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Computation and Analyses of Averaged Monthly Zonal Albedos at the Top of the Atmosphere Using Nimbus-7 ERB Observed Data

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List of Symbols:

A = albedo at the top of the atmosphere

A_c = albedo at the top of cloudy atmosphere

A_s = albedo at the top of cloud free atmosphere

a = surface albedo

subscripts (lowercase except where indicated)

c—indicates cloud

d—indicates day of the year

I—(cap) indicates ice

L—(cap) indicates land

l —is an index indicating the latitude band

O—(cap) indicates ocean

s—indicates surface

w—indicates water

f_c = cloud fraction

f_j — is the fraction of the latitude band that is land (L), ocean (O), land ice (LI) or
ocean ice (OI)

$g(t_c)$ — is the function which relates cloud optical thickness to cloud albedo A_c

$H(t)$ = arc through which the Earth rotates in time t

I_d = the solar irradiance on day d

m = the slope function relating surface albedo to top of the atmosphere

t = the time

t_{df} = time interval measured from noon to either sunrise or sunset

T = is the earth's rotation period (24 hours) with respect to the sun

W_{df} = is weight function

Greek letters (all lower case)

delta δ is the solar declination

theta θ_0 is the solar zenith angle

mu μ_0 is the cosine of the solar zenith angle

phi ϕ is the latitude

INTRODUCTION

Satellite observations of the earth's albedo are constrained due to the characteristics of the satellite orbits. Most of our presently existing albedo data have been collected from satellites situated in sun-synchronous, near polar orbits. Such orbits allow observations at a fixed time of day for each latitude observed. The satellite data are then used in forming monthly averaged values. The assumption usually made in forming such averages is that the albedo observed must be modified if an average daily albedo is desired.

It has been shown that the albedo of clear and cloudy atmospheres do depend on the solar zenith angle. In the present study, the angular models of Nack and Curran (1978) have been used. They parameterized the radiative transfer calculations of Dave and Braslau (1975). They also set up a rapid algorithm to transform surface albedo to surface-atmosphere albedo and irradiance and to obtain temporal averages. An updated version of their algorithm was used to compute corrected monthly averaged zonal and global albedos based on Nimbus ERB-7 Wide-Field-of-View albedo measurements. The corrected results are compared with both the original measurements and with results from an alternate correction scheme used by the ERB Nimbus experiment team and based on empirical directional reflection data.

In recent years analysts have commonly used empirical directional reflectance functions (Raschke et al., 1973, Taylor and Stowe, 1984, and Brooks and Minis, 1984) to transform the observed albedos into daily averaged albedos. The directional reflectance function for a given scene type relates the overhead sun albedo to the scene albedo for any other solar zenith angle. The averaging algorithm used by the Nimbus-7 ERB Experiment Team is discussed in Kyle and Vasanth (1986). The Nimbus-7 ERB experiment and the data processing algorithms used are described in Jacobowitz et al. (1984). These empirical reflectance functions refer to the top of the atmosphere albedo and therefore bypass atmospheric transmission problems and calculations. At present however, there is some uncertainty both as to the accuracy of the various empirical reflectance functions and of how to best use them to

obtain an optimal daily averaged albedo from the measurements of sun-synchronous satellites. In this paper we will use the measured Nimbus-7 ERB Wide-Field-of-View orbital albedos to calculate monthly averaged, latitude band albedos by the updated method of Nack and Curran (1978) and Dhuria (1981). We will then compare our results to the monthly averaged albedos calculated by the ERB Experiment Team's algorithm.

COMPUTATION OF TOP OF THE ATMOSPHERE ALBEDOS

A brief review of the Nack and Curran (1978) procedures and updated versions, Dhuria (1981), is presented here. Dave and Braslou (1974 and 1975) performed radiation transfer calculations for a realistic atmosphere with and without a stratus cloud layer. Nack and Curran (1978) parametrized their results and set up an algorithm to rapidly calculate the top of the atmosphere albedo for a cloud-free, a cloudy atmosphere, and a mixed partly cloudy/partly cloud-free atmosphere. The algorithm includes an isotropic surface reflectivity and can handle a cloud layer of arbitrary thickness. Temporal averaging was also included so that the average daytime albedo could be calculated. The algorithm does require as input the percentage of cloud cover. Curran et al. (1978) applied this algorithm to Nimbus-6 ERB latitude band monthly averaged observed albedos for the period July 1975 through April 1977. They first used the algorithm to estimate cloud fractions at each latitude from the observed albedos. Then using these cloud fractions the daily averaged albedos were calculated.

The albedo at the top of the atmosphere can be expressed in terms of cloud albedo and cloud-free albedo as:

$$A = A_s (1 - f_c) + A_c f_c \quad (1)$$

where

A_s = albedo at the top of cloud free atmosphere

A_c = albedo at the top of cloudy atmosphere

f_c = cloud fraction

Given measured values of A the cloud fraction can be obtained by first calculating A_s and A_c then solving for f_c . To compute the daily averaged value of the albedo $A_{d\ell}$ at latitude ϕ the time from sunrise until local noon ($t_{d\ell}$) is first computed from the equation of astronomy describing the apparent motion of the sun:

$$\begin{aligned}\theta_o(t) &= \cos^{-1}\mu_o(t) \\ \mu_o(t) &= \sin\delta_d \sin\phi + \cos\delta_d \cos\phi \cos H(t) \\ H(t) &= 2\pi t/T\end{aligned}\tag{2}$$

where

$\theta_o(t)$ is solar zenith angle

ℓ is an index indicating the latitude band

ϕ is the latitude

δ_d is the solar declination on the d th day

T is the earth's rotation period (24 hours) with respect to the sun

t is the time

$t_{d\ell}$ time interval measured from noon to either sunrise or sunset for given δ_d and latitude band ℓ .

Averaged daily values of A_s and A_c at latitude ℓ are given by:

$$A_{s_{d\ell}} = A_s(a_{d\ell}, t_{d\ell}) = \frac{1}{2t_{d\ell}} \int_{-t_{d\ell}}^{t_{d\ell}} A_s(a_{d\ell}, \mu_o(t)) \frac{\mu_o(t) dt}{\mu_{d\ell}(t)}\tag{3}$$

$$A_{c_{d\ell}} = A_c(a_{d\ell}, t_{d\ell}, \tau_c) = \frac{1}{2t_{d\ell}} \int_{-t_{d\ell}}^{t_{d\ell}} A_c(a_{d\ell}, \mu_o(t), \tau_c) \frac{\mu_o(t) dt}{\mu_{d\ell}(t)}\tag{4}$$

where $a_{d\ell}$ is the average surface albedo

τ_c is cloud optical thickness

The surface albedo is assumed to be independent of the wave length and Lambertian reflection is adopted. The latitude band average, climatological surface albedo, $a_{d\ell}$, were calculated by using climatological snow and ice cover, and geographical ocean and land fractions and the relationship.

$$a(\phi, \text{month}) = (f_{LI} + f_{OI})a_I + (f_L - f_{LI})a_L + (1 - f_L - f_{OI})a_w \quad (5)$$

where f_j is the fraction of the latitude band that is land (L), ocean (O), land ice (LI) or ocean ice (OI).

a_w is the albedo of water at local noon

In these calculations only latitude band averages are treated. For this reason and for simplicity constant values of a_I and a_L were used:

$$a_I = 0.75$$

$$a_L = 0.18$$

The fractions of land, ocean, land ice, and ocean ice were taken from tables 1, 2, and 3 of Curran et al (1978). Their table 8 also lists the ocean albedo, a_w , as a function of latitude and time of year. At the equator $a_w = 0.06$ but in the Arctic Ocean it has a value of 0.10 to 0.11 in the summer and of 0.23 to 0.25 in the early spring or late fall. Now $\bar{\mu}_{d\ell}$ is the average value of $\mu_o(t)$ at latitude (ℓ) while (d) represents the day of the year:

$$\bar{\mu}_{d\ell} = \frac{1}{2t_{d\ell}} \int_{-t_{d\ell}}^{t_{d\ell}} \mu_o(t) dt.$$

Next to fit the results of Dave and Braslau (1974; 1975) linear functions of A_s and A_c are considered as:

$$A_s(a, \mu_o(t)) = m_s(\mu_o) a + A_s(o, \mu_o) \quad (6a)$$

$$A_c(a, \mu_o(t), \tau_c) = m_c(\mu_o) g(\tau_c) a + A_c(o, \mu_o, \tau_c) \quad (6b)$$

m_s and m_c are slope functions and a is the surface albedo.

Terms dependent on higher powers of a were neglected since the fit resulting from the linear function seemed satisfactory.

The slope factor for 6a depends on $\mu_o(t)$. The slope of 6b has been separated into a factor dependent on $\mu_o(t)$ and a factor $g(\tau_c)$ dependent on the cloud optical thickness.

In the present theory $g(3.35) = 1$. The factor $g(\tau_c)$ adjusts the equation for the cloud optical thickness. It is defined by the relationship:

$$g(\tau_c) = A_c(0,0,3.35)/A_c(0,0,\tau_c)$$

$A_c(0,1,\tau_c) = 0.48$ was chosen as the climatological tuning factor of global cloud albedo. To speed integration procedures, the slope and intercept functions of Eqn. 6 are expressed as functions of $\mu_{od\ell}$ in equations 7-10. The coefficients in the series expansion were obtained by a least square, minimum difference, fit to the calculations of Dave and Braslou.

$$A_s(0,\mu_o(t)) = 0.35057 - 1.0933\mu_{od\ell} + 1.6599\mu_{od\ell}^2 \quad (7)$$

$$- 1.1897\mu_{od\ell}^3 + 0.32105\mu_{od\ell}^4$$

and $A_c(0,\mu_o(t),\tau_c) = 0.73 - 0.25\mu_{od\ell}$ (8)

$$m_{sd}(\mu_o(t)) = 0.31876 + 1.2638\mu_{od\ell} - 1.368\mu_{od\ell}^2 + 1.50833\mu_{od\ell}^3 \quad (9)$$

$$m_{cd}(\mu_o(t)) = 0.16325 + 0.3633\mu_{od\ell} - 0.02501\mu_{od\ell}^2 \quad (10)$$

ALBEDO COMPUTATIONS

Equations (3) and (4) now take the form:

$$A_{sd\ell}(a,\mu_o(t_{d\ell})) = \frac{1}{2t_{d\ell}} \int_{-t_{d\ell}}^{t_{d\ell}} [m_s(\mu_o + A_s(0,\mu_o))] (\mu_o(t)/\bar{\mu}(t)) dt \quad (11a)$$

The monthly averaged latitude band albedos A_{sm1} and A_{cm1} are obtained from the daily albedos weighted by the daily insolation or equivalently:

$$W_{d\ell} = I_d \mu_{od\ell}$$

where I_d is the solar irradiance on day (d). Thus

$$A_{sm\ell} = \left(\sum_{d=1}^n A_s W_{d\ell} \right) / \left(\sum_{d=1}^n W_{d\ell} \right) \quad (12)$$

$$A_{cm\ell} = \left(\sum_{d=1}^n A_c W_{d\ell} \right) / \left(\sum_{d=1}^n W_{d\ell} \right) \quad (13)$$

where n = the number of days in the month, and m indicates the month.

The average monthly latitudinal cloud fraction, required to complete the albedo A in equation (1) is obtained from:

$$f_{c_{m\ell}} = (A_{m\ell} - A_{s_{m\ell}}^*) / (A_{c_{m\ell}}^* - A_{s_{m\ell}}^*)$$

where $A_{m\ell}$ is the measured monthly averaged albedo. We used Nimbus-7 ERB values of $A_{m\ell}$ for the period January 1979–October 1983. The clear and cloudy sky albedos, $A_{s_{m\ell}}^*$, are the latitude band average values at the time of observation; this is close to local noon at most latitudes.

ANALYSIS

Three year-averaged measured orbital albedos, for 1979, 1980, 1981, are shown in Figure 1 in a latitude band averages versus time plot. Minimum albedos of about 22 percent occur in the tropics with steadily increasing albedos towards the poles. Maximum values of 70 to 80 percent occur in the polar regions in the spring and fall. The albedos shown during the polar night are found by interpolation and are in a sense fictitious, since the sun is below the horizon. The equivalent daily averaged albedos calculated by the ERB Experiment Team are shown in Figure 2 while our results are shown in Figure 3. The ratio of our averaged albedos to the orbital measured albedos is plotted in Figure 4, while Figure 5 shows the ratio of our results to those of the ERB Experiment Team.

The daily averaged albedos, Figure 2 and Figure 3, show a pattern similar to Figure 1, however, the differences between the measured and daily averaged albedos are significant. Figure 6 is a graph of local time versus the latitude of the Nimbus-7 subsatellite point. Most of the Earth is observed near local noon (11:00 a.m.–1:00 p.m.). For a fixed scene, albedos are almost always a minimum at local noon and increase as the sun gets lower in the sky. Thus, daily averaged albedos should be larger than observed values at low and mid latitudes but smaller near the terminate which always lies in the polar regions for the Nimbus-7.

This behavior is illustrated in Figure 4, where our computed daily averaged albedo is expressed as percent of the measured albedo. We calculate the daily average albedo to be between 110 percent and

114 percent of the measured, noon time, albedo in the tropics but it drops to between 94 percent and 98 percent of the polar sunrise or sunset albedos. Taylor and Stowe's (1984) data indicates that the noon time-terminate albedo range in the tropics should be a factor of 2 or larger. However, the averaged albedos are insolated weighted and the most intense irradiance occurs near local noon. In the polar regions the sun is always low in the sky. Thus, the measured albedo at 6 a.m. or 6 p.m. will not vary too much from that measured at local noon. In the tropics however, the solar zenith angle will vary from between (0-30°) at local noon to 90° at sunrise or sunset. Correspondingly for a fixed scene the measured albedo will increase from local noon to sunset by between 50 percent and 200 percent depending on the scene.

There is no established optimal procedure for estimating the daily average albedo from a once a day measurement. The daily averaging algorithm used by the ERB Nimbus Experiment Team (Kyle and Vasanth, 1986), is known to be simplistic but tests indicate that it is reasonably accurate. Its two chief defects are that it uses a global, scene independent algorithm to describe the variation of albedo with solar zenith angle and that it is based on Nimbus-2 and 3 MRIR albedo measurements which are not as accurate as more recent satellite albedo measurement.

Our computed daily averages are compared to the Experiment Team's daily average estimates in Figure 5. Our values are expressed as percentages of the Team's values. The major differences between the two daily averaging algorithms should be kept in mind:

- The ERB Team algorithm is scene independent and varies only with solar declination and time of observation. Our algorithm, however, is dependent on the zonally averaged scene (percent of land, ocean, ice and cloud in the latitude band).
- The ERB Team algorithm starts with the measured albedo and simply applies the daily averaging factor. Our algorithm uses climatological surface and cloud albedos combined with radiation

transfer theory to obtain the top of the atmosphere albedo. The measured albedos are used to estimate the amount of cloud present.

In the tropics and mid latitudes the agreement is generally good (± 2 percent). However, our values drop 6 percent below the Team values in a number of places. These regions are associated with minimum cloudiness as indicated in Figure 7. This indicates a definite defect in the Team algorithm which does not adjust for variations in the scene.

In the polar regions the difference between the two algorithms range up to 10 percent but this should be expected since neither algorithm treats these regions properly. The directional reflectance for snow and ice is considerably different from the scene independent model used by the ERB Team. On the other hand our algorithm does a poor job of estimating cloud amounts in the polar region. Its zonally averaged correction factors are therefore less reliable in these regions.

The climatological values used in our model assumes mean global clear sky land, ocean and snow albedos and fixed overcast albedos. Although our daily averaged albedo values appear reasonable in all zones some values of the derived cloud cover in the polar regions appear too low. For instance, a value of 14 percent cloud cover at 60° N latitude in April is much too low. The problem seems to arise from the use of the mean global scene albedos. Use of seasonal and zonal scene albedos would markedly improve our cloud values in regions like this. The low mean sun angles in the polar regions keeps our daily averaged albedo from straying too far from the true value.

CONCLUSIONS

The use of a global, scene independent directional reflectance function to calculate daily averaged albedos does not yield accurate seasonal and zonal variations. The problem is particularly bothersome in the tropics and mid latitudes where cloudy and clear zonal bands occur. The positions and intensities of these bands also vary seasonally.

A heuristic algorithm based on radiative transfer theory has been used to study the problem. The daily averaging functioning accounts for both zonal geographical differences and for varying cloud cover. It has been applied to three years of Nimbus-7 ERB Wide-Field-of-View measured albedo data.

When compared to the global, scene independent algorithm used by the Nimbus ERB Experiment Team it yields more realistic results in the tropics and mid latitudes. In the polar regions both algorithms have noticeable faults.

Based on our results we recommend that an improved daily averaging algorithm be set up to calculate daily averaged albedos and Net radiation from the Nimbus-7 ERB MATRIX tapes. These tapes contain both the observed and daily averaged albedos. The algorithm described in this paper would be useful for this purpose. However, first it should be modified to use seasonal and zonal climatological surface and cloud albedos.

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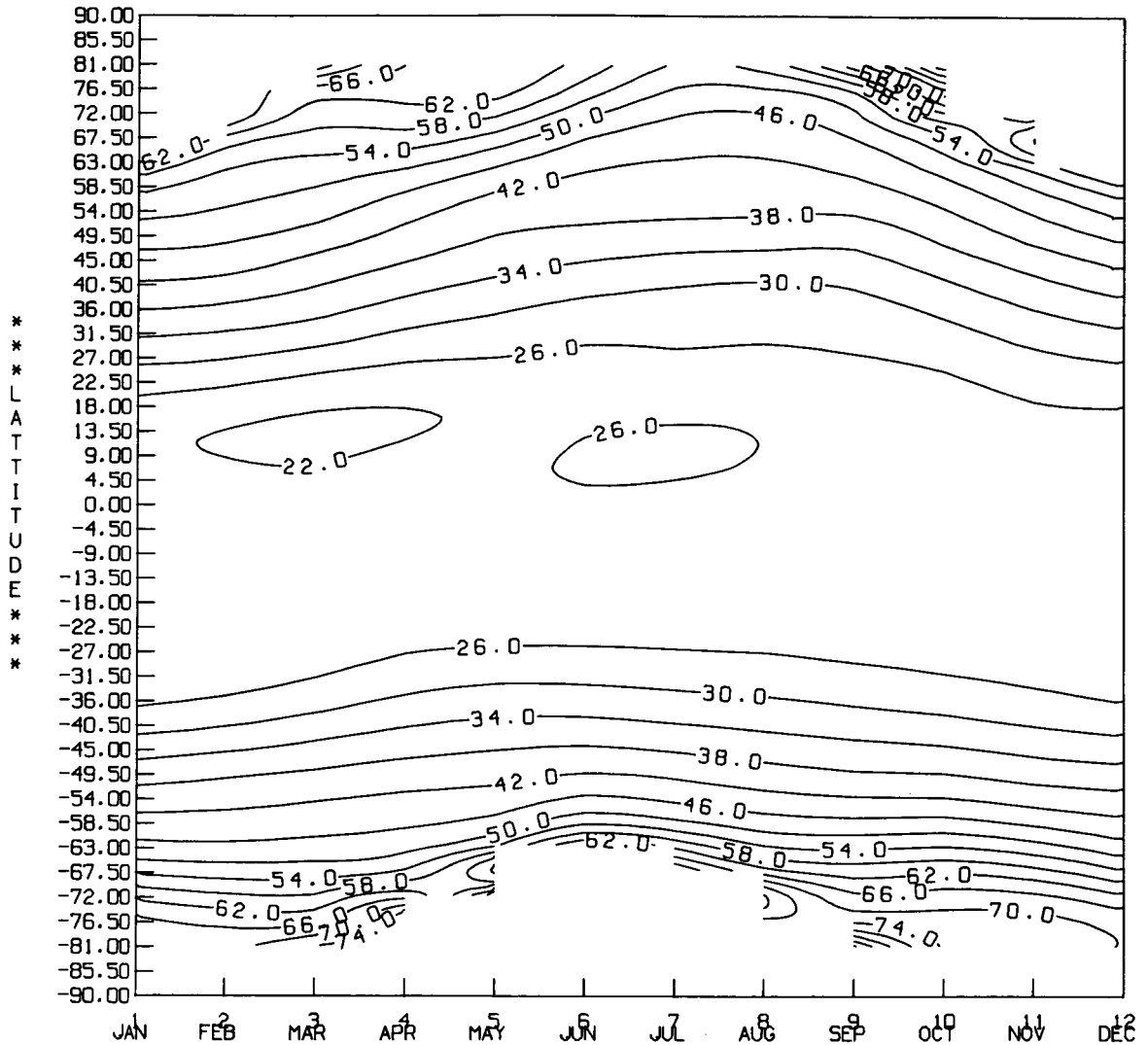


Figure 2. Climatological monthly averaged albedos, in percent, estimated by the ERB Nimbus-7 Experiment Team. The albedos are measured only once a day. An algorithm, see text, is used to estimate the daily and monthly averaged albedo. Latitude band averages are plotted versus month of the year.

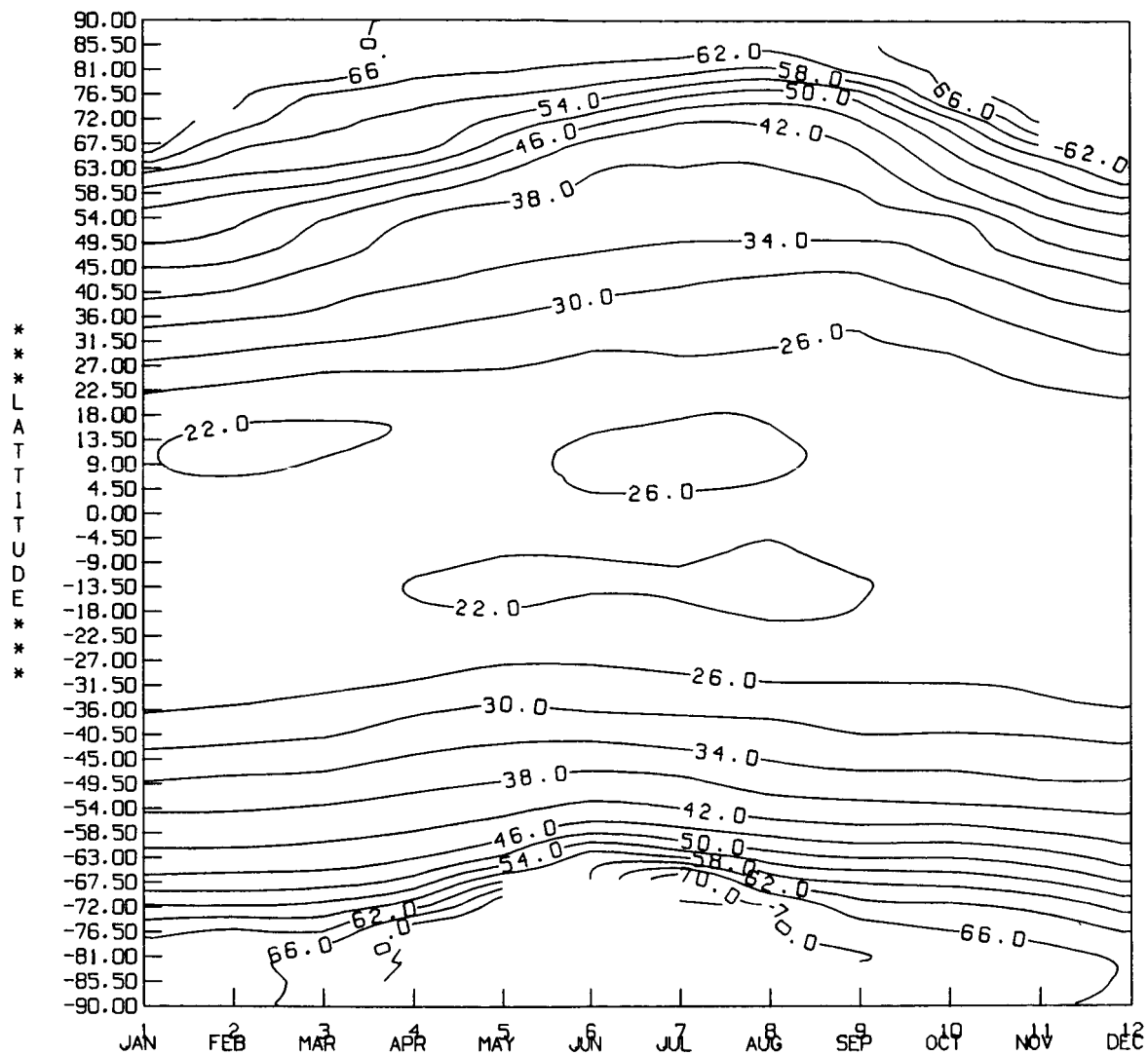


Figure 3. Climatological monthly averaged albedos in percent calculated by the Authors using the procedures described in the text. Latitude band averages are plotted against month of the year.

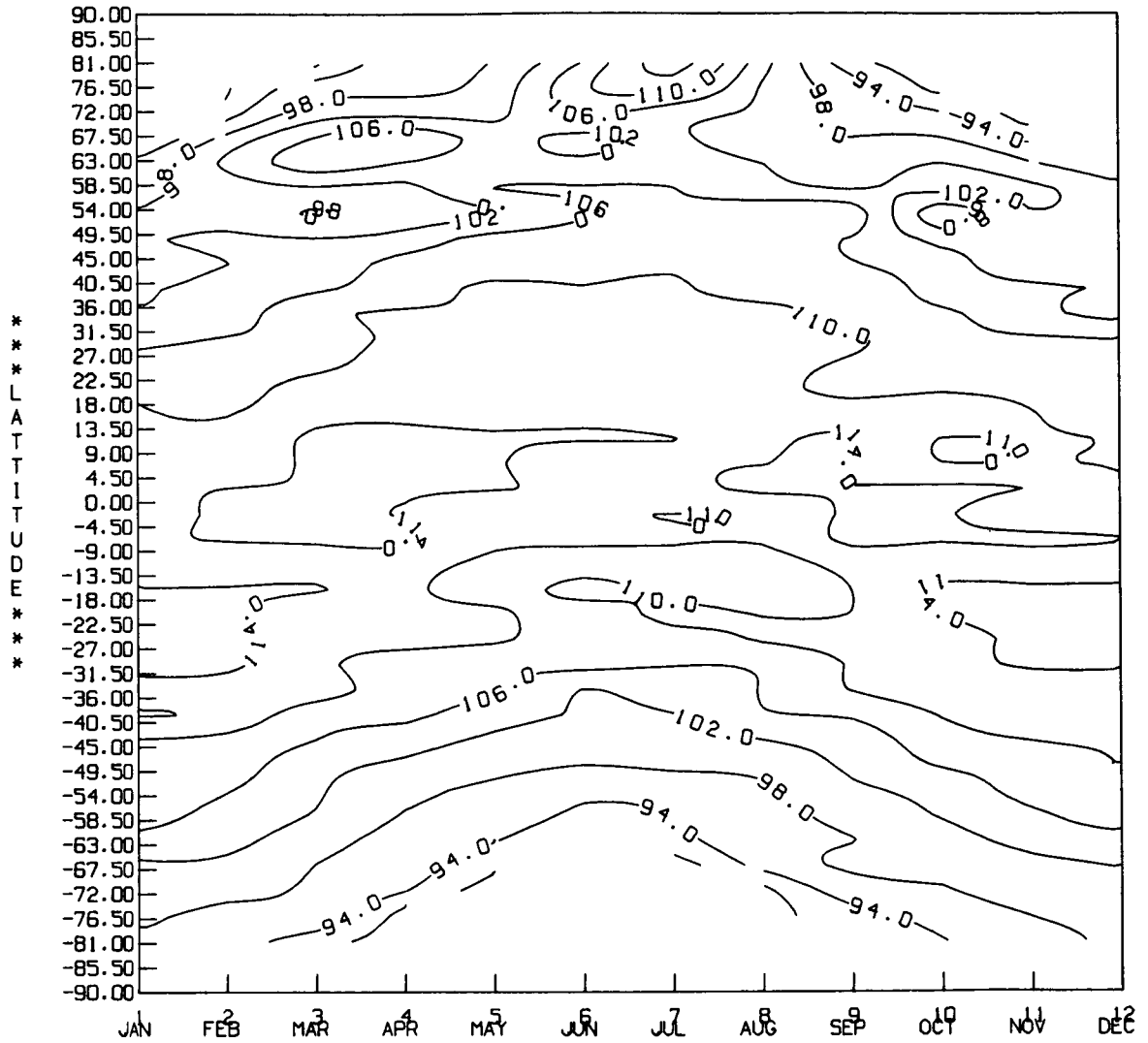


Figure 4. Ratio in percent of the calculated monthly averaged albedos (Fig. 3) and the measured albedos (Fig. 1) given in percent. Latitude band ratios are plotted against month of the year.

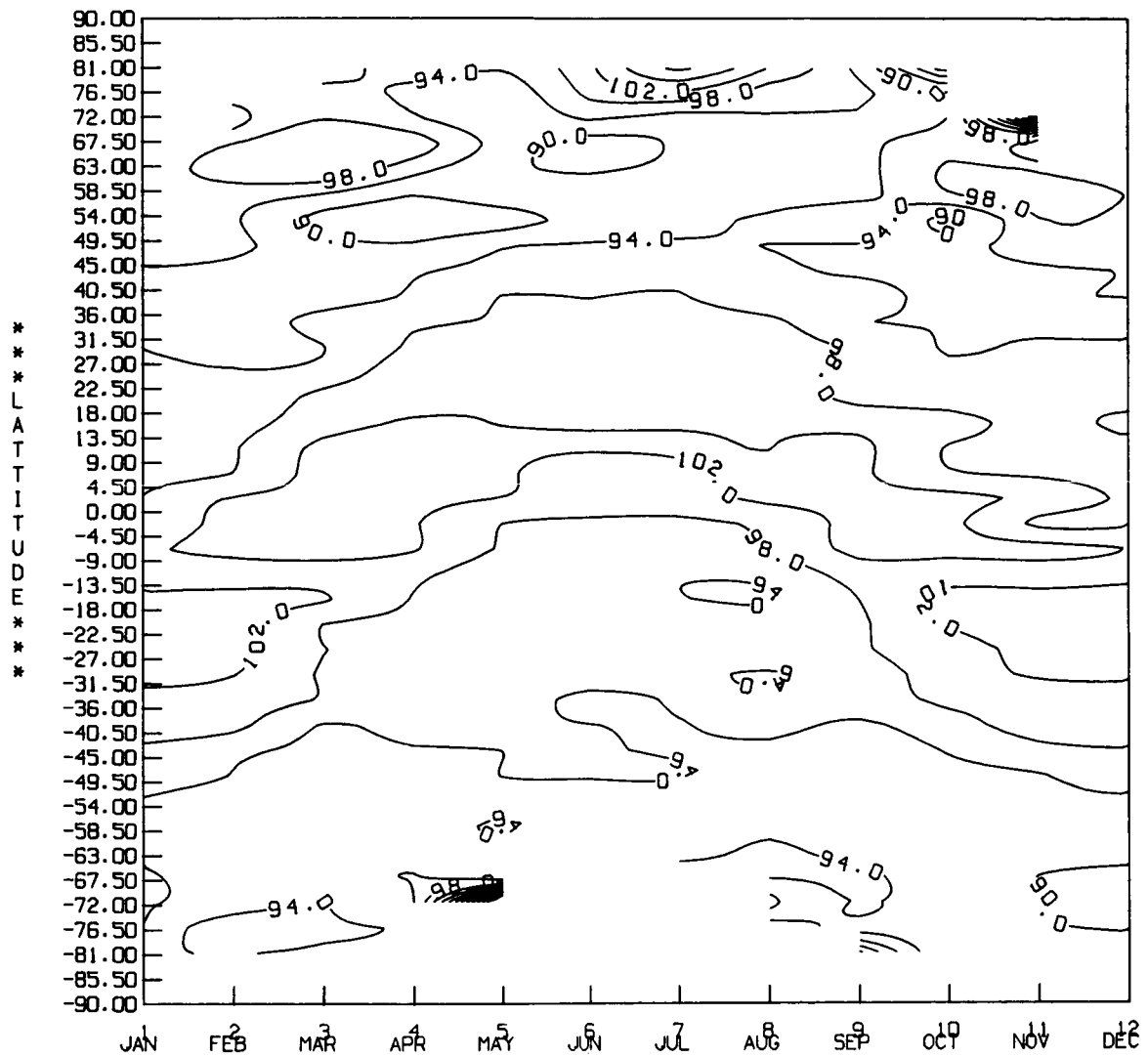


Figure 5. Ratio in percent of the calculated monthly averaged albedos (Fig. 3) to the monthly averaged albedos calculated by the ERB Experiment Team (Fig. 2). Latitude band ratios are plotted against month of the year.

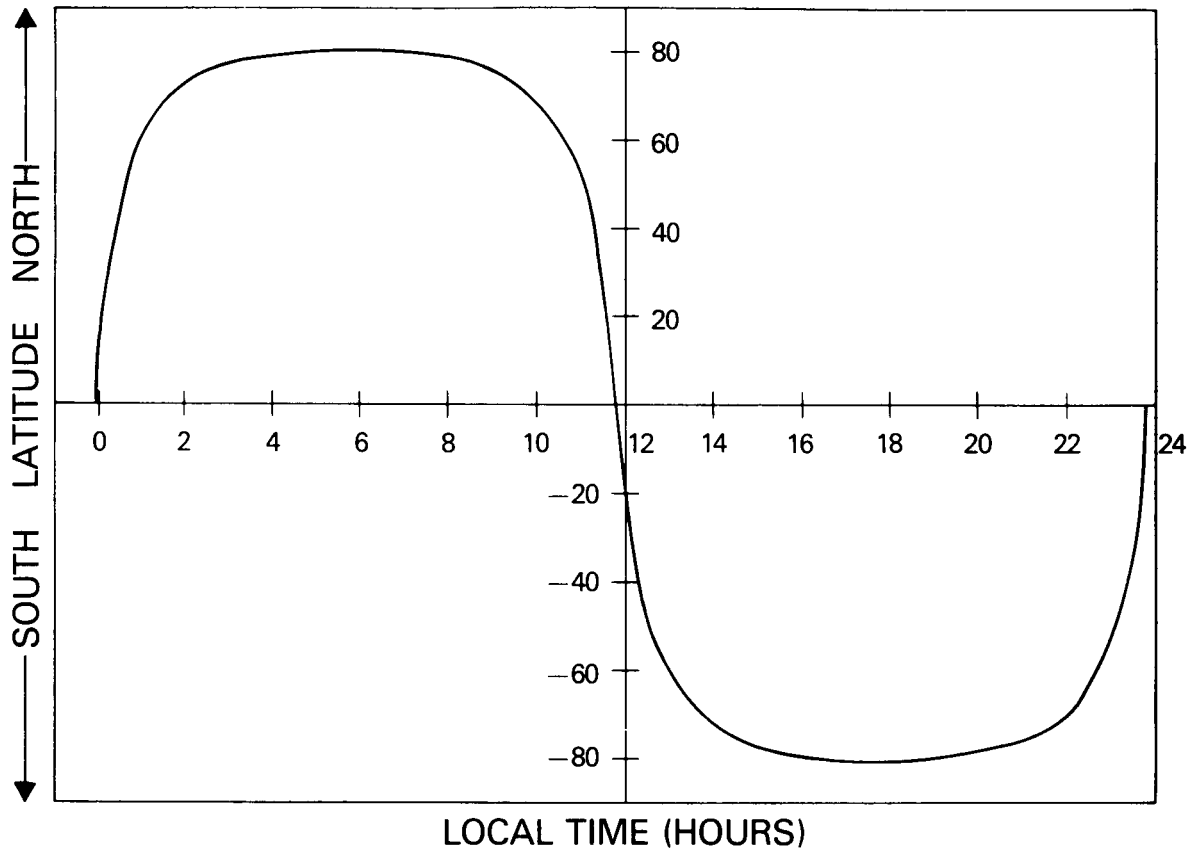


Figure 6. Nimbus-7 local sampling times for nadir point as a function of latitude.



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16. Abstract <p>The Nimbus-7 ERB experiment measures the Earth's albedo from a satellite in a fixed Sun Synchronous orbit. The data is obtained at a fixed time of the day for each latitude observed. For Earth Radiation Budget studies it is normally assumed that the observed scene is invariant during the day and that the albedo varies only with the solar zenith angle. This paper presents a technique for computing mean zonal albedos as a function of the albedo (A_s) of cloud free atmosphere, the albedo (A_c) of cloudy atmosphere and of the cloud fractions. The values of A_s and A_c are obtained from radiation transfer theory and climatological values of the surface and cloud albedos. The albedos are a function of the solar zenith angle, latitude and solar declination. The cloud fraction are estimated from the measured Nimbus-7 ERB albedos. The present study shows the importance of taking into account latitude variations in surface types and in cloud cover.</p>					
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