Improved Diurnal Interpolation of Reflected Broadband Shortwave Observations Using ISCCP Data

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ABSTRACT

The multisatellite Earth Radiation Budget Experiment (ERBE) was designed to provide complete temporal coverage of the solar-reflected and earth-emitted radiation. Following operation of ERBE scanners on as few as one and as many as three satellites between November 1984 and February 1990, narrow-field-of-view earth radiation budget measurements were resumed in March 1994 by the Scanner for Radiation Budget (ScaRaB) mission and in December 1997 by the first Clouds and the Earth’s Radiant Energy System (CERES) instrument, each time on a single satellite. Due to sparse temporal sampling, diurnal variations must be accounted for in order to establish accurate unbiased daily and monthly mean radiant exitance. When the ERBE diurnal interpolation algorithm is used alone, large discrepancies appear between monthly mean radiative fluxes obtained from single- and multisatellite data. The authors extend the algorithm by accounting for diurnally varying cloud cover using International Satellite Cloud Climatology Project (ISCCP) data products. Significant improvements are found in regions where clouds have a pronounced diurnal cycle. Further improvements are obtained by also taking into account diurnally varying cloud properties such as optical thickness using either ISCCP cloud radiance data or a cloud classification. These approaches require the development of directional models to represent the angular dependence of the cloud albedo corresponding to the ISCCP cloud classification.

1. Introduction

In recent years several studies (Stowe 1988; Feijt 1992; Standfuss et al. 1993; Wielicki et al. 1995) have been dedicated to estimating the error sources of past earth radiation budget (ERB) missions. All the studies are not necessarily in agreement, but major error sources—both random and systematic—have been identified as originating from limited sampling. Limited angular and temporal sampling are recognized as the main sources of sampling errors. In addition, calibration is also frequently mentioned as a significant error source.

At the instantaneous pixel level, the predominant source of error is the application to a particular viewing and illumination geometry of a bidirectional reflectance distribution function (BRDF) model, which is only valid in a statistical sense and may, in fact, be wrong (Feijt 1992; Wielicki et al. 1995). However, restricted time sampling (e.g., by an instrument in sun-synchronous orbit) is the major source of error in monthly mean quantities. Calibration errors are estimated at about half the time sampling errors. It should be noted that time and angular sampling errors arise even for a perfect instrument. Moreover, with a geostationary platform yielding complete time sampling (and thus also complete sampling of solar illumination conditions), the sampling of viewing angles is completely restricted, so that any BRDF model errors persist as biases. Standfuss et al. (1993) claim that with the poorly calibrated Meteosat visible channel, the combined calibration, spectral correction, and radiance-to-flux conversion errors increase the uncertainties rather than diminish them.

These studies all agree that the lack of proper diurnal sampling introduces important regional errors into the datasets. Several other studies (Rieland and Raschke 1991; Minnis and Harrison 1984; Cheruy et al. 1991a, b) have discussed the inability of all ERB missions to resolve the diurnal cycle. This notion of diurnal cycle is very important, especially in the shortwave spectral domain. The shortwave diurnal range can be as high as 500 W m\(^{-2}\), whereas in the longwave domain, maximum range values are closer to 50 W m\(^{-2}\) (Harrison et al. 1988). Harrison et al. (1988) show that the mean diurnal range over ocean and land regions is about 2.5 times greater in the presence of clouds than for clear-sky conditions in the shortwave domain. Because the diurnal cycle cannot be resolved by the observations of ERB satellites in polar orbits alone due to the insufficient number of simultaneous platforms, several studies have suggested the use of geostationary satellite data.

Spatial and temporal variations of the earth’s radiation budget are driven to a large extent by the annual, seasonal, and diurnal cycles of solar illumination as a func-
tion of latitude. However, although a single polar-orbiting satellite can observe the entire globe in 24 h, and a single geostationary satellite can observe part of the earth all of the time, no satellite can monitor all of the earth all of the time. Attempts to determine daily, monthly, and seasonal means of ERB components require—either explicitly or implicitly—modeling diurnal variations of the earth’s radiative field at the regional scale. In our study we propose to take advantage of the improved (generally 3 hourly) time sampling of the International Satellite Cloud Climatology Project (ISCCP) observations using this information to account for variations between successive broadband ERB observations. We begin (section 2) with analysis of the ERBE time interpolation and averaging procedures; we stress the implicit and explicit assumptions of the algorithm, considering auxiliary (directional albedo) models used and examining the extent to which random errors are eliminated while systematic errors subsist. In section 3, we examine the results of applying the ERBE algorithm to single-satellite observations. We consider, in particular, the cases of strong diurnal variation—low cloud over ocean and convective cloud over land—for which time sampling bias is strong. We also examine the performance over the globe of the ERBE time interpolation–averaging algorithm for different combinations of satellites. We then (section 4) present three alternative ways to use ISCCP data products to improve the ERBE algorithm. These are (i) the monthly mean diurnal cycle of cloud fraction, (ii) the ISCCP visible-channel radiances obtained every 3 h, and (iii) the two-dimensional (cloud altitude, cloud optical thickness) ISCCP cloud classification given every 3 h. The results of applying these three alternative procedures to single-satellite ERBE data are presented in section 5. In particular, we apply these procedures to the special regions of strong diurnal variation already studied with the original ERBE algorithm and also analyze results over the globe. Our conclusions are given in section 6.

2. ERBE time-averaging procedures

a. Hypotheses and auxiliary models

The ERBE time interpolation algorithm for the reflected SW flux (RSF) takes first into account the basic astronomical fact that solar zenith angle varies systematically as a function of time (Brooks et al. 1986). Second, even for an unchanging scene, reflection to space by the surface–atmosphere system is also a function of solar zenith angle, which, in ERBE, is represented by a directional model empirically developed for the four ERBE cloud cover classes over specific ERBE geographical scene types (Wielicki and Green 1989; Suttles et al. 1988).

An observation of a given ERBE region (2.5° × 2.5° in latitude and longitude) is composed of $N \approx 1$ to 60 pixels, for each of which an instantaneous cloud cover type $i$ and corresponding albedo $\alpha_i$ have been estimated on the basis of the observed radiances and the existing BRDF models for the different scene types. The regional albedo at time $t$ is then given by

$$A_{reg}(t) = \sum_i \alpha_i(t) f_i(t),$$

(1)

where $f_i(t)$ is the fraction of ERBE cloud cover type $i$ for that region, and the corresponding RSF is

$$M_{SW}(t) = E_\alpha \mu(t) A_{reg}(t),$$

(2)

where $\mu(t)$ is the cosine of the solar zenith angle and $E_\alpha$ is the solar constant corrected for the variation of the earth–sun distance. For times $t'$ other than the observation times $t_{obs}$, the radiant exitance is estimated—both in the ERBE algorithm and in the alternative algorithms that we investigate below—using Eq. (2), assuming negligible change in $E_\alpha$ that depends on earth–sun distance, but allowing for the change in solar zenith angle and the concomitant change in albedo. In general, this yields

$$M_{SW}(t') = M_{SW}(t_{obs}) \frac{\mu(t')}{\mu(t_{obs})} \frac{A_{reg}(t')}{A_{reg}(t_{obs})}.$$  

(3)

In the ERBE algorithm, the regional albedo is given as a function of time by Eq. (1). Variations of the scene fractions $f_i(t)$ between ERBE observations are not modeled, which is equivalent to considering the meteorology to be constant during the day. Variations in the cloud field are only taken into account if several measurements are performed during the day. In such a case, the RSF is computed as a time-weighted average of the two surrounding measurements. This weighting scheme assumes the observed scene fraction changes linearly with time from one observed set to the next.

b. Time-sampling errors in time-averaged ERBE products

Over short periods of time (e.g., 24 h) it is clear that determinations of mean RSF may be significantly in error. The basic assumption of the ERBE time–space averaging algorithm is that most of these errors are random in nature, so that the error of a value averaged over a sufficiently long time interval will always be less than the errors in the individual samples. This is indeed correct if errors are truly random and if the sampling is representative. However, if errors are not purely random, that is, if they contain bias, or if the quantities measured have systematic variations on short timescales that are incompletely sampled, averaging will not necessarily reduce uncertainty, and indeed the averages may be biased even if the individual measurements are perfectly accurate. This is the case when the sampling of the diurnal cycle is sparse and the quantities to be determined have a strong diurnal variation. Thus, an instrument on board a sun-synchronous satellite observing only in midafternoon yields biased daily and monthly
means of convective cloud albedo even for perfectly accurate measurements, if convective cloud cover is systematically and significantly greater in afternoon than in the morning.

Because of the time-sampling biases inherent in a single-satellite approach, ERBE was designed as a three-satellite system with time interpolation algorithms designed to correct for the effects of relatively small gaps in time sampling (Brooks et al. 1986). However, the scanners on board the three satellites involved in the ERBE mission—the Earth Radiation Budget Satellite (ERBS), and the ninth and tenth National Oceanic and Atmospheric Administration polar orbiters (NOAA-9 and NOAA-10, respectively)—operated simultaneously for only a short period (end 1986). During most of the mission, only two scanners (first on ERBS and NOAA-9, after January 1987 on ERBS and NOAA-10) were operating simultaneously, so that gaps in time sampling were more significant. After May 1989, only the ERBE scanner on board ERBS was functioning, so that there were generally only two samples every 24 h, although nearly all local times were sampled in the course of a month as a result of the precession of the orbit in local time. Under these conditions, results of the ERBE time interpolation and averaging algorithm designed for a three-satellite system may contain significant bias.

At the regional scale, daily meteorology may appear as a random phenomenon. If this were so, the ERBE monthly regional products, including those obtained with the single-satellite ERBS, would be more accurate than the instantaneous or daily regional mean products, as a result of averaging out of random errors. However, several studies (e.g., Cairns 1995; Duvel and Kandel 1985; Hartmann and Recker 1986) show that over many large areas of the globe, strong diurnal variations dominate the meteorology and persist over several days, weeks, or even months. Considering the sparse temporal sampling performed by one or two satellites in low orbit, such systematic diurnal variation can induce significant bias in daily or monthly means. This remains true for ERBS products even though orbital precession leads to roughly 60 samples spread out over 24 h of local time in the month because the average then represents a convolution of diurnal and longer period variations. In the case of intraseasonal oscillations of periods comparable to or longer than a month (e.g., Madden–Julian oscillations), the bias can be quite strong. If such bias is to be avoided or minimized in estimating monthly (or shorter period) mean ERB components, especially the RSF, one must find a way to take into account quantitative information regarding the short period meteorological variations (especially changes in cloud characteristics between the sparsely sampled broadband radiation observations).

In what follows, we first study the impact of sparse temporal sampling on monthly mean estimates, applying the ERBE time interpolation–averaging algorithm separately to three single-satellite datasets. Single-satellite results are compared to multisatellite results, that is, to estimates of monthly means obtained by combining the datasets from the scanners on board NOAA-9, NOAA-10, and ERBS. December 1986 data were used since it is the only complete month for which the three ERBE scanners were operating simultaneously.

3. ERBE time interpolation algorithm applied to single-satellite data

a. Regional analysis

Figure 1 shows monthly mean diurnal cycles of cloudiness derived from ISCCP data (Rossow et al. 1987) over two regions at latitude 20°S. The solid line corresponds to an ocean region covered by low stratiform clouds (longitude 5°E; west of the Namibian coast), whereas the dashed line represents the convective activity over northern Namibia (longitude 20°E; 500 km east of the Atlantic Ocean).

The time-sampling patterns of the three ERBE satellites above the ocean region for the month of December 1986 are depicted in Fig. 2; they are similar over the land region. Note that NOAA-9 and NOAA-10 are sun-synchronous orbiters, while ERBS has an orbit precessing through 12 h of local time in 36 days.

Figures 3a and 3b represent monthly mean diurnal cycles of the RSF for the month of December 1986 in the ocean and land region, respectively. The solid line represents the diurnal cycle obtained from the multisatellite dataset. The single-satellite cycles are symmetrical with respect to solar noon because they are based on a single measurement and the cloud cover is considered to remain constant throughout the day.

In Fig. 3a it appears clearly that using NOAA-10-sampled data alone in Eq. (3) leads to strong overestimates of RSF at other times; if NOAA-9 and ERBS
are used alone, the results are underestimates. NOAA-10 samples in the morning hours shortly after sunrise during maximum cloudiness, and the extrapolation needed to derive the diurnal cycle of reflected SW radiation will yield overestimates at other times. On the contrary, NOAA-9 samples at a time of day when stratiform cloudiness is near minimum, and using these measurements to derive the reflected SW diurnal cycle will produce underestimates. The absolute difference between NOAA-9 and NOAA-10 monthly RSF is greater than 70 W m⁻², a relative difference above 50%. ERBS-sampled data produce results similar to NOAA-9 results. In Fig. 2 we see that for the last two-thirds of the month, ERBS sampling was similar to that of NOAA-9. In the first third of the month, a closer look at the daily cycles of cloudiness reveals low-amplitude cycles (not shown).

In Fig. 3b NOAA-10-derived fluxes are lower than the ones computed from NOAA-9 measurements because of the convective development of clouds in the afternoon over the land region. In this region, the difference in the monthly mean value of the flux between NOAA-9 and NOAA-10 is about 60 W m⁻² or 40% relative. The monthly mean flux computed from ERBS measurements is less than 5 W m⁻² away from that derived from the three satellites, but the shape of the diurnal cycle does not take into account the asymmetry between morning and afternoon fluxes. It is interesting to note that the combination of ERBS measurements with the diurnal pattern of the meteorology is much more successful in producing an accurate monthly mean flux than for the stratocumulus region. This is a coincidence for this particular region at this particular time of the year. With different times of observation every day of the month the different cloud cover conditions were sampled uniformly, which produced a monthly mean close to that derived from three or more measurements every day.

b. Global analysis

1) SINGLE- AND MULTISATELLITE PRODUCTS

Figures 4a and 4b show zonal averages of the root-mean-square (rms) of the relative difference between single- and multisatellite-derived RSF over ocean and land regions, respectively. The Southern Hemisphere is characterized by larger rms differences because, in December, it is the summer hemisphere in which diurnal variations of cloudiness are accentuated by strong solar insolation.

For both NOAA-9 and ERBS, the rms differences remain below 5% in the Northern Hemisphere, while fluxes derived from NOAA-10 data are close to or more than 10% in error compared to the three-satellite products. It is worth noting that NOAA-9 and ERBS produce comparable monthly mean fluxes in spite of their significant difference in terms of temporal sampling patterns. The peak of the NOAA-10 rms differences in the Northern
Hemisphere around 30°N is due to the combination of a constant absolute error between the equator and 30°N combined with a decreasing solar elevation—near terminator conditions—as the satellite moves poleward, which amplifies angular model errors. In the midlatitudes, the absolute rms differences are lower than in the Tropics due to the synoptic character of cloud cover variations.

In the Southern Hemisphere maximum rms differences are found in the Tropics, which corresponds to maximum solar insolation. NOAA-9 and NOAA-10 monthly mean fluxes are biased by systematic diurnal variations of cloud cover over both land and ocean. The precessing orbit of ERBS provides a more complete sampling of the diurnal cycle, which leads to more realistic monthly mean fluxes as compared to the three-satellite product. Again, NOAA-9 and ERBS are close except in the 10°–30°S latitude band.

2) Difference between NOAA-9 and NOAA-10

To study the impact of sparse temporal sampling on ERB results, we apply this analysis to all regions of the globe included between 50°N and 50°S in latitude. Figure 5 shows the geographical distribution of the relative difference in RSF between two sets of data. Figure 5a shows the difference computed as NOAA-9 product minus NOAA-10 product, and Figure 5b shows the difference computed as NOAA-9–ERBS product minus NOAA-10–ERBS product.

Large negative values appear clearly in regions known for low-level cloudiness during the northern winter. These regions are principally subtropical ocean highs covered by marine stratus clouds. They are located off the African coast (west of Namibia), off the South American coast (west of Peru), as well as south of the Australia coast and south of Polynesia. Large positive values are found on continents east of the subtropical ocean highs, such as in Angola and Namibia in Africa, Peru and Chile in South America, and parts of Australia.

The difference between the two hemispheres, which is particularly clear in Fig. 5b, is due to the much greater insolation of the summer hemisphere. The RSFs are greater not only because the incident solar flux is larger but also because radiatively induced diurnal variations of the cloud cover are stronger.

Figure 5b provides insight on the impacts of changing time-sampling pattern during the lifetime of a mission, which is either due to satellite precession (Staylor 1993) or change in satellite operation. Apart from any calibration shifts, the change in satellite combination does introduce a shift in time-sampling bias between products prior to December 1986 (ERBS plus NOAA-9) and after (ERBS plus NOAA-10). The mean bias for the globe is close to zero (0.5 W m⁻²), but the rms difference is around 8%.

4. Alternative time interpolation procedures using ISCCP products

As noted in section 2a, a basic limiting hypothesis of the ERBE time interpolation algorithm was that there were no changes in cloud cover between broadband observations. We have shown that this hypothesis entails significant bias when observations from only one satellite are available. Data on cloud cover have been compiled since 1983 in the framework of the ISCCP (Schiffer and Rossow 1983). Three-hourly coverage is obtained over most of the globe by using data available from the NOAA polar orbiters and from geostationary weather satellites operated by different agencies.

The ISCCP products are based on spatially and temporally sampled pixel radiance data (B3) and are given every 3 h every day (C1) and as monthly mean diurnal cycles with 3-h time resolution (C2) for regional scales comparable to the 2.5° ERBE latitude–longitude regions. Details regarding cloud parameter retrievals can be found in Rossow et al. (1987). Diurnal inter-

Fig. 4. Root-mean-square of the relative difference between single-and multisatellite–derived monthly mean RSF, computed over 10° zonal intervals. (a) Ocean and (b) land regions (December 1986).
Interpolation can be approached in different ways using different ISCCP data products. For each of these methods, a major difficulty is that ERBE cloud cover types do not correspond exactly to ISCCP classification. The ISCCP cloud classifications are first of all binary—clear or cloudy—with some products further dividing the cloudy classification into nine cloud classes depending on cloud-top pressure and cloud optical thickness for a total of 10 scene types. We have investigated three approaches.

1) The first and simplest (section 4a) uses only the monthly mean diurnal cycle of cloud fraction given on the regional scale in the C2 product. Although this easy-to-implement method gave significant improvement in many cases, it introduced additional bias in others.

2) The second approach (section 4b) uses cloud albedo information as well as cloud fraction, as given every 3 h throughout the month in the C1 product. In this product, the availability of the regional average visible-channel radiances for pixels classified as cloudy makes it possible to take into account diurnal variation of cloud albedo as well as of cloud fraction. However, this approach again was not completely satisfactory, leading to extreme values near the terminator.

3) The third and most successful approach (section 4c) uses the two-dimensional (cloud altitude, cloud optical thickness) ISCCP classification of each pixel, given in C1 as regional scene fractions every 3 h throughout the month, and also available as monthly means for each 3-h period. In this case the diurnal variation of cloud albedo is represented by the variation of the scene fractions according to cloud optical thickness.
In each of these approaches, we represent the time (or rather solar zenith angle) variation of the regional albedo in terms of the corresponding variations of the clear and cloudy portions of the region using the different ISCCP products

\[ A_{\text{reg}}(t) = A_{\text{ul}}(t)[1 - F_c(t)] + A_{\text{cl}}(t)F_c(t). \]  

Here \( F_c(t) \) is an ISCCP regional cloud fraction, generally available every 3 h except over the Indian Ocean sector.

\section*{a. ISCCP monthly mean diurnal cycles of cloud cover}

In the ERBE algorithm, Eq. (3) is used to estimate the RSF at a time between the basic observations with regional albedo \( A_{\text{reg}}(t) \)—defined by Eq. (1)—depending on the scene-type fractions \( f_i \), which can be considered to be the only parameters whose variations are unknown. Variations of ISCCP cloud fraction \( F_c(t) \) are known, and hence \( A_{\text{reg}}(t) \) can be derived from Eq. (4). However, with Eq. (4) the problem arises that ISCCP binary cloud cover classification (clear, cloudy) does not map directly into the ERBE categories (clear, partly cloudy, mostly cloudy, overcast). The method we propose does not try to match the ISCCP cloud classification with the ERBE cloud classification but rather to establish a correspondence between the ISCCP and ERBE cloud albedo. Correspondence is performed at ERBE observation times \( t_{\text{obs}} \), when the \( \alpha_i(\mu) \) are known for the ERBE scene types \( i \) [cf. Eq. (1)], assuming \( A_{\text{cl}} = \alpha_{\text{cl}} \) at that time for the region yields \( A_{\text{cl}}(t_{\text{obs}}) \).

To compute the regional albedo \( A_{\text{reg}}(t) \) at times other than \( t_{\text{obs}} \), the unknown parameters of Eq. (4) are obtained as follows.

- Values of \( F_c(t) \) are extracted from the ISCCP C2 product, that is, the monthly mean cloud fraction for the region under consideration, and this gives eight 3-hourly values. Hourly values of \( F_c(t) \) are obtained by linear interpolation between the original 3-hourly values.
- \( \alpha_{\text{cl}}(t) \) is computed using the ERBE clear-sky directional model.
- The directional variation of \( A_{\text{cl}}(t) \) is estimated from a linear combination of the two ERBE directional models—\( \alpha_i \) and \( \alpha_{i+1} \)—which best fit the value \( A_{\text{cl}}(t_{\text{obs}}) \)

\[ A_{\text{cl}}(t) = A_{\text{cl}}(t_{\text{obs}}) \left[ \beta \frac{\alpha_i(t)}{\alpha_i(t_{\text{obs}})} + (1 - \beta) \frac{\alpha_{i+1}(t)}{\alpha_{i+1}(t_{\text{obs}})} \right], \]  

where \( \beta \) has been determined at \( t_{\text{obs}} \) using \( A_{\text{cl}}(t_{\text{obs}}) = \alpha_i(t_{\text{obs}}) \beta + \alpha_{i+1}(t_{\text{obs}})(1 - \beta) \).

Thus, the following hypotheses underlie this algorithm.

1) Clear parts of the region are identical in the ERBE and ISCCP classifications.
2) Directional variation of clear-sky albedo in the binary classification is correctly described by the ERBE clear-sky directional model.
3) Directional variation of cloudy-sky albedo is also correctly described by an “intermediate” directional model that is established from data at \( t_{\text{obs}} \).
4) Diurnal variation of cloud cover is correctly described by the ISCCP 3-hourly data.
5) Diurnal variations of cloud properties such as optical thickness are not taken into account, that is only one “intermediate” directional model can be defined per day.
6) The monthly mean diurnal cycle of cloud cover is representative of the daily diurnal cycles in the same month.

This last assumption merits attention. Obviously, individual diurnal cycles in the month will exhibit differences from the monthly mean cycle, but the cycle will be representative in an unbiased manner if these differences are random. Cairns (1995) shows that for large parts of the globe the coherent diurnal variance represents a predominant fraction of the total intradiurnal variance. Results are presented in section 5a.

\section*{b. ISCCP visible radiances}

Accounting for variations in cloud optical thickness is important because there are many cases where cloud fraction is constant (particularly when the sky is overcast all day), but where optical thickness and therefore albedo varies significantly between sunrise and sunset. In addition to cloud fraction, ISCCP C1 products provide (every 3 h) the average visible and infrared radiance measurements that are used to determine the cloud fraction and other parameters such as optical thickness. The binary classification is applied, yielding ISCCP cloud fraction \( F_c(t) \) every 3 h, every day. Average radiances are given separately for clear and cloudy pixels; the radiance of cloudy pixels is transformed into a cloudy albedo. The regional albedo is then given by Eq. (4), where one has to express \( A_{\text{cl}}(t) \) in terms of \( A_{\text{r}} \) (reference cloud albedo for near-zenith sun) and solar zenith angle \( \theta_s(t) \), and \( A_{\text{cl}} \) is computed using the clear-sky ERBE directional model \( \alpha_{\text{cl}} \).

The radiance-to-albedo conversion requires discussion. In fact, the parameter called “visible radiance” or \( \text{VIS RAD} \) in the ISCCP documentation (Rossow et al. 1987) is the measured visible radiance \( L_V \) divided by the solar constant weighted by instrument spectral response and corrected for earth–sun distance \( E_V \). We shall write this as

\[ V(\theta_s, \phi) = \frac{L_V(\theta_s, \phi)}{E_V}. \]

This “radiance” gives an indication of the optical thickness or reflectivity of the cloud. The bidirectional reflectance (in the visible domain) can be written
Table 1. Regression coefficient of Eq. (8) defining the third-order polynomial fit between ERBE albedo \( A_0 \) (%) and ISCCP normalized radiance \( V \) (% sr\(^{-1}\)).

<table>
<thead>
<tr>
<th>( C_0 ) (%)</th>
<th>( C_1 ) (sr)</th>
<th>( C_2 ) (sr(^2)/%)</th>
<th>( C_3 ) (sr(^3)/%(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.20560</td>
<td>0.12297</td>
<td>0.01950</td>
<td>-0.00015</td>
</tr>
</tbody>
</table>

\[ R_v(\theta_0, \theta, \phi) = \frac{V(\theta_0, \theta, \phi)}{\cos \theta_0}, \]  

(7)

where the solar zenith angle \( \theta_0 \) is taken to be the value that spatially and temporally corresponds to the pixel of interest. Therefore, although it corresponds to visible radiance measurements, the VIS RAD parameter is in fact a bidirectional reflectance for overhead sun, and after division by \( \cos \theta_0 \), \( R_v \) does indeed characterize the cloud although that characterization may be affected by the viewing angles. Details of the conversion of this quantity into albedo values comparable with ERBE determinations are given below in section 5b(1). The essential point is to match ISCCP estimates and ERBE measurements at the ERBE measurement times.

The relation, for near-zenith sun, between the ISCCP visible radiance \( V \) (equivalent to a reflectance under such conditions) and the corresponding ERBE (overhead sun) albedo \( A_0 \) can be fitted by a third-order polynomial

\[ A_0 = C_0 + C_1 V + C_2 V^2 + C_3 V^3, \]  

(8)

where only observations \( V \) corresponding to near-overhead sun are considered, although they may include a variety of viewing angles. Coefficients \( C_i \)—identical for underlying ocean and land surfaces—are given in Table 1.

We assume that the cloud albedo corresponding to the actual illumination conditions can be computed as a function of \( A_0 \) and \( \theta_0 \), where the ERBE overhead sun albedo \( A_0 \) has been estimated from observation \( V \) using Eq. (6). Considering seven intervals of \( V \) (in percent per steradian) and separating clouds over land from clouds over ocean, we obtain the solar zenith angle variations \( A_{cld}(\theta_0) \) shown in Fig. 6. We have obtained a fit to these variations using the formula

\[ A_{cld}(\theta_0) = B_0 A_0^0 + B_1 \theta_0 + B_2 \theta_0^2, \]  

(9)

Table 2. Coefficients of Eq. (9) defining the solar zenith angle \( \theta_0 \) (deg) variations of the ERBE cloud albedo \( A_{cld} \) for various intervals of cloud cover opacity (ISCCP-normalized radiance \( V \) in % sr\(^{-1}\)).

<table>
<thead>
<tr>
<th>Normalized radiance (%)</th>
<th>Ocean</th>
<th></th>
<th></th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B_0 )</td>
<td>( B_1 )</td>
<td>( B_2 )</td>
<td>( B_0 )</td>
</tr>
<tr>
<td>0–10</td>
<td>1.56890</td>
<td>-0.41628</td>
<td>0.0071862</td>
<td>1.60880</td>
</tr>
<tr>
<td>10–20</td>
<td>1.50950</td>
<td>-0.63933</td>
<td>0.0114780</td>
<td>1.42910</td>
</tr>
<tr>
<td>20–30</td>
<td>1.27430</td>
<td>-0.52742</td>
<td>0.0118980</td>
<td>1.29510</td>
</tr>
<tr>
<td>30–40</td>
<td>1.0073</td>
<td>-0.18925</td>
<td>0.0090791</td>
<td>0.78109</td>
</tr>
<tr>
<td>40–50</td>
<td>0.87204</td>
<td>0.09930</td>
<td>0.0056512</td>
<td>0.77097</td>
</tr>
<tr>
<td>50–60</td>
<td>0.92820</td>
<td>0.07545</td>
<td>0.0046763</td>
<td>0.99874</td>
</tr>
<tr>
<td>60–70</td>
<td>0.98342</td>
<td>0.00012</td>
<td>0.0040179</td>
<td>0.97122</td>
</tr>
</tbody>
</table>

Fig. 6. Directional models of the ERBE regional albedo as a function of the solar zenith angle for various normalized cloud radiances. Underlying surface is (a) ocean and (b) land.
TABLE 3. Definition of cloud types in the ISCCP database. The six highest cloud types can be liquid or ice clouds, depending on whether the temperature at the top of the cloud is above or below 260 K.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Pressure (mb)</th>
<th>Cloud types</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>50–440</td>
<td>Cirrus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cirrostratus</td>
</tr>
<tr>
<td>Mid</td>
<td>440–680</td>
<td>Altostratus</td>
</tr>
<tr>
<td>Low</td>
<td>680–1000</td>
<td>Stratocumulus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nimbostratus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stratus</td>
</tr>
<tr>
<td>Optical thickness</td>
<td>0–3.6</td>
<td>3.6–23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23–379</td>
</tr>
</tbody>
</table>

Fig. 7. Monthly mean diurnal cycles of RSF based on single- or multisatellite data (original ERBE and correlative ISCCP C2 cloud cover data, December 1986). (a) Ocean: 20°S, 5°E and (b) land: 20°S, 20°E.
cycles of RSF over the ocean and land region, respectively. The diurnal cycle derived from the multisatellite dataset is represented by a thick solid line, and the two single-satellite diurnal cycles are shown as thin dashed and long dashed lines (same curves as in Fig. 3). The two new curves, shown as dashed and long dashed thick lines, represent diurnal cycles computed from NOAA-10 and NOAA-9 datasets, respectively, for which correlative cloud cover information has been used.

Figure 7a reveals a significant improvement for both datasets. Not only are the cycles closer to each other and to the multisatellite curve but also their shapes represent the realistic asymmetry between morning and afternoon. The absolute difference between NOAA-9 and NOAA-10 monthly RSF is now about 35 W m$^{-2}$, which corresponds to a relative difference of the order of 25%, compared to 70 W m$^{-2}$ or 50% in the case of ERBE original data.

In Fig. 7b the improvement provided by the use of cloud mean diurnal variability data is very significant. The diurnal cycles derived from single-satellite datasets are closer to each other and correspond better to the multisatellite results. Note the strong asymmetry between morning and afternoon fluxes, which is due to convective development of clouds following the radiative heating of the surface. The absolute difference between the monthly mean RSF derived from NOAA-9 data and NOAA-10 data has been reduced to 30 W m$^{-2}$ as opposed to 60 W m$^{-2}$ for the original data. This 50% improvement is very satisfactory considering the correlative data is limited to the fraction of cloud cover and the diurnal variability of the cloud cover is represented by a monthly mean parameter.

(ii) Global analysis

To check the validity of the algorithm, it is applied to regions in the latitude domain 50°N–50°S. Figure 8a shows the relative difference between NOAA-9- and NOAA-10-derived RSF. Figure 8b represents changes brought by the algorithm compared to ERBE original data. This change can be considered as the difference...
between Fig. 5 and Fig. 8a. Regions for which the algorithm significantly improved the fluxes are shown in dark gray. If the algorithm increased the difference between NOAA-9 and NOAA-10, the region is shown in light gray. White areas represent regions where either the algorithm was not applied due to lack of ISCCP data or the algorithm did not produce a significant modification. A threshold of 5 W m\(^{-2}\) is used to determine whether or not the change is significant. This threshold is based on the accuracy of the algorithm used to reproduce the ERBE data processing algorithm and on the accuracy of the monthly mean fluxes determined from ERBE data, which was estimated to be 5 W m\(^{-2}\) (Barkstrom et al. 1989).

Significant improvements are found for all tropical and subtropical marine stratocumulus regions. Improved monthly means are also obtained on the African and Australian continents at tropical latitudes. However, for the major part of the Northern Hemisphere, this algorithm does not bring significant improvement to the data. In many of these regions, the monthly mean diurnal cycle is not very representative of the daily meteorology. This shows the limitation of using a “climatological” approach to improve diurnal interpolation of ERB observations.

In some cases the additional ISCCP C2 data increases somewhat the difference between NOAA-9 and NOAA-10 estimates. The cloud cover variation does not always represent or follow the diurnal evolution of the physical properties of the cloud. In some cases an increasing cloud cover can correspond to a decreasing optical thickness. In such a case the algorithm will not take into account the important factor, and the difference between the two single-satellite datasets cannot be corrected. Note that no geostationary satellite information is available in the longitude domain 60\(^{\circ}\)\(\pm\)75\(^{\circ}\)E due to missing INSAT data.

b. Using ISCCP visible radiances

1) ISCCP radiance to ERBE-albedo conversions

Visible radiances of cloudy pixels can be converted into SW albedos by taking into account bidirectional and directional effects. In a first step ERBE regional albedos (ERBE type S9 product) are compared to cloudy-sky normalized radiances issued from ISCCP C1 data. The comparison is performed on measurements that are quasi-simultaneous and collocated. The difference between the cosines of the solar zenith angles cannot be greater than 0.1, and measurements cannot be more than 1.5 h apart. To get the best possible match, only cloudy pixels are considered within a 2.5° region, and the ERBE albedo is computed as the weighted sum of the albedos of the three cloudy scene types.

Figure 9 shows ERBE regional albedo as a function of ISCCP visible cloud reflectance \(R_v\), obtained according to Eq. (7), thus taking into account the solar zenith angle \(\theta_0\). Distinguishing different values of \(\theta_0\), all the curves are close together and have approximately the same slope. The alignment is not perfect because in the ISCCP data inversion, the anisotropy of the scene is not accounted for in the visible radiance parameter. The difference between the curves increases with increasing \(\theta_0\) angle, which corresponds to the known behavior of angular dependence models. The difference is greater for low albedos because they correspond to clear or partly cloudy scenes, for which the anisotropy is stronger. The difference becomes smaller as the albedo increases since large albedos usually correspond to mostly cloudy or overcast scenes, which are more isotropic. Furthermore, a significant difference is observed between ocean and land surfaces. The scene anisotropy is significantly less for land surfaces than for oceans. Thus, for land surfaces, the difference between ERBE albedos and ISCCP reflectance is less sensitive to cloud cover.
In spite of possible bias in the regression, angular correlations are established to compute ERBE SW albedos for any given solar zenith angle from a normalized visible radiance. These angular correlations are similar to ERBE directional angular models in that they give the variation of SW albedos as a function of solar zenith angle variations. The difference is that the various cloud conditions are represented by seven intervals of ISCCP parameter $V$ instead of the four ERBE cloud cover types, as described in section 4b.

2) RESULTS AND DISCUSSION

(i) Regional analysis

Figures 10a and 10b show five diurnal cycles of RSF over the ocean stratocumulus and land convective regions described in section 3a. Figure 10a reveals a significant improvement for both datasets compared to the original ERBE data. These improvements are greater than the ones shown in Fig. 7. Use of cloud cover and normalized-radiance variations allows the asymmetry of the regional albedo between morning and afternoon to be taken into account. The shapes and magnitudes of the two single-satellite cycles are now very similar to the multisatellite curve. The absolute difference between the NOAA-9 and NOAA-10 monthly RSF is now about 15 instead of 70 W m$^{-2}$ for the original ERBE data. This absolute difference corresponds to a relative difference of 10% as opposed to 50% originally.

In Fig. 10b, the absolute difference between the RSF derived from NOAA-9 and NOAA-10 is less than 5 W m$^{-2}$. This result must be interpreted with caution even though the single-satellite monthly mean fluxes are within 5 W m$^{-2}$ of the multisatellite result. On average, four ISCCP measurements are obtained over this region during the daylight hours, the first measurement being close to sunrise and the last in the late afternoon. The relative value of the first measurement with respect to the other measurements the same day has a very significant effect on the diurnal extrapolation performed from a NOAA-10 measurement, both in terms of normalized radiance and cloud cover. The diurnal cycle of RSF derived from NOAA-10 data is modified in a much greater fashion than is the cycle derived from NOAA-9 data. If we assume that the uncertainty associated with a very early morning measurement is greater than the uncertainty at any other time because of the very low solar elevation, correction of NOAA-10 diurnal cycles will not be as reliable as the correction of NOAA-9–derived fluxes. This effect varies, of course, from one region to the next since the result depends on a combined effect of the time of measurement and meteorology.

(ii) Global analysis

The algorithm is applied to all regions between latitudes 50°N and 50°S. Figure 11a shows the relative difference between NOAA-9– and NOAA-10–derived RSF, while Fig. 11b represents the changes produced by applying the algorithm. Very significant improvements are found for all tropical and subtropical marine stratocumulus regions, as well as some midlatitude marine regions. Note in particular marine regions west of the South American coast in the latitude interval 15°–45°S. However, in some cases, the correlative ISCCP C1 data increase significantly the difference between NOAA-9 and NOAA-10 estimates.

In the equatorial Pacific Ocean west of Indonesia, significant negative and positive differences are observed next to each other. Studying the temporal sampling of ISCCP data reveals that this area corresponds to a geostationary satellite limit. The diurnal sampling of regions east of this limit, appearing with negative differences, is shifted 3 h earlier than that of the western...
regions. We believe this sampling introduces biased diurnal cycles of cloud properties that must be studied with care before utilizing them to improve diurnal interpolation of ERB observations.

c. Using the ISCCP cloud classification

1) ERBE DIRECTIONAL MODELS FOR ISCCP CLOUD TYPES

As noted in section 4c, the angular models to be applied to ISCCP cloud types are determined from collocated ERBE and ISCCP measurements. For a given 2.5° region, we require that the cosines of the solar zenith angles of the two measurements agree within 0.1 and that the time difference between the two observations be less than 90 min. The average albedo of the (partly, mostly, completely) cloudy pixels detected by ERBE is then assigned to the major cloud type identified by ISCCP.

Figure 12 shows the nonnormalized directional models for different ISCCP cloud types and for underlying surfaces for ocean and land. The figure clearly shows that there are three distinctive cloud groups: thick, medium thick, and thin. Deep convection clouds, nimbostratus and stratus clouds, respectively, high, mid-, and low-altitude clouds, are opaque clouds. The angular variations of the albedo associated with these three types of clouds are similar to that associated with overcast conditions defined by the ERBE scene identification algorithm. Due to atmospheric absorption and scattering, the high-altitude clouds are sensed as being more opaque than the midaltitude clouds, which in turn are sensed as being more opaque than the low-altitude clouds. Similarly, cirrostratus, altostratus, and stratocumulus clouds are combined in a single class of medium optical thickness. For these cloud types the angular variation of the albedo is similar to the mostly cloudy class of the ERBE classification. The actual albedo values fall between overcast and mostly cloudy types of ERBE albedos. Finally, the three thin cloud types, cirrus, altocumulus, and cumulus, behave similarly to clouds in the partly cloudy or mostly cloudy ERBE types.
Fig. 12. Directional models of the ERBE regional albedo as a function of solar zenith angle for various ISCCP cloud types. The geographical type of the underlying surface is (a) ocean and (b) land.

Fig. 13. Monthly mean diurnal cycles of RSF based on single- or multisatellite data (original ERBE and correlative ISCCP C1 cloud classification data, December 1986). (a) Ocean: 20°S, 5°E and (b) land: 20°S, 20°E.

The correspondence between the ISCCP and ERBE cloud classification strongly suggests that the latter is not exclusively based on the fraction of cloud cover, but also, in an implicit way, on the optical properties of the clouds. The availability every 3 h of ISCCP cloud types and the consistency of the directional models that can be assigned to these argue in favor of their use for time interpolation as in Eq. (4) (section 4) above. We now consider the results of such use for different cases.

2) RESULTS AND DISCUSSION

(i) Regional analysis

The diurnal cycles of RSF for the selected ocean and land regions are shown in Figs. 13a and 13b, respectively. Figure 13a reveals significant improvements in the diurnal cycles computed using the ISCCP cloud classification data compared to ERBE original estimates. The strong asymmetry between morning and afternoon fluxes is very well accounted for. The absolute difference between the monthly mean derived from NOAA-9 and that derived from NOAA-10 is now close to 15 as opposed to 70 W m⁻², as given by the original ERBE data. This difference corresponds to a relative difference on the order of 10%. For this particular region, the cloud classification data do not allow as good a correction as does the ISCCP radiance data. Indeed, the ISCCP cloud classification method averages out the cloud information since the radiance data are expressed in terms of a limited number of cloud types.

For the land region, the ISCCP cloud classification provides the necessary information on the diurnal variations of the properties of the cloud cover. The asymmetry between morning and afternoon is well represented, which confirms that the angular models derived for land regions are satisfactory. The change in optical properties of the cloud cover between morning and afternoon is characterized in the ISCCP data as a change from cumulus clouds in the morning to cumulonimbus...
clouds in the afternoon. It is interesting to note, by comparing Fig. 13b to Fig. 7b, that the use of the cloud classification associated with angular models brings considerable improvements to the correction of single-satellite estimates compared to the use of the total cloud fraction. This cloud classification accounts well for optical thickness variation as an important factor in the diurnal variations of the albedo. NOAA-9 data associated with ISCCP data produce a particularly good diurnal cycle when superimposed on the diurnal cycle derived from the multisatellite dataset. The NOAA-9-derived monthly mean is almost exactly that obtained from the three-satellite dataset. The difference in monthly mean RSF between NOAA-9 and NOAA-10 is 15 W m$^{-2}$, which represents a 75% decrease with respect to the difference in the original data.

(ii) Global analysis

To validate the algorithm, we apply it to all regions between 50°N and 50°S. Figure 14a shows the relative difference between RSF derived from NOAA-9 and NOAA-10 data. Figure 14b represents the deviation from ERBE original data after the algorithm is applied. Studying Fig. 14 reveals significant improvements in the major part of the Southern Hemisphere. As before, the tropical and subtropical ocean regions covered by stratuscumulus clouds show great improvements. The detection of low-level clouds over oceans works very well, and the temporal coverage of meteorological phenomena in the Southern Hemisphere is very satisfactory. The areas where the algorithm is not successful are the northern Atlantic, the southern Pacific, and the eastern Indian Oceans. Part of the difficulty can be explained by cloud identification problems for high-altitude ice crystal clouds. ISCCP reprocessing corrects this problem (Rossow et al. 1996), but these products were not yet available for our study.

6. Conclusions

Due to sparse temporal sampling, polar-orbiting satellites cannot completely resolve the diurnal cycle of
the RSF. Over extensive parts of the globe, significant biases can be propagated to the monthly means when the diurnal cycles of cloud cover and cloud properties are not correctly sampled. Datasets obtained from NOAA-9 and NOAA-10 can produce monthly mean RSF that differ by more than 50%. Using information on the diurnal cycle of cloudiness from ISCCP data can significantly improve the time-averaging algorithm, particularly for regions where clouds have a pronounced diurnal cycle. It may also help to reduce the particular strong bias that can arise when near-terminator observations are the only ERB measurements available—for example, from NOAA-10 for ERBE, and during certain months for ScaRaB–Meteor-3 (Viollier et al. 1997). Although the RSF is necessarily low for low sun, it has strong leverage on the diurnal interpolation used to compute daily and monthly means.

Figure 15 shows zonal values of the rms difference between multi- and single-satellite-derived RSF. In the Northern (winter) Hemisphere, original ERBE single-satellite RSF derived from NOAA-9 data remain within 5 W m$^{-2}$ of the multisatellite RSF results. None of the three proposed methods yields significant improvement on this already good result. This suggests that in these latitudes, at least for the winter period considered, systematic diurnal variations account for only a small part of the total cloud cover variability and that the time sampling, although limited, is adequate with regard to the spectrum of temporal variations of the RSF.

In the Southern (summer) Hemisphere, however, RSF products can be improved by using ISCCP cloud information. The method using monthly mean diurnal cycles of cloudiness (C2 data) has the advantage of using a simple algorithm and a low volume of cloud data. If contemporary ISCCP data are not available for operational data processing, climatology data could be used instead to allow timely production of RSF data. The rms differences shown in Fig. 15 are reduced over all Southern Hemisphere latitudes for ocean and land for both NOAA-9 and NOAA-10.

The method based on ISCCP cloud cover and cloud radiance (C1 data) requires that contemporary ISCCP data be accessible in order to process the RSF data. This method is significantly more complicated than the first one since it also requires the use of new directional models. This method provides improved NOAA-9 RSF...
but is not convincing when used in combination with the terminator measurements of NOAA-10.

Finally, the method using the two-dimensional (altitude, optical thickness) ISCCP C1 cloud classification associated with ERBE angular models allows the time-sampling error to be reduced with both NOAA-9 and NOAA-10 data. In particular, for NOAA-9, the rms differences are lower (ocean) or equivalent (land) to that obtained with ERBS data alone (cf. Fig. 15 to Fig. 4).

This result in itself shows the superiority in time sampling of a precessing satellite, such as ERBS, compared to a sun-synchronous one, over latitude bands where the precessing satellite can observe. However, it also suggests that, over some regions at least, products based on ERBS data alone (ERBE data after May 1989) could be significantly improved by applying our method using ISCCP cloud classification data. Moreover, the same method could be usefully applied to improve the ScaRaB–Meteosat 1994–95 dataset (Kandel et al. 1998) and products to be based on the CERÉS–TRMM data (Wielicki et al. 1996) now being received.

Improved results from our algorithm, which uses the ISCCP cloud classification data, can be expected after the ISCCP data has been reprocessed with a new radiative transfer model with improved optical thickness computations (Rossow et al. 1996). Further improvement can be expected when geostationary satellite data become available for the Indian Ocean sector, and still better results could be obtained if sampling frequency was increased.

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