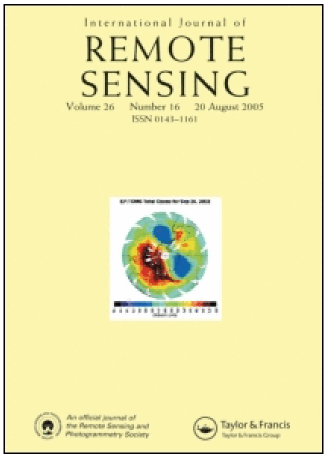

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Estimating albedo from limited spectral and angular data

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Abstract. A database of synthetic albedo and directional reflectance values for vegetated surfaces was constructed utilizing mathematical models. This database enables the comparison of albedo with reflectances measured in narrow spectral bands in particular viewing directions for specified vegetation canopy and solar conditions. The analysis reported here is for spectral bands and angular regimes corresponding to the Along-Track Scanning Radiometer (ATSR-2) sensor on ERS-2.

In the analysis multiple linear regression is used to calculate the best fit between modelled reflectance and modelled albedo. A primary estimate of albedo is calculated using reflectance data from the nadir direction only. Data from the forward view of the ATSR sensor are then used to provide additional information to correct the nadir estimate. The relationship between the regressed coefficients and the illumination conditions was investigated in order to provide a universal albedo estimation. Preliminary results for representative solar zenith and azimuth angles show an extremely good fit between modelled albedo and that estimated using the modelled ATSR-2 reflectance.

1. Introduction

Shortwave hemispherical reflectance, or albedo, is one of the most important climatic parameters, and both its mean value and temporal variation are essential input parameters in global climate and weather prediction models. Satellite-borne remote sensing instruments present the only realistic means of obtaining reflectance measurements on a global scale at a reasonable temporal resolution. The utility of remotely sensed albedo data, however, is hindered by the limited spectral and angular ranges of satellite sensors. Typically, radiance is measured in one direction only, usually at nadir view, and in a small number of narrow spectral bands. Albedo must therefore be estimated from a restricted sample of the three-dimensional reflectance

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field, although the scattering of radiation from the Earth's surface, for example, is neither isotropic nor spectrally uniform (Kimes and Sellers 1985). To extrapolate the available data to all angles of view and parts of the spectrum, assumptions must therefore be made.

Previous authors have addressed the issues of spectral and angular integration in different ways. Saunders (1990) used a spectral weighting for the Advanced Very High Resolution Radiometer (AVHRR) based on a split of the solar spectrum midway between the two channels. For the angular integration he used top-of-atmosphere (TOA) anisotropic reflectance factors reported by Taylor and Stowe (1984). Ranson *et al.* (1991) and Starks *et al.* (1991) similarly weighted the solar spectrum according to the irradiance in each band, assuming that any variations in reflectance between the measured bands have a negligible effect. Both studies investigated the bidirectional reflectance model of Walthall *et al.* (1985) as a means of dealing with view angle effects. Saunders' sensitivity analysis indicated that a 10% variation in spectral and anistropic factors causes errors in albedo estimates of 1% and 2% respectively.

This paper is particularly concerned with the estimation of the albedo of vegetation canopies showing seasonal changes. The reflectance of vegetation depends on solar and view zenith and azimuth angles, the spectral properties of the canopy elements and, particularly, leaf and canopy geometry. Mathematical models have been constructed to represent these angular and spectral reflectance variations. In this paper we utilize such models to simulate values of albedo for vegetated surfaces by modelling the full range of viewing angles across the entire spectrum. We then compare these with albedo values estimated from a limited subset of spectral bands and observational angles corresponding to those offered by the Along-Track Scanning Radiometer (ATSR-2) sensor on ERS-2. The spectral bands and bandwidths are given in table 1. The forward view of ATSR-2 has an incidence angle of 55° (at the central pixel in the swath). The nominal orbit height of ERS-2 is 785 km and the pixel size is about 1 km at nadir, increasing to about 1.5 km × 3 km in the forward view (Prata *et al.* 1990).

If real ATSR-2 data were used, the input data would be TOA or 'apparent' reflectance. Therefore the 5S (Simulation of the Satellite Signal in the Solar Spectrum (Tanré *et al.* 1987)) atmospheric model was used in this study to simulate the effect of the atmosphere on the 'observed' signal. As albedo is a surface characteristic, a method for retrieving surface reflectance from apparent reflectance is outlined and the retrieved bidirectional reflectance of the surface is compared to the surface reflectance integrated over all the modelled wavelengths and angles. The aims of this study were therefore defined as follows.

(i) To derive weighting factors which, when applied to the retrieved bidirectional surface reflectance in the satellite bands, produce the best achievable estimate of albedo.

Table 1. ATSR-2 band positions and bandwidths.

Channel number	Centre wavelength (μm)	Bandwidth (μm)
V1 (green)	0.555	0.545–0.565
V2 (red)	0.659	0.649–0.669
V3 (near-infrared)	0.865	0.855–0.875
1b (middle infrared)	1.610	1.58–1.64

(ii) To formulate the weighting factors as functions of solar zenith and relative azimuth angles, to enable generalization of the albedo estimation to any solar condition (as defined by latitude and day of the year).

(iii) To determine the precision of the albedo estimation procedure (as defined by the models applied).

2. Method

2.1. *Mathematical models*

This section reviews the models used to produce the database of synthetic albedo and reflectance measurements. A brief description of the atmospheric correction procedure employed is given.

2.1.1. *Modelling surface reflectance, albedo and apparent reflectance*

The vegetation canopy model used was an improved version of SAIL (Andrieu *et al.* 1997) that combines four well established sub-models. The SAIL radiative transfer model (Verhoef 1984) was used to calculate reflectance from a homogenous canopy of leaves, for specified values of leaf area index (LAI), mean leaf inclination angle (an ellipsoidal leaf angle distribution was assumed), solar irradiance and fraction of diffuse light (both as a function of wavelength). The input values of solar irradiance and fraction of diffuse light were calculated from the 5S atmospheric model, described in more detail later. The PROSPECT model (Jacquemoud and Baret 1990) was used to estimate leaf spectral properties given leaf chlorophyll (*a* and *b*) content, water content and structure. The Kuusk hotspot (Kuusk 1991) model was employed to model the effects of self-shadowing on the canopy reflectance, required inputs being the leaf diameter and the height of the canopy above the ground (or between leaf layers). The soil was modelled using SOILSPECT (Jacquemoud *et al.* 1992), which uses as input parameters measured values of single scattering albedo of soil (as a function of wavelength), soil moisture content and soil roughness for representative soils.

The combined model was used to generate bidirectional reflectance values for representative vegetation canopies and environmental conditions. However, each sub-model has its own known limitations. For example, the SAIL model assumes horizontal, infinite, homogeneous layers of small, flat, Lambertian leaves. The PROSPECT model assumes a uniform distribution of water and pigments throughout the leaves, and constant leaf surface roughness. The Kuusk hotspot model is unable to account for large inhomogeneities in the vegetation canopy (such as seen in row crops or open canopy forests) and the SOILSPECT model was prepared by fitting parameters to a small number of soil samples under different moisture and roughness conditions. These limitations must be borne in mind when examining the results discussed below.

The albedo was estimated by integrating the directional reflectance over the full range of angles and across the solar spectrum, using 224 frequencies from 401–2455 nm, at eight view zenith and eight relative azimuth angles (table 2):

$$\alpha = \sum_{i=1}^{224} \alpha_i s_i \Big/ \sum_{i=1}^{224} s_i \tag{1}$$

$$\alpha_i = \frac{1}{\pi} \sum_{j=1}^{8} \rho_{i,j}(\lambda_i, \theta_j) \Delta\Omega_j \tag{2}$$

$$\rho_{i,j}(\lambda_i, \theta_j) = \frac{1}{8} \sum \rho_{i,j,k}(\lambda_i, \theta_j, \phi_k) \tag{3}$$

$$\Delta\Omega_j = \pi(\sin^2\theta_j - \sin^2\theta_{j-1}) \tag{4}$$

Table 2. Angles used in integration scheme.

Zenith angle bands (°)	Nominal zenith angle (°)
0–5	2.5
5–15	10
15–25	20
25–35	30
35–45	40
45–55	50
55–65	60
65–90	77.5
Azimuth angles (°)	0, 45, 90, 135, 180, 225, 270, 315

where α is the modelled albedo, λ is the wavelength, θ is the view zenith angle, ϕ is the view azimuth angle and $\rho(\lambda, \theta, \phi)$ is the directional reflectance at angle θ, ϕ and wavelength λ.

The cosine weighting of directional reflectance in albedo is incorporated in the definition of $\Delta\Omega$.

The apparent reflectance measured at the satellite was calculated using the 5S model, for specified canopy reflectance and atmospheric conditions. The atmospheric profile and aerosol type must be set; the standard options available are tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer and sub-arctic winter. Aerosol types defined are continental, maritime or urban. The optical depth of the atmosphere is also required, which can be estimated from the horizontal visibility at the Earth's surface. A geometric model (Prata *et al.* 1990) was used to calculate the appropriate solar zenith and azimuth angles for the day and latitude of the modelled ATSR-2 passes. Longitude is not required as ERS-2 follows a Sun-synchronous orbit; the local solar time of overpass is approximately 10: 30 at all points on the descending pass.

2.1.2. *Atmospheric correction procedure*

To simulate correction of satellite data for atmospheric effects, we used a method developed specifically for the ATSR-2 sensor by Mackay *et al.* (1995). This correction procedure assumes that the form of the Bidirectional Reflectance Distribution Function (BRDF) of a surface is the same in two wave bands, so that the ratio of the surface reflectances in nadir and forward viewing modes (at incidence angles of 0° and 55° respectively) is the same in both bands. The modelled surface reflectance is then retrieved from the apparent reflectance in each of the ATSR-2 bands in both forward and nadir views and for the complete range of possible atmospheric optical depths. For vegetation canopies, the optical depth chosen is that which minimizes the term (see table 1 for nomenclature) [1b(55°)/1b(0°) − V1(55°)/V1(0°)]. Over bare soil surfaces, replacing 1b with V2 in this term produces the best retrieval of surface reflectance from apparent reflectance. Preliminary results of this procedure are shown in figure 1: the modelled surface bidirectional reflectance could be retrieved from the apparent reflectance to within about 2% over a wide range of canopy conditions. The data shown are for mid-summer (day 173), mid-latitude (45.0° North) solar conditions, with a standard atmospheric profile for those conditions, continental aerosol and 23 km horizontal visibility.

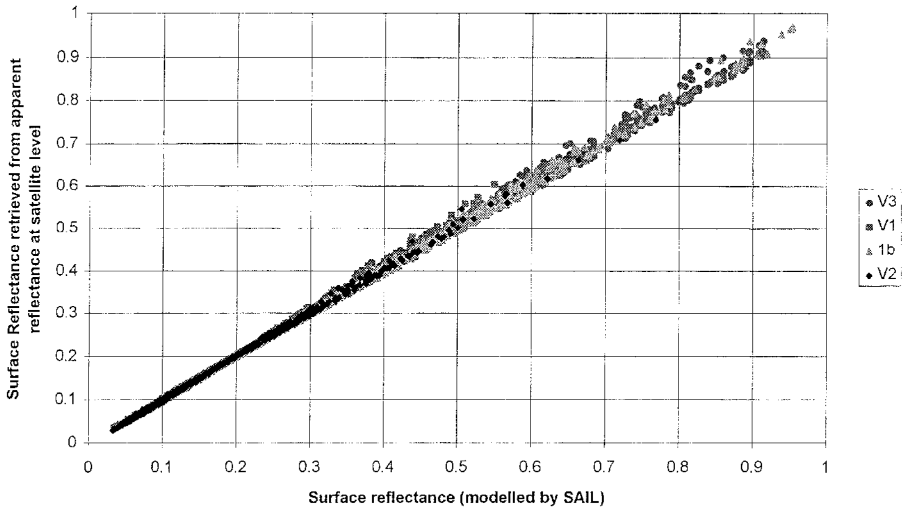

Figure 1. Retrieved surface reflectance (after atmospheric correction) versus modelled surface reflectance. Nadir view only. Mid-latitude (45° N) mid-summer (day of year 173) solar conditions and atmosphere, continental aerosol, visibility= 23 km.

2.2. *Retrieval of albedo from nadir reflectance*

This section outlines the comparison of modelled albedo and nadir reflectance. A multiple linear regression was used to assess the sensitivity of the regressed coefficients to the modelled canopy variables investigated.

The 5S model was employed to calculate solar irradiance and the proportion of diffuse to direct light at solar zenith angles of 20°, 40° and 60°. The SAIL model was then run for a variety of canopy conditions, i.e. for all 26 soil types from the SOILSPECT model; for LAIs of 0 (bare soil), 1, 2 and 4; for planophile, spherical and erectophile leaf angular distributions; and for coupled leaf moisture and chlorophyll contents of 0.005 cm and 5.0 μg cm^{-2}, 0.02 cm and 20.0 μg cm^{-2} and 0.04 cm and 40.0 μg cm^{-2} respectively. This yielded 936 input combinations (i.e. the total number of loops/runs). The leaf moisture content is quoted as an equivalent water thickness over the leaf surface. The void area index in PROSPECT and the Kuusk hotspot parameter were held constant at 1.5 and 0.1 respectively, as these had little effect on the modelled albedo and adding further variables would have caused a significant increase in computation time. Similarly, the leaf moisture and chlorophyll contents were coupled because, although these parameters affect different bands, their net effect on albedo is equivalent.

Albedo and nadir reflectances in each of the four ATSR-2 spectral bands (V1, V2, V3 and 1b) were calculated for the 936 combinations of canopy variables at each solar condition. The 5S model was used to calculate nadir and forward view apparent reflectance as measured at the satellite. The Mackay *et al.* (1995) atmospheric correction procedure outlined above was then used to retrieve surface reflectance from the apparent reflectance. Weighting factors for the retrieved surface reflectances at nadir in each spectral band were calculated using multiple linear regression against the modelled albedo. A correlation of 0.961 was obtained between the modelled albedo and that estimated by a weighted combination of the nadir reflectances; the rms difference between modelled and estimated albedo was 0.024. The solar zenith angle is a major source of variation within the dataset, so separate linear regressions were carried out on the data at each solar zenith angle. Correlations between modelled and estimated albedo of 0.990, 0.988 and 0.971 with rms differences of 0.012, 0.014 and 0.024 were then found for solar zenith angles of 20°, 40° and 60° respectively.

A sensitivity analysis was undertaken to ascertain which of the canopy variables has the greatest impact on the fit between modelled and estimated albedo. Canopy geometry was found to be the most important factor in the remaining uncertainty. Figure 2 shows estimated albedo plotted against modelled albedo at a solar zenith angle of 60°. It can be seen that the major variation about the 1∶1 line is explained by the variation in leaf angle distribution. Further linear regressions were thus carried out for each of the leaf angle distributions separately. Correlation coefficients between modelled and estimated albedos of 0.999, 0.995 and 0.991 with rms differences of 0.003, 0.008 and 0.011, were found for planophile, spherical and erectophile canopies respectively (at a solar zenith angle of 60°).

Clearly, reducing the dataset using prior knowledge of the solar zenith and leaf angle improves the fit between the weighted average of modelled nadir reflectance and modelled albedo. The solar zenith angle can be calculated for any satellite observation, and thus splitting of the dataset by solar angle can be justified. However, it is unlikely that the leaf angle distribution of a canopy will be known *a priori*, and thus a correction for this would not be possible in reality. Furthermore, the case presented above is rather simplistic; the differences in scattering between the different leaf canopies do not depend upon the leaf angle distribution alone, but also depend on the interaction between leaf angle distribution, view zenith angle and solar zenith angle.

2.3. *Exploiting the forward view in ATSR data*

The use of the reflectance data obtained from the forward view of ATSR-2 was examined, and a method of combining these data with those collected from the nadir view was investigated. Albedo and reflectance were modelled for various canopy and

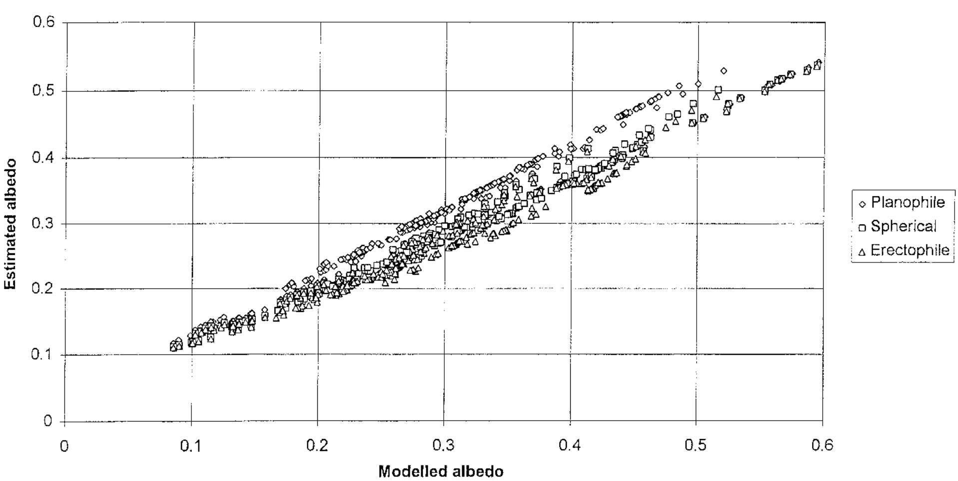

Figure 2. Albedo estimated from retrieved surface reflectance at nadir in ATSR-2 bands, grouped by leaf angle distribution. Solar zenith angle = 60°.

solar conditions. Weighting factors for each of the bands were calculated using linear regression and the variation of these weighting factors with solar angles was also investigated. The weighting factors were then formulated in terms of the solar zenith and relative azimuth angles, to enable generalization of the albedo estimation to any day and latitude.

The nadir reflectance samples a single point in the BRDF. Estimation of albedo from nadir reflectance alone is subject to error because canopy reflectance depends on the interaction between solar and view zenith angles and canopy geometry. The forward view data may be used in a number of ways to 'correct' the estimate of albedo using nadir data alone. In this study the difference between the reflectance in all bands in the nadir scan and the reflectance in all bands in the forward scan was utilized:

$$\alpha = \sum_{i=1}^{4} \omega_i V_i(0^\circ) + \omega' \left\{ \left(\sum_{i=1}^{4} [V_i(0^\circ) - V_i(55^\circ)] \right) \right\} + \omega_0 \quad (5)$$

where α is the estimated albedo, w_i ($i=1,4$) are the weighting factors for nadir data in band i, $V_i(x^\circ)$ ($i=1$, 4) is the retrieved surface reflectance in ATSR band i at an incidence angle of x°, w' is the weighting factor for difference between nadir and forward data and w_0 is the offset.

Applying this correction procedure, the average correlation between estimated and integrated albedo increased from 0.985 (using the nadir data only) to 0.989. The average rms difference between estimated and integrated albedo was reduced from 0.0184 to 0.0181. Other methods were considered which resulted in a comparable correction to the nadir estimate of albedo, but were rejected due to their relative complexity compared to the method above.

The sensitivity of the weighting factors w_i and w' to solar zenith and relative azimuth angles was determined. Formulation of the weighting factors in terms of these angles is necessary to produce a technique for albedo estimation which can be applied universally. The range of combinations of solar zenith and relative azimuth viewed by the ATSR-2 sensor is limited, as ERS-2 follows a Sun-synchronous orbit. The angles were calculated by the geometric model of Prata *et al.* (1990) and a synthetic database containing the weighting factors for solar zenith and relative azimuth corresponding to mid-summer, mid-winter and equinox conditions was compiled for sites at 45° N, 45° S and on the Equator.

These results were used to investigate the relationship between nadir weighting factors (w_i) and solar zenith angle and that between the correction weighting factor (w') and relative azimuth. A variation of the correction weighting factor with relative azimuth would be expected because the relative azimuth angle defines the part of the canopy BRDF sampled by the forward view and its relation to the hotspot. Fitting by least squares was carried out between the nadir weighting factors and linear, quadratic and trigonometric functions of the solar zenith angle. The variations in w_i appeared to be comparatively well modelled by a linear relationship with the cosine of the solar zenith angle, while a quadratic relationship was found between w' and relative azimuth. These results are given in the appendix. However, as these factors were calculated for solar zenith and relative azimuth angles at specific latitudes and days of the year it is necessary to test them at other latitudes and days of the year to determine their goodness of fit.

2.4. *Albedo retrieval test*

Modelled data corresponding to three arbitrary locations and days of the year were chosen to test the weighting factors. These locations were Shoreham-by-Sea, UK (ca 50.8° N, 0.3° W) on 21 November (day 325); Mount Cook on the South Island of New Zealand (43.6° S, 170.15° E) on 7 May and Cuenca, Ecuador (2.8° S, 79.15° W) on 25 January, corresponding to northern and southern mid-latitude and equatorial sites respectively. These sites were selected to provide a range of solar and viewing conditions and the modelled data do not represent actual data for these locations. The solar dependent weighting factors were applied to the modelled data for each site and date and the retrieved surface reflectances in the satellite bands applied to estimate the albedo. Figure 3 shows the estimated versus the modelled albedo for the Shoreham-by-Sea simulations. For these data a correlation of 0.980 was found. The best results were achieved for Cuenca, Ecuador which gave a correlation coefficient of 0.996, while that for Mount Cook was 0.980.

2.5. *Separate estimation of soil albedo*

Internal testing of the albedo estimation algorithm gave generally good results, with only a small number of outlying points, which represented data for bare soil. It is not unexpected that using the same weighting coefficients for areas of bare soil and vegetation would cause anomalies, due to their different spectral reflectances. In an operational albedo estimation system a Vegetation Index (e.g. Normalized Difference Vegetation Index (NDVI) or Optimised Soil Adjusted Vegetation Index (OSAVI), Rondeaux *et al*., 1996) could be used to 'flag' pixels as vegetation or bare soil areas at a preliminary stage of processing. It was therefore decided to investigate possible improvements by calculating separate weighting factors for vegetation and bare soil.

The dataset of modelled albedo and retrieved surface reflectances was split into subsets corresponding to bare soil and vegetation. Weighting factors were calculated as before. The results for vegetation using nadir data only show that the fit between estimated and integrated albedo improves as the solar zenith angle decreases. In all

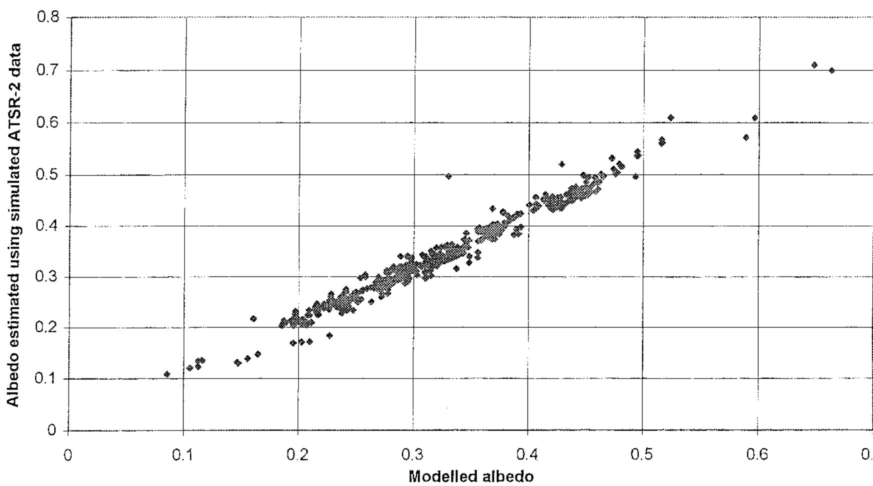

Figure 3. Albedo estimated using retrieved surface reflectance in ATSR-2 bands, solar zenith and relative azimuth angles versus modelled albedo. Latitude 50.83°, day of year 325 (21 November).

cases the albedo estimations are improved when data from the forward view are considered. The greatest improvements are seen where the fit using nadir data only is at its worst (at the largest solar zenith angles), decreasing the rms difference from 2.5% to 1.5% and increasing the correlation between modelled and estimated albedo from 0.922 to 0.971 in the case of Shoreham-by-Sea. For Cuenca, Ecuador, the correlation was 0.995 and for Mount Cook the correlation was 0.980. Although the correlation coefficients were not improved, and in some cases were even reduced from the previous case (where a fit to all data including bare soil areas had been carried out), the rms difference between estimated and modelled albedo decreased in relative terms by 21% to 56% when treating soil and vegetation separately.

For the bare soil areas the estimated albedo is very good even when using nadir data alone. Indeed, in most cases 'correction' by adding the forward scan data caused an increase in rms difference between estimated and modelled albedo. The correlations between estimated and integrated albedo, using nadir data only, were 0.997, 0.998 and 0.998 for Shoreham-by-Sea, Cuenca and Mount Cook respectively.

3. Conclusions

A method for the estimation of land surface albedo based on weighted averages of the band reflectance values measured by the ATSR-2 sensor has been proposed. Weighting factors were expressed as functions of solar zenith and relative azimuth angles. Promising results have been obtained, but certain limitations must be borne in mind. The use of a synthetic database prepared by models introduces uncertainties into the results. The range of input parameters utilized were selected to give a representative sample of the conditions found in reality. Indeed, the use of models is necessary in order to test a method over the wide range of possible conditions. However, the fitting procedure will bias results towards discrete samples rather than the true, continuous, case. Furthermore, the only validation possible is a demonstration of internal consistency within the simulated dataset. In order to test the results fully, the described method must be applied to 'real world' data.

The nature of each of the models used introduces known simplifications into the analysis. Using the SAIL canopy model assumes a homogeneous vegetation canopy structure, which would not be applicable over some areas. However, as we are applying the method to estimate a 'first order' parameter (albedo), globally, with no *a priori* knowledge concerning the observed vegetation, a simple homogeneous canopy model may be the most appropriate. The utilization of more complex vegetation models is needed in order to test this hypothesis.

In general, the study compares estimates of albedo based on a limited sample of spectral bands at one or two angles with more elaborate estimates based on a complete sample of angles and bands. The ATSR-2 spectral bands can be regarded as broadly representative of the major variable components of the reflectance spectrum for most natural surfaces and the derived weighting factors are not expected to be overly sensitive to imprecision in the spectral modelling. However, the angular sampling by ATSR-2 is sparse and biased towards the nadir. Nadir reflectances from partial vegetation canopies tend to have a larger soil contribution than off-nadir data and, although the SAIL model accounts for this effect in homogeneous canopies, the size of the soil contribution will vary according to heterogeneities in the canopy. Such effects can be complex and quite marked, particularly with regular heterogeneities such as row crops. However, for the sake of making progress, it is assumed here that such effects are largely randomized over the large pixel sizes of ATSR-2, especially when considering the even larger scales used in climate modelling, so that albedo estimates based on the assumption of homogeneity will suffice.

In terms of the preliminary simulations that are possible, the method shows good retrieval of the modelled albedo for a wide variety of conditions. Outlying points correspond to bare soil, and it is suggested that a vegetation index could be used to discriminate between bare soil and vegetated areas in the satellite data, to permit appropriate weighting factors to be applied in each case. Separating bare soil and vegetated areas and modelling them separately (with different weighting parameters) reduced the rms difference between modelled and estimated albedo markedly. Even for the worst case investigated (when the solar zenith angle is at its furthest from nadir), the rms difference was less than 2%. This discrepancy may still be acceptable in terms of measurements of albedo for use in global circulation and weather prediction models. The analysis described is suitable for application to data from other satellite sensors, such as National Oceanic and Atmospheric Administration (NOAA) AVHRR, Landsat Thematic Mapper and the Moderate Resolution Imaging Spectroradiometer.

Acknowledgments

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Appendix—Fitted parameters for albedo estimation using atmospherically corrected ATSR-2 data

Different fitted parameters were used for the vegetation and bare soil cases as follows.

A.1. *Vegetation case*

$$\begin{aligned} \text{Albedo} = {} & [-0.1447(\cos\theta_s)+0.5744]\ \text{V1}(0°) \\ & +[0.0521(\cos\theta_s)-0.1583]\ \text{V2}(0°) \\ & +[0.0975(\cos\theta_s)+0.133]\ \text{V3}(0°) \\ & +[-0.0842(\cos\theta_s)+0.2232]\ \text{1b}(0°) \\ & -0.1285(\cos\theta_s)+0.1617 \\ & +[-2\times10^{-5}(\varphi_{rel})^2+3.4\times10^{-3}(\varphi_{rel})-0.13]\ \textit{Correction Factor} \\ & -8\times10^{-6}(\varphi_{rel})^2+1.4\times10^{-3}(\varphi_{rel})-0.1479 \end{aligned}$$

Correction Factor =

$$\{[\text{V1}(0°)+\text{V2}(0°)+\text{V3}(0°)+\text{1b}(0°)]-[\text{V1}(55°)+\text{V2}(55°)+\text{V3}(55°)+\text{1b}(55°)]\}$$

θ_s = Solar zenith angle (in degrees)

φ_{rel} = Relative azimuth angle (in degrees)

A.2. *Bare soil case*

$$\begin{aligned} \text{Albedo} = {} & (-0.0192\theta_s+0.8892)\text{V1}(0°) \\ & +(0.0301\theta_s-1.0717)\text{V2}(0°) \\ & +(-0.0121\theta_s+1.0637)\text{V3}(0°) \\ & +(0.0042\theta_s-0.0848)\text{1b}(0°) \\ & +0.0008\theta_s-0.0275 \end{aligned}$$

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