proposed and discussed. This method, which uses METEOSAT imagery and routine surface global radiation measurements, is shown to be relevant for climatological studies.

The accuracy in the estimated albedos is analyzed with respect to the intervening physical parameters. It is shown that a main source of error lies in the estimate of 0.4–1.1 μm radiances from filtered METEOSAT radiances. This problem limits the expected attainable accuracy in albedo to about 10% for typical land surface albedos.

1. Introduction

The relative importance of surface albedo for climate modeling was investigated through several studies almost ten years ago; an extensive review of this problem is given by Henderson-Sellers and Wilson (1983). The African Sahel is one of the climatic regions often considered when analyzing forcing mechanisms of atmospheric circulation that result from a change in albedo. It has been shown by Charney (1975) that a drop in precipitation of about 40% can result from an increase of surface albedo from 0.14 to 0.35 north of the Intertropical Convergence Zone (ITCZ). The importance of this result illustrates the necessity of estimating albedos accurately over this region. Henderson-Sellers and Wilson (1983) have indicated that the required accuracy in surface albedo data for general circulation climate models must be 0.05.

To infer surface albedo from satellite measurements, different methods and satellite systems are presently used (e.g., Otterman and Fraser, 1976; Rockwood and Cox, 1978; Mekler and Joseph, 1983; Chen and Ohring, 1984). The method developed here is used to discuss the possibility of obtaining Sahelian surface albedo values from METEOSAT radiances. The description of the method and its application over the Sahel region is given in Sections 2 and 3. The sensitivity of the estimated albedo to the intervening parameters is discussed in Section 4. In Sections 5 and 6 a proposed new method permitting direct inference of surface albedo data at the grid scale of a general circulation climate model is analyzed.

2. Method description

The present method of inferring albedo values uses simultaneous satellite measurements of radiance L_S and surface global radiation E_G. The upwelling radiance to the satellite, over a flat homogeneous terrain with Lambertian albedo α, is the sum of backscattered radiance from the impinging solar radiation at the top of the atmosphere and surface irradiance reflected by the surface multiplied by the transmittance of the atmospheric path within the sensor's field of view:

$$L_S = \frac{E_S}{\pi}[\alpha_a + \alpha T(\theta_0)T(\theta_V)/(1 - \alpha\alpha_S)], \qquad (1)$$

where E_S denotes the solar irradiance at the top of the atmosphere, α_S the atmospheric albedo for upwelling diffuse radiation, α_a the intrinsic atmospheric reflectance, and $T(\theta_0)$ and $T(\theta_V)$ the total transmittance for solar zenith angle θ_0 and satellite viewing angle θ_V, respectively. The term $(1 - \alpha\alpha_S)$ takes into account the multiple reflection between the ground and the atmosphere. Equation (1) is analogous to the satellite radiance equation proposed by Gautier *et al.* (1980) for a clear air model.

With these definitions, the surface global radiation E_G is given by

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$$E_G = E_S T(\theta_0)/(1 - \alpha\alpha_S). \quad (2)$$

As long as $T(\theta_0)$ and $T(\theta_V)$ are close to each other, the combination of Eqs. (1) and (2) leads to the following approximation for the satellite radiance:

$$\pi L_S \approx C + A\alpha + B\alpha^2, \quad (3)$$

where $A = E_G{}^2/E_S$, $B = -A\alpha_S$, $C = E_S\alpha_a$.

Equation (3) is strictly valid for $T(\theta_0) = T(\theta_V)$; however in the following we are dealing with geographical areas where the sun angle θ_0 and the satellite angle θ_V remain small (less than 30°). In that case, under clear sky conditions (optical depth less than 0.75), it is reasonable to assume that the transmittance is the same for the two atmospheric slant paths for θ_0 and θ_V angles because the characteristic spatial scale of transmittance is typically about (1–2) $\times 10^5$ m. Although the sun and satellite angles can be different, it must be noticed that for low angles, the total transmittance exhibits a very low angular dependence. [In the case of a tropical atmosphere with continental aerosols, the LOWTRAN IVB program (Selby *et al.*, 1978) indicates a variation of about 4.5% in total transmittance for a variation from 0 to 30° in solar zenith angle.]

Equation (3) shows that if α_S, α_a and E_G are known, the albedo can be estimated by solving a second-order equation in α.

3. Application of the method

The region selected for an application of the method is located in the African Sahel. Over this region, the solar radiance reflected by the earth–atmosphere system can be derived from METEOSAT imagery and simultaneous measurements of surface global radiation are provided by the AGRHYMET (W.M.O. Bulletin, 1980) network. To test the method, observations obtained on 2 July 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 Upper Volta have been selected. The diurnal sequence of infrared METEOSAT pictures indicates that all of these sites were under cloudless conditions on 2 July 1979.

a. Physical parameters

1) SURFACE GLOBAL RADIATION

The three studied sites are instrumented with Kipp pyranometers; at time of the present investigation the AGRHYMET Office only delivers the mean daily value of surface global radiation. Therefore, prior to application of the method, the surface global radiation must be estimated as a function of local time.

Under clear sky conditions and with the hypothesis of an independent atmospheric transmission function with solar zenith angle, the mean daily surface global radiation can be expressed as follows:

$$E_G = \frac{E_{G_0}}{\pi}[\sin\delta \sin\phi \arccos(-\tan\delta \tan\phi) + \cos\delta \cos\phi(1 - \tan^2\delta \tan^2\phi)^{1/2}], \quad (4)$$

where E_{G_0} is the irradiance at the surface, δ the solar declination and ϕ the latitude of observation.

Derivation of (4) with respect to local time leads to

$$E_G(t) = E_{G_0}(\sin\delta \sin\phi + \cos\delta \cos\phi \cos\Omega t), \quad (5)$$

where Ωt is the diurnal phase of the sun with respect to local noon.

Since geographical locations and local times are known, E_{G_0} can be obtained from (4) and the surface global radiation is then estimated from (5) at the required local times corresponding to METEOSAT observations.

2) INTRINSIC REFLECTANCE AND SPHERICAL ALBEDO OF THE ATMOSPHERE

Besides the surface global radiation, solution of (3) necessitates the knowledge of the intrinsic reflectance and spherical albedo of the atmosphere. Since no measurements of these parameters are available, the only approach is to compute their values. In the present work, the computation uses approach formulations suggested by Deschamps *et al.* (1981); these formulations are based on the aerosol model of McClatchey *et al.* (1971) and a real refractive index of 1.50 for the particles. The required actual visibilities at each site are provided by the ASECNA Office (Agence pour la Sécurité de la Navigation Aérienne).

b. Meteosat conversion factor

The first task in determining the flux reflected by the earth–atmosphere system using METEOSAT data is to convert the digital counts from the visible channel (0.4–1.1 μm) to radiances over the whole spectral range.

The wavelength response of the METEOSAT visible channel is approximately triangular. Thus, the first step is to convert the filtered to unfiltered radiances in the range (0.4–1.1 μm) with the appropriate conversion factor (FREC). Several conversion factors using *in situ* measurements and/or radiative transfer models have been proposed. For a land surface, Kriebel (1981) suggested the value of 1.29 ± 5%, Möser *et al.* (1980) 1.12 ± 0.07, while Koepke (1982) indicates a set of factors between 1.06 and 1.19 ± 6% [all the above listed values are in units of W $\mathrm{m^{-2}\,sr^{-1}}$ per count (8 bits)].

The second step is to convert the radiances over the range (0.4–1.1 μm) into radiances over the total solar energetic range. This can be achieved by assuming that the METEOSAT albedo in the (0.4–1.1 μm) range is identical to the albedo over all wavelengths. Proceeding in this way, the appropriate factor (already used by Saunders *et al.*, 1983) is given by the ratio of the solar constant 1376 W m^{-2} (Hickley *et al.*, 1980) to the solar constant measured over the range (0.4–1.1 μm): 900.9 W m^{-2} (Thekaekara and Drummond, 1971).

c. *Test results*

Data sets used at each of the three considered sites are summarized in Table 1, together with the corresponding albedo values computed from (3). In this application, satellite radiances have been spatially averaged over an area of size $\approx$ 25 10^8 m^2. The conversion factor that has been used to derive unfiltered METEOSAT radiances is 1.12. For a given site, differences occurring in α_a values from 1100 to 1230 GMT are due to variations in solar zenith angle, viewing angle and relative azimuthal angle. The slight deviations between the estimated albedos at different times are expected to be mainly due to the broad digitization steps of METEOSAT signal (Koepke, 1982). Using the basic zonation pattern suggested by Griffiths (1972), it appears that the considered sites are located near a significant climatic boundary between tropical wet/dry and semi-arid regions. This fact could explain the latitudinal increase in albedo observed between the sites of Ouagadougou and Dori. Although no detailed vegetation maps are available at the scale and time of our investigation, the values derived from the present method are within the range of albedo values obtained by Rockwood and Cox (1978) over the same area on 2 July 1974.

4. Sensitivity study

Since the present method requires measurements of E_G, parameterization of α_a and α_S, and the knowledge of the conversion factor to derive unfiltered radiances, it is necessary to examine the sensitivity of the estimated albedo to uncertainties in each of the intervening parameters. This sensitivity study is simply done by comparing the reference albedo value given in Table 1 to corresponding values obtained when introducing variations in either E_G, α_a, α_S or FREC. The deviation from the reference value is then expressed as follows:

$$E_r(x) = (x_p - x_t) \times 100/x_t, \qquad (6)$$

where $E_r(x)$ is the percentage of error in parameter x, the subscripts p and t denote the resulting and reference values of x.

The results of this sensitivity study are illustrated in Figs. 1a–c. The albedo dependence with E_G, α_a and α_S is presented in Figs. 1a–c, respectively for the site of Dori. Mekler and Joseph (1983) showed that for albedo values α ranging from 0.2 to 0.4, the relative error in albedo is practically independent of α even for different optical depths. With this assumption, the results presented in Figs. 1a–c should be representative over the range of typical albedo surface values. From these figures, it appears for example that an error of 5% in albedo can result from an error of 2.5% in E_G, 9% in α_a, or 100% in α_S. These results show that the quality of albedo estimates from satellite radiance depends mainly on the accuracy of the knowledge of the surface global radiation. It illustrates the necessity of making either good quality measurements or accurate parameterization of surface global radiation—i.e., total optical depth—in order to derive the albedo from the radiance equation. On the other hand, since the computed albedo is not very sensitive to changes in the values of α_a and α_S, a very accurate parameterization of these two atmospheric parameters is not crucial for the present purpose.

Figure 1d represents the uncertainty in albedo resulting from an imprecise knowledge of the ME-

TABLE 1. Mean surface albedos estimated from Eq. (3) over three different sites. Data are for 2 July 1979.*

Site	Time (GMT)	θ_0 (deg)	θ_V (deg)	E_S (W m^{-2})	E_G (W m^{-2})	α_a	α_s	$\bar{\alpha}$
Ouagadougou	1100	16	14	1271	877	0.046	0.122	0.285 ± 0.002
	1130	12	—	1299	895	0.046	—	
	1200	11	—	1306	899	0.045	—	
	1230	13	—	1292	890	0.045	—	
Dori	1100	14	16	1287	866	0.045	0.122	0.375 ± 0.001
	1130	10	—	1309	880	0.046	—	
	1200	9	—	1311	882	0.045	—	
	1230	13	—	1292	869	0.045	—	
Fada-Ngourma	1100	15	14	1281	835	0.045	0.122	0.279 ± 0.008
	1130	11	—	1301	849	0.045	—	
	1200	12	—	1302	850	0.046	—	
	1230	15	—	1282	838	0.046	—	

* Definitions: θ_0, solar zenith angle; θ_V, satellite viewing angle; E_S, solar irradiance at the top of the atmosphere; E_G, surface global radiation; α_a, intrinsic atmospheric reflectance; α_S, atmospheric albedo for upwelling diffuse radiation; $\bar{\alpha}$, mean surface albedo.

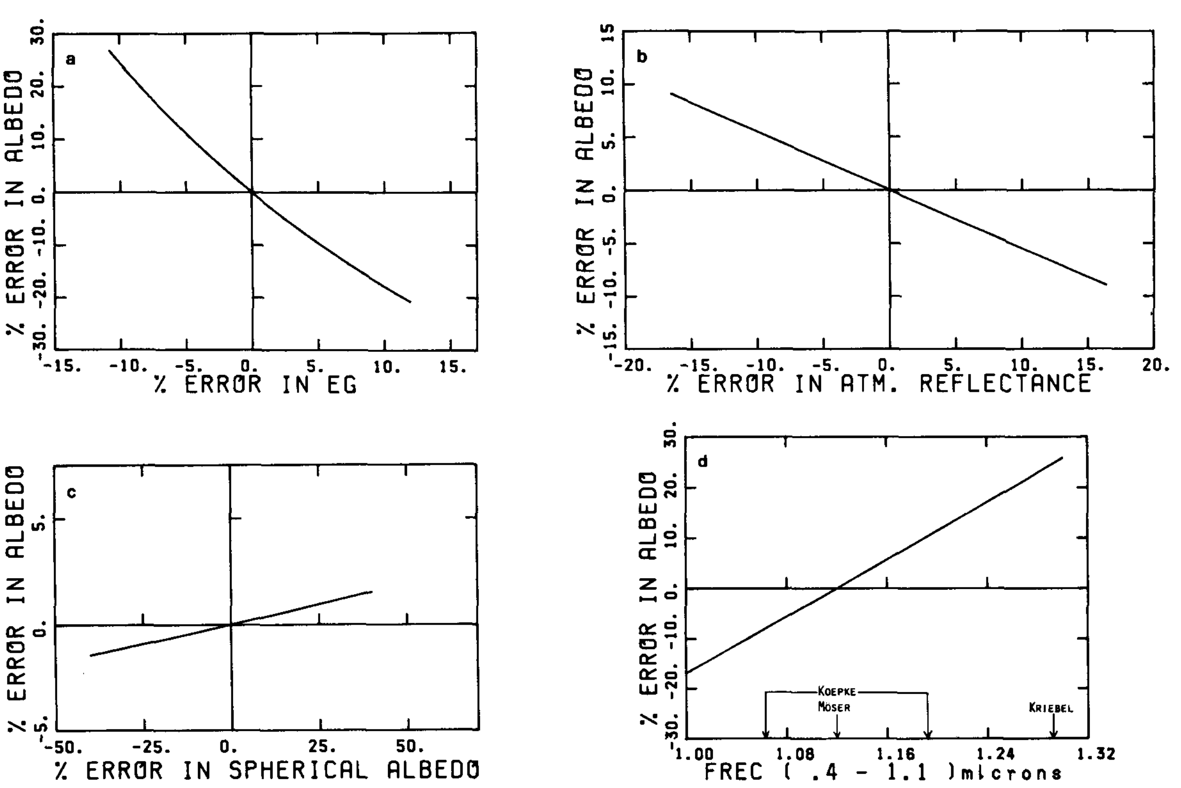

FIG. 1. Relative error in (a) surface global radiation (b) intrinsic atmospheric reflectance α_a, (c) spherical albedo α_S and (d) the METEOSAT conversion factor FREC (count 8 bits) each versus the relative error in surface albedo. Curve is computed using the values at Dori on 2 July 1979.

TEOSAT conversion factor FREC. With respect to the extensive range of conversion factors published by various authors, an error of 10% in surface albedo can be easily expected. It must be mentioned that another source of uncertainty in the estimate of the total reflected flux by the earth–atmosphere system lies in the assumption that the albedo integrated over METEOSAT visible channel is considered equivalent to the planetary albedo (integration over the whole spectrum).

5. Scale representativeness of the estimated albedo

In a recent paper, Mekler and Joseph (1983) investigated the problem of estimating albedo values. They suggested a direct method involving three local ground measurements of albedo over the study area together with Landsat imagery. It is shown that, as long as the spatial variation in optical depth is small, the albedo can be computed over the entire image. In the present method, we suggest using surface global radiation values instead of *in situ* albedo measurements. Because of its scale representativeness, which is about (1–2) 10^5 m in clear sky conditions, only one measurement of surface global radiation allows the estimate of albedos over the given area. The size of the area for which the albedo can be reasonably estimated with this method is limited by the one characteristic spatial scale of atmospheric transmittance.

6. Albedo estimate at a GCM grid scale

The spatial scale involved in the present method is compatible with general circulation climate model (GCM) studies. Therefore, it is valuable to investigate the direct use of a spatially-averaged satellite radiance to infer the albedo at this scale. This can be achieved by analyzing the relationship defined by Eq. (3) between the average radiance and the corresponding surface albedo.

The standard deviation σ_{L_S} of the satellite radiance is expressed as follows:

$$\sigma_{L_S}{}^2 = \langle L_S{}^2 \rangle - \langle L_S \rangle^2, \qquad (7)$$

where the angle brackets represent a spatially-averaged value.

Under the conditions required for the application of the method (i.e., that the hypothesis of a constant optical depth less than 0.75 over a grid mesh is satisfied) the use of Eq. (3) leads to the following relationship between σ_{L_S} and σ_α:

$$\sigma_{Ls}^2 \approx \frac{A^2}{\pi^2}\sigma_\alpha^2(1 - 4\alpha_S\langle\alpha\rangle + 2\alpha_S^2\sigma_\alpha^2 + 4\alpha_S^2\langle\alpha\rangle^2). \tag{8}$$

A Gaussian distribution of the albedos has been taken for sake of simplification.

An investigation of (8) with numerically realistic values of α_S, σ_α and $\langle\alpha\rangle$ shows that the last two terms in parentheses can be ignored, leading to the following approximation:

$$\sigma_\alpha \approx \frac{\pi}{A}\sigma_{L_S}(1 - 4\alpha_S\langle\alpha\rangle)^{-1/2}. \tag{9}$$

Equation (9) relates the albedo standard deviation to that of the radiance.

This relationship has been tested with estimated and observed values on 2 July 1979 over the three considered test sites in Upper Volta. For each site, the albedo of each pixel was derived from Eq. (3) over an area corresponding to 60 pixels^2 (about 9 10^{10} m^2), approximatively centered over the site. These areas were then subdivided in areas of growing sizes (3, 5, 7, · · ·, 61 pixels squared) and the average and associated standard deviation values of albedo and radiance computed over several subgrids. The comparison between these actual standard deviations (all sites considered) and those directly derived from σ_{LS} [Eq. (9)] is shown in Fig. 2. The good agreement between the two estimations indicates that (9) can be reasonably utilized as an indicator of dispersion around an average value of albedo. The value of σ_α can be related to heterogeneities in albedo values present within each surface area associated with a particular grid scale. This means that the uncertainty in the albedo at a GCM grid scale will depend on the ground features of the investigated area.

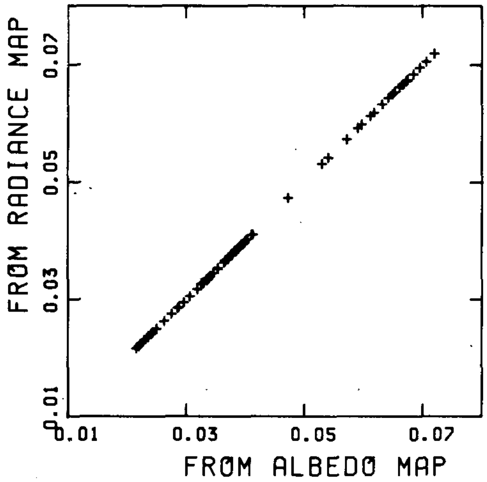

FIG. 2. Relation between the standard deviations estimated from Eq. (9) and the actual standard deviations in surface albedos. The three sites are considered.

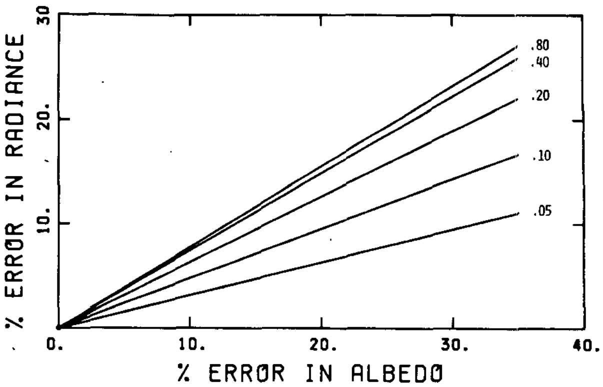

FIG. 3. Relative error in surface albedo versus relative error in radiance for different albedo values.

Equation (9) can also be used to analyze the error involved in determining surface albedo from satellite radiance data. Results are illustrated in Fig. 3. From this figure, for example, we find that for a required accuracy of ±20% and an albedo of 0.2, the accuracy in satellite radiance must be better than 12%. Another important result illustrated in Fig. 3 is that the required accuracy of 0.05 for climatological applications implies radiance errors lying in the range 7–18%. It is interesting to note that this range, expected for such satellite radiances, corresponds to standard deviations 1.5 to 2.5 times higher than the ones existing for the solar constant (Forgan, 1977).

For the particular case of METEOSAT, Koepke (1982) has shown that mainly because of the broad digitizations steps, the accuracy of METEOSAT visible radiances is about ±6%. For such a value, the calculations shown in Fig. 3 indicate that it will be difficult to expect a precision better than 9% for typical land surface albedos (0.2–0.5) and 20% for water surfaces from METEOSAT measurements. It must be kept in mind that other sources of uncertainty exist; they are, mainly, the estimate of planetary albedo over the whole energetic range and the hypothesis of Earth's surface being a Lambertian reflector.

7. Conclusions

A method of inferring surface albedo maps from simultaneous satellite radiance and surface global radiation measurements has been developed. Besides being applicable to the assumption of a homogeneous Lambertian albedo, this method is applicable for clear atmospheres (optical depth less than 0.75) and for situations in which both the solar zenith angle and satellite viewing angle are small with regard to the instrumented site.

In the case studied here, the method has been applied with METEOSAT data and routine measurements of the mean daily surface global radiation. The knowledge of only the mean daily value has limited the application of the method to a clear-sky day (optical depth about 0.3), since the surface global radiation as function of local time must be deduced from the daily mean. However, as long as instantaneous surface global radiation is available, the method is applicable under cloudless conditions with optical depth less than 0.75. Such optical depths are within the usual range except in the particular case of extensive dust layer.

We have applied this method and derived albedo values over the Sahel region from METEOSAT data and surface global radiation measurements provided by the AGRHYMET Office. The sensitivity study of the resulting albedo to the intervening physical parameters shows that the method can be reasonably routinely used; a major source of inaccuracy lies in the conversion of METEOSAT counts to total radiances over the whole solar spectrum. It is shown that the expected maximum accuracy in surface albedo is about 10% for typical land surface albedo values.

It is important to note that as long as the required conditions are fulfilled, the proposed method can be used over other areas readily viewed by satellites. The possibility of directly inferring a spatially-averaged value of albedo at a GCM grid scale using this method has also been investigated and an expression relating the standard deviation of the surface albedo to satellite radiances has been proposed.

The major value of this method is that it allows an estimation of albedos over an area which corresponds to the grid mesh of GCMs (1–4) 10^{10} m^2. Since routine measurements of surface global radiation are available, it is possible to build albedo maps and follow the seasonal variations for different Sahelian sites. This application is fundamental to climatological studies of the "desertification" and drought problems in the African Sahel.

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