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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite Service

Review of Satellite Measurements of Albedo and Outgoing Long-Wave Radiation

ARNOLD GRUBER

WASHINGTON, D.C.
July 1973

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U.S. DEPARTMENT OF COMMERCE
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NOAA Technical Memorandum NESS 48

REVIEW OF SATELLITE MEASUREMENTS OF ALBEDO AND OUTGOING LONG-WAVE RADIATION

Arnold Gruber

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July 1973

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- ERRATA -

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Equation, page 4, should read:

$$A = 1 - (N+E)/I_o$$

Page 4, 5th paragraph, sentence starting "However, despite ..." should read: However, despite the obvious uncertainty of the magnitude of the albedo and outgoing long-wave radiation, it appears that there is general agreement in the shape of the latitudinal profiles,particularly in the infrared.

Page 5, figure 3, Rashke should be Raschke.

Page 9, 3rd paragraph, sentence starting "However, on a hemispherical ..." should read: However, on a hemispherical and global basis, they appear to be in general agreement, the ESSA 7 data implying slightly higher albedo and slightly more outgoing long-wave radiation.

REVIEW OF SATELLITE MEASUREMENTS OF ALBEDO AND OUTGOING LONG-WAVE RADIATION

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ABSTRACT. A review of satellite measurements of albedo and outgoing long-wave radiation has been made. The review has concentrated on zonal, hemispherical, and global averages for periods ranging from 15 days to several years. The results of various investigators have been compared. Differences in results obtained from different satellites and years as well as differences in results between investigators using the same satellite data are discussed. Possible reasons for the differences are variable data-reduction procedures, differences in satellite sensors, variable sampling in space and time and real year-to-year variability.

INTRODUCTION

Starting with the TIROS series of satellites, a variety of satellite measurements of the albedo and outgoing long-wave radiation of the earth-atmosphere system exists. A brief review of the literature points out that there is a dramatic difference between results of various investigators using essentially the same data. A more detailed review indicates that the differences arise as a result of various data-reduction procedures and assumptions concerning the processes occurring in the earth-atmosphere system. Differences observed in annual values of global albedo and emitted long-wave radiation, obtained from different satellites and years, are not so readily identified. In addition to causes previously mentioned, differences may be due to differences in satellite observing systems, variability in spatial and temporal coverage, and real year-to-year variability.

This note contains a brief summary of estimates of albedo and outgoing long-wave radiation based on satellite data. The main concern is with zonal, hemispherical, and global averages for time periods as short as 15 days (15 d) and as long as several years. Available information on the assumptions and types of data-reduction procedures used by each investigator are summarized for each type of satellite.

TIROS DATA

TIROS was equipped with both scanning radiometers and hemispherical radiometers. Among the investigators who examined TIROS scanning radiometer data, Winston (1967, 1969), Bandeen et al. (1965), and Arking and Levine (1967) are the most prominent. The Bandeen and Winston studies used the same data from TIROS 7. In figures 1A through 1D, a comparison of the results (season for season) for the period June 1963 through May 1964 are shown. Results from TIROS 4 for the season March-May 1962 are also included for comparison. Before examining the results in detail, a brief discussion of the data-reduction techniques is appropriate.

Outgoing Long-Wave Radiation

Both Bandeen's and Winston's studies deduced the total outgoing long-wave radiation from measurements in the 8- to 12-μm region. Both used the relationships derived by Wark et al. (1962) to obtain the total outgoing flux from data in the 8- to 12-μm range. However, Bandeen et al. (1965) used the limb-darkening corrections suggested by Wark et al. (1962) but modified it slightly by the results of an empirical study of limb darkening using TIROS 4 data. The important point is that the limb-darkening correction used by Bandeen is proportional to the absolute value of the radiance. Subsequent work by Lienesch and Wark (1967) have shown that to be incorrect.

Winston (1969), on the other hand, used the limb-darkening correction rederived by Lienesch and Wark. It was not clear what the magnitude of the differences between the two methods is.

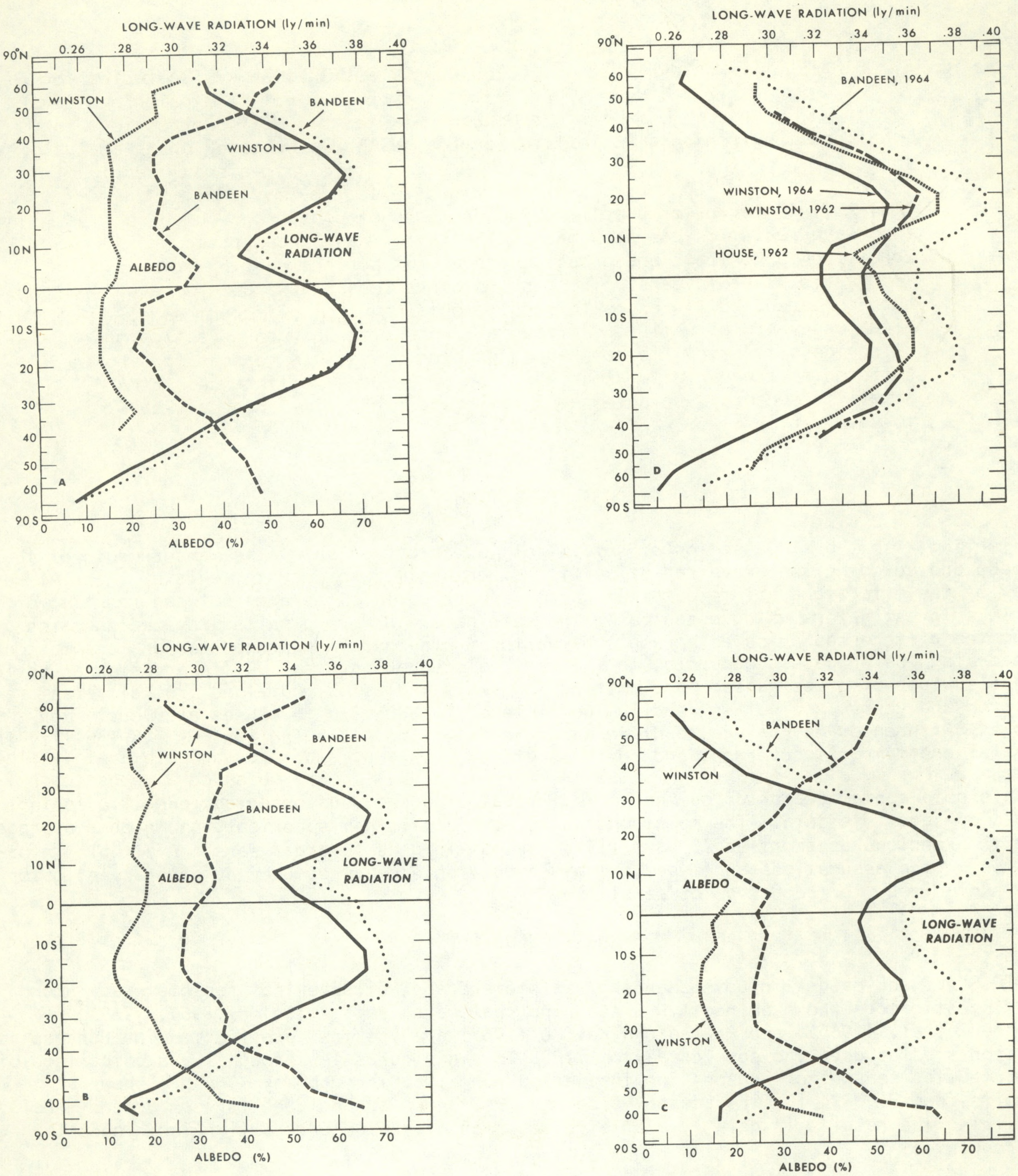
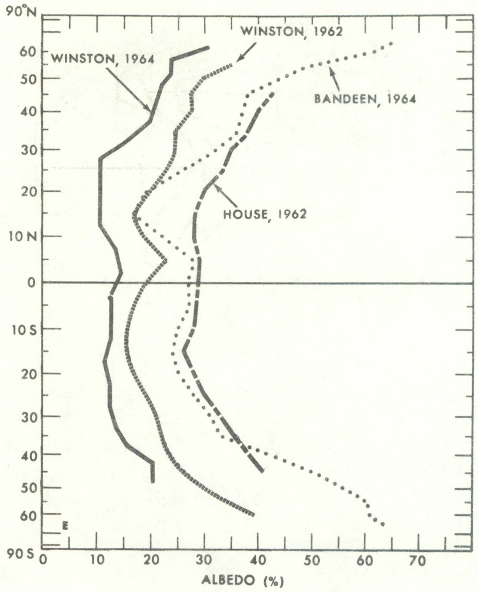


Figure 1.--*Profiles of albedo and outgoing long-wave radiation (obtained from TIROS 7) for (A) June through August 1963, (B) September through November 1963, and (C) December 1963 through February 1964; (D) profiles of outgoing long-wave radiation for March through May of 1962 and 1964 (1964 values obtained by Bandeen and Winston and 1962 values obtained by Winston and House); (E) profiles of albedo for the same periods as in (D)*

Instrument degradation was corrected for in Bandeen's study but not in Winston's study, although Winston did apply corrections for instrument degradation based on an analysis by Rao et al. (1965) to a small sample of TIROS 4 data (March-May 1962).



Albedo

Both Winston and Bandeen utilized the 0.55- to 0.75-µm channel of TIROS 7 to obtain a measure of planetary albedo. Both used solar constants of 2.0 ly/min.

Again, Bandeen corrected TIROS 7 data for instrument degradation, whereas Winston did not; both assumed that the reflecting and scattering properties of the earth-atmosphere system are isotropic. Winston (1967) points out that the number of days with data varied considerably. Because of the way of averaging, this resulted in zonal averages often composed of limited data. The situation was apparently worse for the albedo than the outgoing long-wave radiation since only daytime observations were available. However, the largest differences probably come about as a result of corrections to the albedo that Bandeen made based on the assumption that planetary radiative equilibrium exists for the whole year. Using the annual value of outgoing long-wave radiation, he deduced the annual planetary albedo necessary for radiative balance. He then rescaled all his TIROS 7 observed albedos (each 1-week sample) by the ratio of the calculated annual value to that observed, a multiplication factor of 1.6. Winston (1967) has pointed out some of the pitfalls inherent in this approach and so did not make any such adjustments in his analysis of the data.

Discussion

With these differences in mind, examine the outgoing long-wave radiation for June through August 1963 (fig. 1A). Here, there is fairly good agreement between the two sets of observations. Apparently, the degradation correction was not very large at this time. However, as time progresses, the differences between the two become larger, a reflection, probably, of instrument degradation corrections rather than differences in limb-darkening corrections.

The differences in albedo are expected, considering the corrections applied by Bandeen et al. (1965). We expect his results to be higher than Winston's.

The graphs for the spring season (March-May) also include data from studies of TIROS 4 conducted by House (1965) and Winston as summarized by Winston (1969). House's data were obtained from a hemispherical net radiometer rather than the scanning radiometers used by Winston and Bandeen. It is interesting to note that the outgoing long-wave radiation calculated by House and Winston for 1962 are in general agreement. However, the long-wave data presented by Winston for 1964 are everywhere less than that of 1962, and the data presented by Bandeen for 1964 are everywhere greater than that observed by House for 1962. The indications are that Bandeen's results have too great a correction, whereas Winston's 1964 results require correction.

The albedo values presented by House, however, are systematically higher than the albedo calculated by Winston using the scanning radiometer data for the same period. House's 1962 results are in closer agreement with Bandeen's 1964 results.

It is apparent that the absolute values of albedo are uncertain. However, one possible explanation for the albedo differences between the three results is the following: House obtains the albedo from a knowledge of the incoming solar radiation, the outgoing long-wave radiation, and the net radiation of the earth-atmosphere system, that is,

$$A = 1 - (N+E)/I_o)$$

where A is albedo; N, net radiation; I_o, incoming solar radiation at the top of the atmosphere; and E, outgoing long-wave radiation.

In this computation, House assumed that the outgoing long-wave radiation during daytime was the same as during nighttime. This was necessary since he could measure only the net radiation. This could lead to considerable error where there is a marked diurnal variation in outgoing long-wave radiation. The important point to note is that he does not measure the albedo but calculates it from his other measurements. Thus, his albedo determination is essentially a quantity that accounts for the anisotropic properties of the earth-atmosphere system. This may account for some of the differences in albedo between Winton's 1962 data (where isotropy was assumed) and House's data.

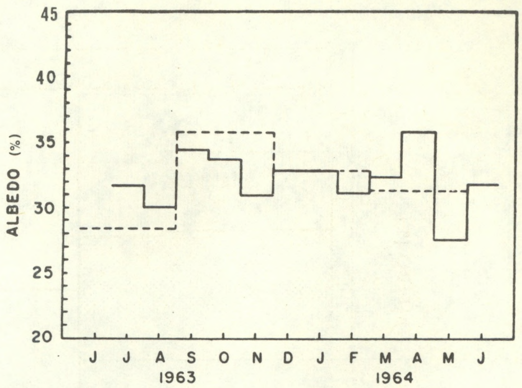


Figure 2.--*Comparison of the seasonal variation of albedo determined from TIROS 7 0.55- to 0.75-µm data by Arking and Levine (1967, solid line) and Bandeen et al. (1965, dashed line). This is after Arking and Levine (1967).*

Bandeen's 1964 albedo data, which were corrected for instrument degradation, also contain an adjustment factor necessary for radiative equilibrium. This probably turns out to be a crude way of accounting for anisotropy (as well as other sources of error) and may be the reason for the general agreement between House's 1962 results and Bandeen's 1964 results.

Arking and Levine (1967) also examined TIROS 7 data in the 0.55- to 0.75-µm region to study the planetary albedo. Their treatment of the data differed appreciably from Winston and Bandeen's in that they applied corrections to the data to account for the anisotropic behavior of the earth-atmosphere system. Their results are presented in figure 2 where they are compared to those of Bandeen et al. (1965). They scaled the results upward to the same global albedo as Bandeen so that the comparison illustrates the effects of considering the angular dependence of the scattered radiation. The large differences suggest that the anisotropic behavior of the reflecting surface is important in deducing the albedo. However, there is still much uncertainty as to the "correct" angular law. For example, Ruff et al. (1968) studied the angular distribution of solar radiation reflected from clouds and concluded that there was little change from an isotropic assumption.

In summary, various types of corrections applied to TIROS 7 data result in albedo estimates varying by as much as a factor of 2 and outgoing long-wave estimates varying by as much as 13%. The implications of these variations on computations of the global heat balance are obvious. However, despite the obvious uncertainty of the magnitude of the albedo and outgoing long wave, it appears that there is general agreement in the shape of the latitudinal profiles particularly in the infrared. Thus, we can have more confidence in north-south gradients than in the absolute values of the quantities involved.

NIMBUS DATA

Both Raschke (1968) and Winston (1972a) have done extensive analysis of Nimbus 2 data. Nimbus 2 was a polar orbiting sun-synchronous satellite crossing the Equator near local noon and local midnight.

Observations of outgoing infrared radiation were made in the 5.0- to 30.0-µm region, and observations of reflected energy were made in the 0.2- to 4.0-µm region. Both Winston and

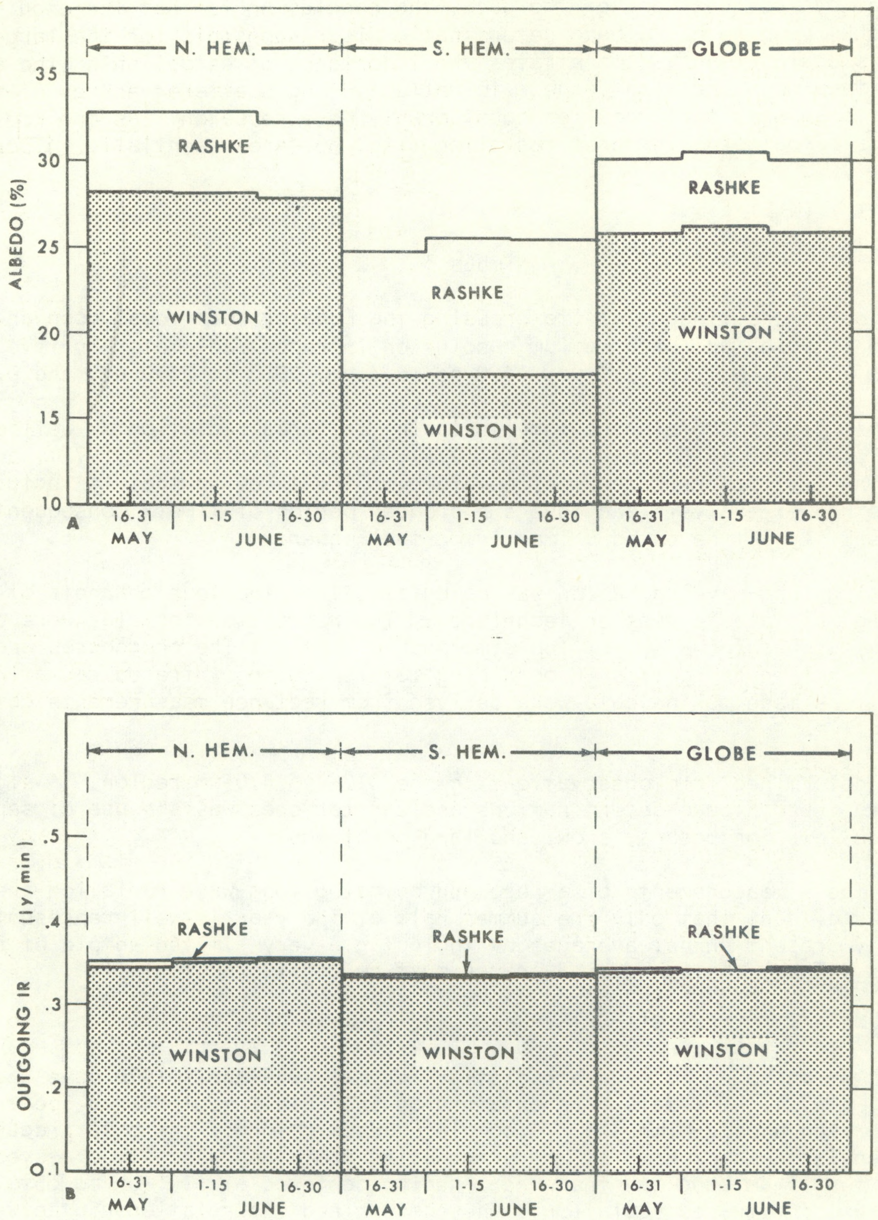


Figure 3.--*(A) comparison of albedo values determined from Nimbus 2 data for 1966 by Raschke and Winston. (B) is the same as (A) except outgoing infrared values are compared.*

Raschke applied the limb-darkening corrections established by Liënesch and Wark (1967) in their treatment of the outgoing infrared data.

In analyzing the albedo, however, Raschke empirically took into account the anisotropic nature of reflecting energy, whereas Winston assumed isotropic conditions. In addition, Raschke used a solar constant of 2.00 ly/min, whereas Winston used 1.95 ly/min.

Neither researcher indicated that there was any instrument degradation, so it is assumed that this was not a factor in their analysis. Figure 3A presents a comparison between

Raschke and Winston albedo determination. As can be seen, there are significant differences between them particularly in the Southern Hemisphere.[1] Since the differences are undoubtedly caused by the treatment of the data, the conclusion is that the angular dependence law Raschke used in his albedo determination is responsible for the large differences. This again clearly demonstrates the importance of establishing the anisotropic nature of the earth-atmosphere with respect to reflected and scattered energy of the incoming radiation. This is an area that requires considerably more research. As one would suspect, their computations of outgoing infrared radiation (fig. 3B) are essentially in agreement.[2]

Nimbus 3

Nimbus 3 was a polar orbiting satellite crossing the Equator near local noon and local midnight. Measurements were made by a medium resolution infrared radiometer in five separate channels: 6.0 to 7.0 μm, 9.1 to 12.1 μm, 14.0 to 16.3 μm, 20.2 to 23.9 μm, and 0.2 to 4.8 μm.

Analyses of these data to obtain the total outgoing infrared radiation as well as the albedo have been performed by Raschke et al. (1971), Vonder Haar et al. (1972), and Raschke et al. (1973). The last paper is the most complete of the three in that it includes more details on the method of analysis and covers a broader period of time. Consequently, the summary of the results will be based primarily on that paper.

The total outgoing long-wave radiation was calculated from the four channels of infrared measurements using multiple regression techniques. The regression formulas were derived from radiances calculated for a set of 160 atmospheric models. The procedures are similar to those used by other investigators in obtaining total outgoing infrared radiation. Limb-darkening corrections made to the data were derived from radiance measurements obtained from the Nimbus 2 satellite.

The albedo was determined from observations in the 0.2- to 4.0-μm region. A significant difference between these albedo determinations and earlier ones was the use of separate angular dependence laws for oceans, snow, and land or clouds.

The results of their measurements of albedo and outgoing long-wave radiation are presented in table I. It is evident that only the summer half of the year is well represented. Nevertheless, they present annual averages by including a very limited sample of data from the other seasons. Thus, their annual averages must be considered tentative.

Satellite Infrared Spectrometer Data

Annual profiles of outgoing long-wave radiation for May 1969-April 1970 have been presented by Winston et al. (1972). The data were obtained by the Satellite Infrared Spectrometer (SIRS A) that operated aboard Nimbus 3. A complete description of the data processing and reduction is given in their paper. It is worth noting that they used six of seven channels in the region of the 15-μm band and the window region centered at 11.1-μm to obtain the total outgoing flux of infrared radiation. They determined the relationship between the total outgoing flux and SIRS-A spectral radiances through a stepwise multiple regression of data generated by use of a set of 106 model atmospheres (Wark et al. 1962). The most serious problems associated with the analysis were (1) large data gaps existed between successive orbits and (2) observations were averaged over 4° of latitude centered at every 10° of latitude. This resulted in a set of data composed of only 40% of the SIRS observations and obviously limits the north-south vertical resolution. Their results are discussed in the next section where a comparison is made of the mean annual outgoing long-wave radiation arrived at by various investigators.

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[1] If we adjusted Raschke's albedo to a solar constant of 1.95 ly/min, the difference would be greater by about 2.5%.

[2] Raschke's analysis was through 28 July 1966. Figures 3A and 3B cover only the period for which both Winston and Raschke have results.

Table 1.--*Global and hemispherical radiation balance components (after Raschke et al. 1973)*

Date		Incoming solar energy † (cal cm^{-2} min^{-1})	Albedo	Outgoing long-wave radiation (cal cm^{-2} min^{-1})
16-30 Apr.	N*	0.586	0.300	0.349
1969	S	.379	.270	.342
	G	.483	.288	.346
1-15 May	N	0.618	0.302	0.351
1969	S	.334	.269	.343
	G	.476	.291	.347
16-31 May	N	0.641	0.314	0.355
1969	S	.310	.264	.346
	G	.476	.298	.350
1-15 June	N	0.656	0.308	0.359
1969	S	.290	.267	.343
	G	.473	.296	.351
16-30 June	N	0.659	0.299	0.362
1969	S	.283	.271	.362
	G	.471	.291	.352
1-15 July	N	0.652	0.296	0.365
1969	S	.291	.267	.344
	G	.471	.286	.355
16-31 July	N	0.633	0.290	0.363
1969	S	.311	.261	.345
	G	.472	.281	.354
1-15 Aug.	N	0.609	0.287	0.365
1969	S	.340	.271	.341
	G	.474	.280	.353
3-17 Oct.	N	0.443	0.270	0.351
1969	S	.541	.291	.344
	G	.492	.282	.348
21 Jan-3 Feb.	N	0.343	0.273	0.332
1970	S	.663	.287	.342
	G	.501	.283	.337
Annual	N	0.483	0.287	0.350
	S	.492	.280	.344
	G	.488	.284	.345

*N, Northern Hemisphere; S, Southern Hemisphere; G, global
† Based on a solar constant of 1.95 cal cm^{-2} min^{-1}

LONG-TERM AVERAGES

Recently, Vonder Haar and Suomi (1971) published data on the earth's radiation balance covering a 5-yr period. Their sample consisted of data from selected months of 1962 through 1966. The data are from TIROS 4 and 7 satellites, the Nimbus 2 satellite, the ESSA 3 satellite (flat-plate radiometer), and observations made with low-resolution disc sensors. It is not clear from the paper what types of adjustments, if any, were made to the data or if the anisotropic problem of reflected energy was treated for the nonplate-type measurements. However, in an earlier publication, Vonder Haar (1968) points out that the TIROS 7 data were adjusted for instrument degradation and restricted spectral region (0.55-0.75 µm) when obtaining the albedo. The instrument degradation adjustment was the same as that suggested by Bandeen et al. (1965), but the final albedo value was adjusted to make the low resolution disc and medium resolution sensors of TIROS 7 agree. There were apparently no corrections made (for the anisotropic nature of the reflected energy) to the data obtained from the medium resolution sensors of the Nimbus 2 and TIROS 4 and 7 satellites.

Their average results are shown by latitude belt in figure 4. Table 2 presents pertinent statistics for each hemisphere and for the globe. It is difficult to compare these results with the other studies reviewed because of the differing time periods involved. Nevertheless, such a comparison is made (with the outgoing long-wave radiation in fig. 5) between Vonder Haar and Suomi's results and the studies by Bandeen (1965), Winston (1969), and Winston et al. (1972). As in the comparisons previously presented, the north-south gradients are in general agreement. Comparison of the magnitudes shows considerable variability in

Table 2.--*Mean annual albedo and outgoing radiation (after Vonder Haar and Suomi 1971)*

Area	Albedo (%)	Radiation in cal cm^{-2} min^{-1} Incident solar	Absorbed	Emitted IR
Northern Hemisphere	30	0.48	0.34	0.33
Southern Hemisphere	30	.49	.34	.33
Globe (whole earth)	30	.49	.34	.34

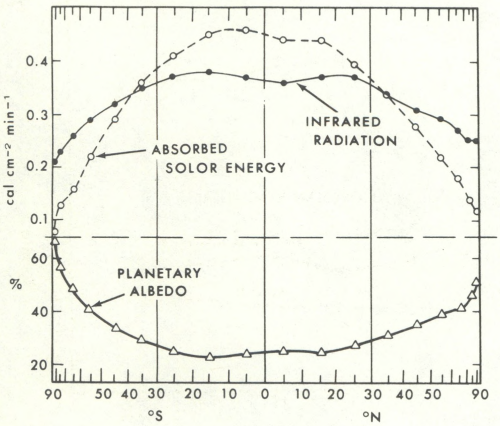

Figure 4.--*Mean meridional profiles (averages, within latitude zones) of the earth's radiation budget measured during the period 1962-1966 (after Vonder Haar and Suomi 1971)*

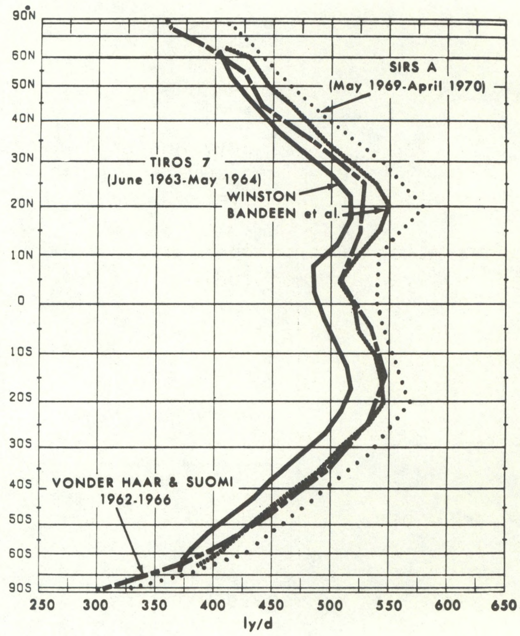

Figure 5.--*Summary of the mean annual outgoing long-wave radiation*

some places showing excellent agreement between Vonder Haar and Suomi and either Bandeen's or Winston's TIROS 7 results and in other places poor agreement. The results from SIRS A indicate systematically more outgoing long-wave radiation than any of the other estimates. Under radiative equilibrium, this implies a lower albedo for May 1969-April 1970 than in the other years represented. However, because of the widely different periods covered, one should not attach great significance to differences or similarities, particularly since so little is known about interannual variations. Other complicating factors are that different instruments as well as different limb-darkening corrections and different model atmospheres were used to establish the outgoing infrared radiation flux.

It should also be pointed out that there is some question concerning the reliability of the mapped quantities presented by Vonder Haar and Suomi (Winston 1972b). This casts some doubt on their global average, although the possibility exists that the global averages are essentially correct but that a mapping error caused misplacement of the data.

The ESSA 7 satellite was equipped with a flat-plate radiometer capable of providing outgoing long-wave radiation and albedo measurements. The flat-plate radiometer is a low-resolution instrument and differs from the scanning radiometer of the Nimbus and TIROS satellites in that it provides a measure of the flux of energy (i.e., total power) rather than intensity (flux/solid angle). Thus, when looking at a fully illuminated earth, the flat-plate radiometer provides a measure of reflected energy that does not have to be corrected for the anisotropic behavior of the earth-atmosphere system.

MacDonald (1970) reported on the reduction procedures of these data. Because of inadequate calibration, it was found necessary to assume global net radiation balance to obtain the parameters necessary to compute the albedo. Albedo determinations for less than global areas (e.g., zonal averages) are thus dependent on the above constraint. The procedure is analogous to the one Bandeen (1965) used.

A summary of the albedo and outgoing radiation as calculated by MacDonald (1972) for November 1968-April 1969 is presented in figure 6. Also included for comparison are values obtained by Vonder Haar and Suomi (1971) for winter (December, January, February) and spring (March, April, May). These values were placed at the midmonth of their respective seasons.

Once again, because of the different time periods involved in the studies, one cannot compare them too closely. However, on a hemispherical and global basis, they appear to be in general agreement, the ESSA 7 data implying slightly more outgoing long-wave radiation.[3]

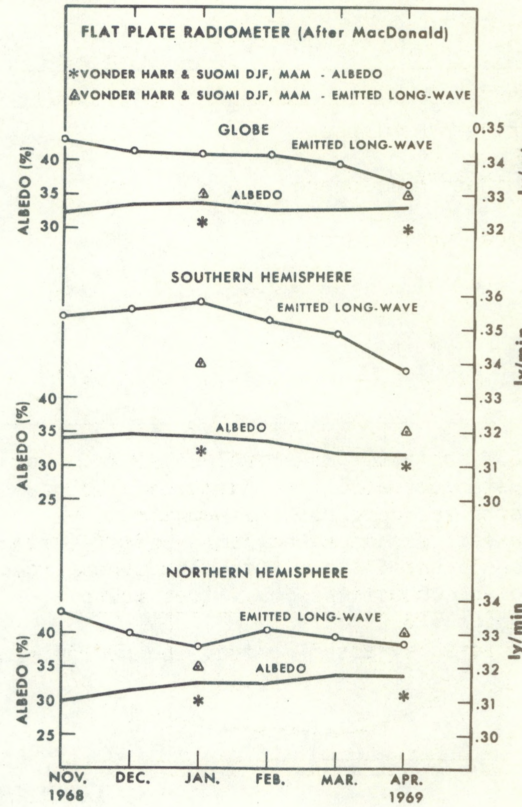

Figure 6.--*Mean monthly global and hemispherical albedo and outgoing long-wave radiation obtained by MacDonald from ESSA 7 data. Seasonal values from Vonder Haar and Suomi (1971) are also plotted for comparison; these values are placed at midseason points.*

ANNUAL HEAT BUDGET COMPONENTS ON A GLOBAL SCALE

The albedo and outgoing infrared radiation results have been examined and comparisons made on periods ranging from weeks to years and space scales ranging from latitude zones to global. This section deals with the components of the radiation budget (incoming solar, outgoing infrared radiation, and albedo) on an annual time scale and global space scale.

Although much of these data are contained either explicitly or implicitly in the preceding tables and figures, it is desirable to collect the data in one place so that an overall comparison can be made. Table 3 presents such a collection. Footnotes to the table supply information on the data.

It is interesting to note that the emitted infrared radiation shows a relatively small variation. The range of values (0.015) represents 4.3% of the average of the four measurements. The albedo, however, has a range (0.030) that is 10.3% of the average. It is not possible to determine how much of this variability is due to instrumentation differences, data reduction procedures, inadequate sampling, or real atmospheric variability.

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[3] MacDonald's albedo determinations are based on a solar constant of 2.0 ly/min. When adjusted for a solar constant of 1.95 ly/min, the value used by Vonder Haar and Suomi, the albedo becomes still higher than Vonder Haar and Suomi's while the outgoing infrared become closer to their value, under the assumption of radiative equilibrium. For example, for the period December 1968 and January-February 1969, the adjusted global albedo is 34.4% versus 33.5% for the unadjusted and the adjusted global emitted infrared radiation is 0.330 ly/min versus 0.342 ly/min for the unadjusted values. Vonder Haar and Suomi's corresponding values are 31% for albedo and 0.33 ly/min for emitted infrared radiation.

Table 3.--*Comparison of annual global radiation balance components*

Investigator	Incoming solar (cal cm^{-2} min^{-1})	Albedo	Absorbed (cal cm^{-2} min^{-1})	Emitted IR (cal cm^{-2} min^{-1})	Radiation balance (cal cm^{-2} min^{-1})
Bandeen* (1969)	0.488	0.304†	0.339	0.339	0‡
Vonder Haar and Suomi § (1971)	.488	.30	.340	.340	0
Raschke et al. ∫ (1973)	.488	.284	.349	.345	+0.004
Winston et al. X (1972)	.488	.274 ϴ	.354	.354	0‡

* TIROS 7 data for June 1963-May 1964. Data extend from 63.5°N to 63.5°S.
† Adjusted for a solar constant of 1.95 cal cm^{-2} min^{-1}
‡ Constrained to zero by assumption
§ Five-year data sample from a variety of satellites
∫ Nimbus 3 satellite. Although authors present annual values, they are based on 5 mo spread throughout the year. See table 1.
X Based on SIRS A data
ϴ Calculated by assuming that the radiation balance is zero

CONCLUDING REMARKS

This brief review has been concerned primarily with the examination of the zonal, hemispherical, and global values of albedo and outgoing long-wave radiation as derived from satellites. This does not imply that the spatial and short-term temporal variations are considered to be unimportant -- quite the contrary. A variety of studies on the spatial and temporal variations of albedo point out that there is much to be learned about the behavior of the atmosphere (Winston 1967, 1969, 1971; Winston and Rao 1962, 1963). Restriction to the large-scale averages appeared to be the most promising way of performing a comparative summary of the data.

It also becomes obvious from this summary that one of our most pressing problems is the determination of representative albedos for the earth-atmosphere system. This requires knowledge about the anisotropic behavior of clouds of various types as well as different surface features. It also requires a knowledge of the variation of the cloudiness as a function of time since clouds are the main contributor to the albedo. All of the studies cited so far assume that the instantaneous observations of cloudiness are representative of the entire day. While this may be a satisfactory assumption over areas where the diurnal variation is small, it can lead to serious errors in regions where the diurnal variation is large (e.g., Equatorial South America).

The variations of cloudiness also have a significant effect on the outgoing long-wave radiation. Thus, measurements of long-wave radiation only twice a day may also be deficient in providing a representative view of the outgoing long-wave radiation. Both of these areas require considerably more research.

It is also clear that we must be able to measure physical quantities reliably. This requires the ability to calibrate the sensing devices aboard the spacecraft, a capability we did not have for the scanning radiometers aboard the TIROS and Nimbus spacecrafts when measuring reflected energy.

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