The Annual Radiation Balance of the Earth-Atmosphere System During 1969–70 from Nimbus 3 Measurements

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ABSTRACT

Measurements of reflected solar radiation and emitted thermal radiation taken with a radiometer on the meteorological satellite Nimbus 3 during 10 semi-monthly periods (April–15 August, 15–17 October, 1969; 21 January–3 February, 1970) provided for the first time high-resolution data on the earth's annual global radiation budget. Results on the planetary albedo, the amount of absorbed solar radiation, the infrared radiation loss to space, and the radiation balance of the earth-atmosphere system are discussed at various scales: global, hemispherical, and zonal averages; as well as global and polar maps with a spatial resolution of about synoptic scale (10°–10° km).

The incoming solar radiation (taking the most recent value of the solar constant $S_0 = 1.95 \text{ cal cm}^{-2} \text{ min}^{-1}$) is balanced within the accuracy of the measurements and evaluation procedure by a global albedo of 28.4% and an infrared heat loss to space of 0.345 cal cm$^{-2}$ min$^{-1}$, which corresponds to a mean planetary effective radiation temperature of 255K. These results confirm those found from earlier satellite data, which showed that our planet is darker and radiatively warmer than previously assumed from estimates with climatic data. From zonal averages of the radiation balance the required poleward transport of energy was found to be larger over the Northern than over the Southern Hemisphere during the 1969–70 observational period.

1. Introduction

The radiation balance $Q_N$ is the net radiant flux density at a fictitious horizontal element of area outside the atmosphere that is crossed by fluxes in incoming solar radiation and outgoing reflected solar and emitted thermal radiation. It is defined as

$$Q_N = W_S - W_R - W_E$$

where at that area element $W_S$ is the irradiance of solar electromagnetic radiation, and $W_R$ and $W_E$ are radiant flux densities reflected and emitted from the earth to space. The planetary albedo is determined by the ratio $W_R/W_S$.

Solar electromagnetic radiation reaching the earth's atmosphere is the principal energy source for the atmospheric-surface system since the solar particle flux, electromagnetic radiation from other stars, and the heat flux from the earth's interior are some orders of magnitude weaker. Part of the solar electromagnetic radiation is reflected and scattered back to space, primarily from clouds and other lower atmospheric constituents, while the rest is absorbed and heats the atmosphere, land surfaces, and the oceans. Also, clouds, aerosols and gases in the lower atmosphere, and to some lesser extent at the earth's surface, emit infrared radiation to space. Therefore, these discussions of the radiation balance of the earth-atmosphere system refer to the exchange of radiative energy between space and the earth-atmosphere system, viz. the earth's surface and the lower atmosphere up to about 50 km altitude.

The earth's radiation balance has been the subject of detailed scientific studies for many years, since its geographical distribution (heat gain at the equator and heat loss over both poles) is the key mechanism that forces our atmospheric circulation; it also is of fundamental importance to climate and weather. Detailed knowledge of it permits investigations of the poleward energy transport required to maintain the observed state of the earth-atmosphere system; estimates of the radiation budget at the surface and, thus, of the atmosphere and ground (oceans) separately; verifications of the energy budget of modern numerical circulation models at their upper boundary; and determinations of local and global climatic trends. Some preliminary re-
sults of such applications have already been reported in the literature (e.g., Fritz et al., 1964; Hanson et al., 1967; Holloway and Manabe, 1971).

The acquisition of such detailed knowledge will require, over periods of several years, precise and properly sampled measurements that are not available so far. The measurements of the meteorological satellite Nimbus 3, however, provide for the first time estimates of the annual radiation budget with a high spatial resolution over the entire globe. They were done in 10 semi-monthly periods during all seasons during the period from 16 April 1969 through 3 February 1970 with a stable and calibrated radiometer.

The evaluation methods and their possible error sources were described in a previous paper by the same authors (Raschke et al., 1973). Some preliminary results from Nimbus 3 were presented by Raschke et al. (1971), Raschke and Vonder Haar (1971), Vonder Haar and Raschke (1972), and Vonder Haar et al. (1972) in earlier papers. The present paper provides the most extensive

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**Fig. 1.** Change of the directional reflectance \( r(\gamma) \) with the sun’s zenith angle \( \gamma \).

**Fig. 2.** Time-latitude diagram of the albedo of the earth-atmosphere system. Dashed portions of isopleths were found by interpolation.
### Table 1. Global and hemispherical radiation budget (cal cm⁻² min⁻¹) of the earth-atmosphere system (N = north, S = south, G = globe).

<table>
<thead>
<tr>
<th>Period</th>
<th>Solar radiation</th>
<th>Albedo</th>
<th>Outgoing longwave radiation</th>
<th>Radiation balance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Incoming</td>
<td>Absorbed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–15 May 1969</td>
<td>.618 .334 .476</td>
<td>.431 .244 .337</td>
<td>.302 .269 .291</td>
<td>.351 .343 .347</td>
</tr>
<tr>
<td>1–15 June 1969</td>
<td>.656 .290 .473</td>
<td>.454 .213 .333</td>
<td>.308 .267 .296</td>
<td>.359 .343 .351</td>
</tr>
<tr>
<td>1970</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual*</td>
<td>.483 .492 .488</td>
<td>.344 .354 .349</td>
<td>.287 .280 .284</td>
<td>.346 .344 .345</td>
</tr>
</tbody>
</table>

* Estimated.

The discussion of annual results obtained so far from the Nimbus 3 measurements.

### 2. Previous studies of the radiation budget

Many authors based their studies of the radiation budget on climatological data and relatively simple radiative transfer models (Dines, 1917; Simpson, 1929; Baur and Phillips, 1934, 1937; Houghton, 1954, London, 1957; Gabites, 1959; Budyko, 1963; Gavriloa, 1963; Vinnikov, 1965; Fletcher, 1963; Katayama, 1967; London, and Sasamori, 1971; Kondratiev and Dyachenko, 1971) or of the albedo alone (Fritz, 1949). Danjon’s observations, since they were done mostly from the territory of France, did not allow a proper sampling over all sunlit portions of the earth as visible from the moon during a period of several years. It was recognized many years ago that direct observations from satellites, if properly sampled (Godson, 1958; House, 1962) could overcome this problem (e.g., Suomi, 1958).

Weinsteint and Suomi (1961) discussed the first measurements obtained with omnidirectional sensors
from Explorer 7 in 1959. Other measurements with the afore-mentioned techniques and with flat-plate sensors were described in the following years by several authors (House, 1965; Vonder Haar, 1968; Vonder Haar and Suomi, 1971; McDonald, 1970). They provided only very low spatial resolution due to their observing geometry. Results on the annual and seasonal radiation budget have been obtained with proper assembling of this large variety of data by Vonder Haar (1968) and Vonder Haar and Suomi (1969, 1971). They showed that the earth has a warmer effective radiation temperature and is darker than previously assumed from theoretical studies and earthshine measurements. This was especially true in the tropics. Holloway and Manabe (1971) compared the radiation budget of their simulation model at its upper boundary with these earlier results and found good agreement considering the radiation parameterization employed within the model.

Other satellite measurements of the radiances in narrow fields of view allowed a much higher spatial resolution of the earth's radiation field (~200 km x 200 km). Results were discussed in various papers by Bandeen et al. (1965), Rasool and Prabhakara (1966), Winston and Taylor (1967), Boldyrev and Vetlov (1970), Raschke and Pasternak (1968), Raschke et al. (1968) and Raschke and Bandeen (1970). These latter two and other subsequent papers reported detailed studies of the radiation budget obtained with a calibrated scanning radiometer over a period of 2½ months in the middle of 1966. This instrument was onboard the satellite Nimbus 2. Global averages of the albedo and the outgoing longwave radiation derived from those measurements were similar to those reported by Vonder Haar (1968) from the other satellite measurements with hemispherical radiometers (e.g., the lower albedo in the tropics) and balanced within the probable accuracy of evaluation of the incoming solar radiation. Similar measurements are now available during all seasons of one annual cycle from Nimbus 3. Their nature and evaluation are discussed in the two following sections of this paper.

The available satellite observations at present do not allow observation of climatic trends that might have occurred over various parts of the globe during the last decade, since they were done with various instrumental designs and primarily from only one satellite during a specific time period.

3. Nimbus 3 measurements

The satellite Nimbus 3 was launched on 14 April 1969, into a sun-synchronous circular polar orbit where it passed the equator northbound at about 1130 and southbound at 2330 local time at a mean orbital height of 1100 km.

These orbital parameters enabled the cross-track scanning, five-channel radiometer (McCulloch, 1969) to measure reflected solar radiation once and emitted thermal radiation at least twice a day over most areas of the earth. They did not, however, allow observations of a primary factor in the total outgoing radiation, viz. the diurnal variations of cloudiness over low-latitude regions. This radiometer provided continuous data during the four-month period between 16 April and 15 August, 1969. Malfunction of one of the tape recorders and the data flow from other experiments onboard Nimbus 3 allowed continuous recordings during only two additional, nearly semi-monthly periods, which were selected specifically to sample an entire annual cycle (3–17 October 1969 and 21 January–3 February, 1970).

One channel of this radiometer was sensitive, but not with an ideal filter curve, in the spectral interval between 0.2 and 4.8 μm, which covers the spectrum of solar radiation reflected and scattered from the earth back to space. The consistency of its measurements had been checked carefully with reflectance measurements over various cloud-free parts over the Libyan desert where no instrumental deterioration could be detected during the entire period of observation.

The accuracy of the other four channels sensitive in separate narrow bands in the infrared (6.3–μm band sensing upper tropospheric water vapor; surface radiation between 10–12 μm; 15-μm band of carbon dioxide; and emission of lower tropospheric water vapor and clouds between 20 and 23 μm) was checked continuously with onboard calibration systems. The experiment data had very high relative accuracy and no observable bias error. Random errors of measurements of about 1% were expected due to digitization errors. Absolute accuracy of the results was affected both by sensor detectivity and techniques of data processing described in the next sections.

Over most areas of the earth, measurements of the upward radiation were made daily from Nimbus 3. Small gaps occurred, in particular during the period 21 January–3 February, 1970, over North America and the adjacent Pacific Ocean (daytime measurements) and over the Atlantic Ocean along the western coastal areas of Europe and Africa.

4. Evaluation method

a. General outlines

Due to the orbital parameters and the narrow field of view of the instrument the primary purpose of the evaluation methods was to compute daily averages of the orbit flux densities of reflected solar and emitted thermal radiation from respective single measurements of the radiance over each area.

Daily averages of the orbit flux densities of reflected solar and emitted thermal radiation from each global area element were then computed from the measured "filtered" radiances by: 1) computation of the total radiance from the "filtered" measurements, 2) correction for dependence on zenith and azimuthal angle, 3) computation of the radiative densities at the
time of observation, and 4) computation of the daily average over each area.

The results were assembled in Mercator maps with a mean spatial resolution of about 500 km × 500 km in near-equatorial regions and in polar-stereographic maps with a spatial resolution of about 250 km × 250 km per grid area.

This evaluation procedure was based on several generalized models which will be described briefly in the next two sections. They were essentially the same as applied previously to Nimbus 2 data (Raschke and Bandeen, 1970), although the newer reflectance models were slightly different. To avoid obstruction by clouds, all those measurements which were obtained at nadir angles >45° were omitted. Further, measurements of reflected solar radiation that were obtained over areas illuminated by a very low sun (solar zenith angle larger than 80°) were also omitted. The radiation balance results were grouped into semimonthly periods to average over variations of the radiation fields due to travelling disturbances.

b. Outgoing shortwave radiation

To compute the total (0.3–4.0 μm) flux density from the measured “filtered” radiance, $N_I$, it is assumed that the bidirectional reflectance $ρ$ computed by use of (2) equals that of the total solar spectrum (Raschke et al., 1973):

$$ρ(λ, θ, ϕ, t; θ_s, ϕ_s) = \frac{N_I(λ, θ, ϕ, t; θ_s, ϕ_s)}{S_{α'} L \cos^3(λ, θ, ϕ)} \text{sr}^{-1}, \quad (2)$$

where $ξ$ is the sun’s zenith angle at the moment of measurement on day $t$ of the year, and $S_{α'}$ is the extraterrestrial “filtered” solar radiation obtained by weighting of Labs and Neckel’s (1968) spectral irradiance data which were adjusted to a value of the solar constant of $S_0 = 1.95$ cal cm$^{-2}$ min$^{-1}$ (Drummond, 1970; Thakkarara, 1970) with the spectral response of the radiometer; $L$ accounts for the deviation of the true earth-sun distance from one astronomical unit; $θ$ and $ϕ$ are the zenith and azimuthal angle of measurement with respect to the principle plane, and the sun’s zenith angle, respectively; while $λ$ and $ϕ$ are geographical longitude and latitude of an observed area.

The directional reflectance $r$, i.e., the ratio between the radiant flux density of reflected radiation and the irradiance of solar radiation, has been determined with corrections for anisotropic reflection properties of the earth-atmosphere system. Since, over most areas, the cross-track scan of the instrument and the satellite...
orbit did not allow measurements of ρ over each area at various angles θ and ϕ, only gross-empirical models could be used to relate ρ to r. These models were derived from published airplane, balloon and satellite measurements of reflected solar radiation. Nine models were developed for three different ranges of the sun’s zenith angle (0–35°, 35–60°, 60–80°) and three types of observed surfaces representing high-latitude ice and snow fields (latitude > 65° and τρ > 50%), cloud-free ocean areas (τρ < 10%) and effective blackbody temperature T_b > 273K for concurrent measurements in the 10–12 μm channel), and all other land and cloudy areas. The values in parentheses specify the conditions used to objectively assign each single satellite measurement to a specific model category.

The integration over the entire daylight period made use of three other models which account for the change of the directional reflectance r with the sun’s zenith angle θp, for different surface types. They were also obtained from observational material (see Raschke et al., 1973). These relations are shown in Fig. 1, where for comparison the one used for the evaluation of Nimbus 2 data (Raschke and Bandeen, 1970) is also drawn. All show an increase of r(θp) with increasing θp, which is largest over cloud-free oceans (low albedo of the surface) and smallest over snow and ice fields. This latter curve has been obtained from ground observations published by Kondratiev (1969). Recent ground observations over snow at 3000 m altitude reported by Korff and Vonder Haar (1972) show a similar small increase of the directional reflectance of snow with increasing θp. The relative increase of r from 1 to 4 for the OCEAN model is of a similar magnitude to that obtained by theoretical calculations of the radiation transfer in an atmosphere-ocean system within the wavelength interval between 0.325–0.95 μm (Raschke, 1972).

Comparisons of albedo values computed with the CLOUD-LAND model, (used in all non-snow and non-ocean cases) and the Nimbus 2 model resulted in values by the latter which were higher by a factor of about 1.1 than the former. Thus, it should be expected that the global albedo obtained from Nimbus 3 data by use of these three models would be somewhat smaller than the Nimbus 2 value. The simple assumption of a diffusely reflecting earth-atmosphere system, used by Bandeen et al. (1965) and Rasool and Prabhakara (1966), caused the albedo to be too low at almost all latitudes. Since reflectance models must be used to evaluate radiance measurements from satellites for...
radiation budget studies, the uncertainty they introduce into resulting albedo values must be considered. Based on information available today, the models used in our Nimbus 3 work are thought not to enlarge the overall experimental uncertainty of ±5%.

c. Outgoing longwave radiation

The total radiance (4.0–200.0 μm) has been computed from concurrent radiance measurements of all four infrared channels using a multiple least-square regression formula that was derived from calculations of the radiation transfer in 160 atmospheric models representing eight climatological regimes (moist and dry atmospheres and different cloud situations). These computations were made with a program developed by Kunde (1965) and checked with one written by Wark et al. (1964).

Corrections for the dependence on the zenith angle

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Fig. 5. Time-latitude diagram of the radiation balance of the earth-atmosphere system. Dashed portions of isopleths were found by interpolation.

Fig. 6. Annual zonal averages of the outgoing longwave radiation and albedo of the earth-atmosphere system from Nimbus 3 data and other satellite measurements (Vonder Haar and Suomi, 1971) and from climatological analyses by London (1957).

Fig. 7. Required meridional energy transport.
of measurements, $\theta$, and the computation of the outgoing radiative emittance, $W_{\theta}$, were performed with a "limb-darkening" function derived statistically from samples of Nimbus 2 radiance observations in the spectral interval from 5–30 $\mu$m obtained over various areas of the earth. A more accurate approach would have been possible if a differentiation between measurements over cloud-free and cloud-covered areas could have been made.

The daily infrared averages were computed with the assumption that the values of the radiant flux density obtained from daytime (nighttime) measurements were representative for the whole daylight (nighttime) period over a grid area. These values were weighted according to the fraction of day and nighttime period of a day to account for any diurnal variation (as expressed by differences between the day and night values of the outgoing longwave radiation, measured near local noon and midnight) is remarkably large ($> +0.03$ cal cm$^{-2}$ min$^{-1}$) over most continental areas at middle and lower latitudes, but very small ($\sim 0.015$ cal cm$^{-2}$ min$^{-1}$) over most ocean areas (e.g., Raschke and Bandeen, 1970).

In the discussion of this evaluation procedure it must be kept in mind that the orbital characteristics of Nimbus 3 did not allow complete observations of diurnal variations of radiation due to both cloudiness and surface temperature changes. Such observations will be possible over limited regions with measurements from future geosynchronous meteorological satellites. However, a complete global coverage will require a system of several satellites in properly chosen orbits around the earth.

5. Results

a. Global and hemispheric budget

Values of global and hemispheric averages of the incoming and absorbed solar radiation, the albedo, the outgoing longwave radiation, and the radiation balance obtained from the measurements of all 10 semi-monthly periods are summarized in Table 1. The estimated annual averages for the entire earth and two hemispheres are listed at the bottom of this table. They were computed by interpolation from graphs of all semi-monthly averages, where the values of the incoming solar radiation were directly computed for missing periods. All numbers in Table 1 are written with an equivalent accuracy of 1–2%, although an overall experiment accuracy of about $\pm 5\%$ (Raschke et al., 1973) should be expected from the type of evaluation. They allow, even considered with less accuracy, studies of some interesting features of the seasonal variations of the earth's radiation budget, provided that those observable variations were not caused by variations in the instrumental detectivity, which could not be checked otherwise. Annual cycles have an amplitude not much larger than the assumed accuracy of 5%, but similar trends have been found from Nimbus 2 measurements (Raschke and Bandeen, 1970) and from the earlier satellite data (Vonder Haar, 1968, 1972).

In the annual average the absorbed solar radiation of 0.349 cal cm$^{-2}$ min$^{-1}$ (which is 71.6% of the incident radiation) is almost completely balanced ($Q_N = 0.004$ cal cm$^{-2}$ min$^{-1}$) by a global thermal radiation of 0.345 cal cm$^{-2}$ min$^{-1}$. The difference should be considered more as an error residual than as an actual heat gain during the period of measurement. With the same
Fig. 9. Annual albedo of the Earth-atmosphere system over the Northern Hemisphere.
Fig. 10. Annual isoto of the earth-atmosphere system over the Southern Hemisphere.
emission and insolation a global planetary albedo of 29.2% would enable complete balance. In their magnitude these values confirm results found previously by Vonder Haar and Suomi (1971) from measurements obtained from several hemispherical and flatplate radiometers on satellites during a period of more than five years. All pre-satellite investigations based on climatological data had estimated a lower global emission corresponding to $T_e \approx 250$K and a higher global albedo of more than 33%.

In their most recent calculations, London and Sasamori (1971) using the climatological data used earlier by London (1957) but with more recent absorption models, obtained a mean albedo of 29% over the Northern Hemisphere, in good agreement with the results from satellites. They obtained, however, a mean albedo of 33% over the Southern Hemisphere, a value markedly higher than either that from Nimbus 3 or that measured from other satellites. Recent calculations by Sasamori et al. (1971) resulted in an even higher albedo of 35% for the Southern Hemisphere.

In an objective discussion of the Nimbus 3 results in Table 1, the incompleteness of the data set and possible biasing errors in the evaluation methods preclude firm conclusions based on small differences between large numbers. However, averages of albedo measurements over both hemispheres show a seasonal variation which could be attributed: 1) to the well-known changes of the surface albedo due to changes in the ice and snow cover, and 2) the seasonal change of the sunlit portion of the earth. Explanation of observable variations of the global albedo are hampered by the large data gaps between those observed periods. However, our observations do not support those of Danjon who found a maximum global albedo in October. The Northern Hemisphere was warmer during its summer than the Southern Hemisphere, which shows almost no seasonal variation in infrared emission.

A seasonal variation can be observed in the radiation balance of the globe with a small deficit in the period May–August and an energy gain in October and January. One might attribute this variation to the ellipticity of the earth’s orbit, which causes a seasonal change of the sun’s input by about 7% ($\sim 0.030$ cal cm$^{-2}$ min$^{-1}$) from June to January. This variation of the balance seems to be even slightly amplified by the seasonal variation of the mean planetary effective radiation temperature.

Since these measurements from Nimbus 3 required many assumptions in their evaluation and may contain sampling errors, the results in Table 1 and their discussion here must retain a preliminary character. More definite and detailed studies of the annual and seasonal variations of the earth’s radiation balance and of possible exchange mechanisms between both hemispheres as might be observed in these data require continuous and precise global satellite observations of incoming and outgoing radiation over a period covering several annual cycles.

b. Zonal radiation budget

Changing from the planetary scale to a zonal scale one can clearly observe the annual variation and
Fig. 12. Solar radiation absorbed in the earth-atmosphere system over the Northern Hemisphere.
Fig. 13. Solar radiation absorbed in the earth-atmosphere system over the Southern Hemisphere.
The latitudinal distribution of the absorbed radiative energy available for circulation processes (Fig. 2), the albedo (Fig. 3), the outgoing longwave radiation (Fig. 4) and the radiation balance (Fig. 5) as demonstrated in time-latitude diagrams. Annual zonal averages of the albedo and the outgoing longwave radiation are compared with results of other investigations in Fig. 6. They were computed only from measurements during four 1970 semi-monthly periods (1–15 May, 16–30 July, 3–17 October 1969, 21 January–3 February). These measurements were assumed to be representative for these entire respective seasons.

In tropical and subtropical latitudes of both hemispheres the albedo and the outgoing longwave radiation change their magnitude due to the annual movement of the ITCZ and the Asian monsoon cloudiness. Over the northern mid-latitudes the albedo decreases rapidly from winter to summer due to melting of snow over large areas, and the continents warm up considerably. However, over the Southern Hemisphere only small variations can be observed at some latitudes, where oceans almost exclusively cover the earth’s surface. The scarcity of observations during the period October–March does not allow more detailed studies of variations of the extent of antarctic icefields and of associated albedo variations.

The albedo of the northern and the southern polar regions does not exceed values of 72%, while from Nimbus 2 measurements during the period 15 May–28 July, 1966, consistently higher values had been found in the north (Raschke and Bandeen, 1970). This difference is due to the use of different evaluation models to account for the change of the directional reflectance with the sun’s zenith angle (see Fig. 1). Albedo values calculated from measurements over Greenland and adjacent areas using the Nimbus 2 relation are about 1.12 times higher than those calculated with the model SNOW applied in the present study to all Nimbus 3 measurements.

For comparison of these results with surface measurements of albedo, it should be kept in mind that these results show the albedo of the earth-atmosphere system averaged over the entire spectral interval between 0.2 and 4.0 μm. Usually the albedo values obtained from ground observations are somewhat higher than those of the earth-atmosphere system, since at the ground for the most part, only radiation of the spectral range between 0.3 and about 1.5 μm will be observed, and where most surfaces will have a higher albedo than the atmosphere for the radiation of longer wavelengths which is strongly absorbed by atmospheric gases. Therefore, Nimbus 3 albedo values of only 50–70% over snow-covered regions at both poles do not contradict those of the snow and ice surface itself, which were measured to be about 75–80% (Kasten, 1963; Hoinkes, 1958; Kuhn, 1971).

The variations of the albedo over the central part of the Arctic can be attributed to the melting of the snow and formations of fractures in the ice and water cover on the ice. Such structural variations do not occur over Antarctica and Greenland highlands. Thus, the changes of the albedo over the Antarctic observable from Octo-

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2 M. Kuhn, private communication.
Fig. 15: Longwave radiation emitted annually to space from the Northern Hemisphere.
Fig. 6. Longwave radiation emitted annually to space from the Southern Hemisphere.
ber to January might be caused to some extent by improper corrections of the dependence of the Antarctic albedo on the angle of insolation.

The seasonal change of the radiation balance (Fig. 5) is dominated by seasonal variations of the insolation and demonstrated with the curve showing the sun's declination. Areas of major gain of radiative energy in each corresponding season are the subtropical belts, while a major deficit is found poleward of about 60° latitude. Over the Southern Hemisphere a reversal of the gradient of the radiation balance is caused by very low emission from the cold and high plateaus of the Antarctic continent during winter 1970.

The comparison of annual zonal averages of the albedo and the outgoing longwave radiation obtained from Nimbus 3 data with those from other satellite observations (Vonder Haar and Suomi, 1971) and from calculations with climatological data (Fig. 5.5) shows clearly that in the early calculations (London, 1957) the cloudiness and/or its effects on the transfer of shortwave and longwave radiation has been overestimated, particularly in lower latitudes. There the earth-atmosphere system absorbs approximately 40% more radiation than previously assumed. The Nimbus 3 data resulted in a much higher radiation deficit over the arctic than over the antarctic primarily due to higher mean annual effective radiative temperature over the former area.

The required latitudinal transport of energy (Fig. 7) has been calculated from the measurements by distributing the global net gain of 0.004 cal cm\(^{-2}\) min\(^{-1}\) (Table 1) equally by area over the entire globe to obtain balance. This implies the assumption that no energy had been stored in the system during the measurement period 1969–70. Results show a northward cross-equatorial transport of about 1.1 \(10^{16}\) cal year\(^{-1}\) and a much higher required transport at 30–40° latitude than at the same southern latitudinal belt. Results derived from earlier satellite measurements and from computations show energy transport requirements which are nearly symmetrical to the equator with almost no transport through the equator. These latter results were obtained from averages of measurements and other observations over many years and may much better represent, therefore, the mean behavior of the energy transport in the earth-atmosphere system, whereas the Nimbus 3 data pertain only to four 15-day periods of one specific year. In addition, the cross-equatorial transports inferred from all satellite data are very close to the error level resulting from 5% measurement accuracy. Therefore, it cannot be concluded, yet, from these measurements whether a northward atmospheric transport of 0.4 \(10^{16}\) cal year\(^{-1}\), as found recently by Oort (1971), is required to be accompanied by a simultaneous transport in the oceans in the same direction.

On the other hand, several authors (e.g., Flohn, 1967) explained the asymmetrical circulation patterns over both hemispheres on the basis of different radiation budgets. Although Vonder Haar and Suomi (1971) did not observe different hemispheric radiation budgets in the mean, satellite observations over several years will enable observations of interannual variations of the
Fig. 18. Annual radiation balance of the earth-atmosphere system over the Northern Hemisphere.
Fig. 19. Annual radiation balance of the earth-atmosphere system over the Southern Hemisphere.
transport requirements implied by the comparisons of Fig. 7.

**c. Geographical distributions**

For the calculation of global distributions of all annual averages of radiation budget parameters, again only results of absorbed solar radiation and the outgoing longwave radiation derived from measurements of only four 1970 semi-monthly periods (1–15 May, 16–30 July, 3–17 October 1969, 21 January–3 February) were used. These measurements were assumed to be representative for their entire respective seasons. The sun’s irradiance at the top of the atmosphere was obtained independently from geometrical considerations.

Results are shown here in global Aitoff projections with a spatial resolution of about 500 km × 500 km for each grid point in low-latitude regions and for a better resolution of the patterns over polar regions (250 km × 250 km) in true polar-stereographic projections covering each pole (Figs. 8–19).

The patterns in the albedo map (Fig. 8) clearly reveal the land-sea distribution and the general circulation as it is represented by the mean cloud patterns over both hemispheres. The small continents alone would cause a more zonal pattern over the Southern than over the Northern Hemisphere. The high reaching convective clouds associated with the ITCZ and partly with the Asian monsoon appear as a belt of relatively high albedos of more than 25–30%, and low emission of less than 0.33 cal cm⁻² min⁻¹ (Fig. 14). Low persistent stratus clouds along the western coastal areas of North and South America and Africa do not appear in the map of outgoing longwave radiation, but appear with albedo between 25 and 35% (see Vonder Haar, 1970). The albedo of both polar regions (Figs. 9 and 10) is considerably higher than 50%. The patterns are closely associated with permanent and dense ice fields. Regions of major absorption of solar radiative energy (Figs. 11 and 12) are the oceanic areas in the subtropics of both hemispheres. They are also the areas of the major gain of radiative energy (Figs. 17 and 19) of more than 0.06 cal cm⁻² min⁻¹, while the African and Arabian deserts at the same latitude have a radiative deficit of more than 0.03 cal cm⁻² min⁻¹. Especially in contrast to regions to the east and west, such deficit areas in the tropics stimulate thoughts of large-scale east-west circulations. The Saharan deficit might be energetically balanced by subsidence warming associated with a direct circulation having an ascending branch over the summer monsoon area. Both polar regions, poleward of about 45° latitude, are in the annual average deficit areas with a surprisingly smaller deficit (due to low emission; see Figs. 14 and 16) over the South Pole.

Additional Nimbus 3 radiation budget results (for the four seasonal periods) are presented in map form by Raschke et al. (1973).

**d. Temporal variability of the radiation balance**

The temporal variability of the albedo over each grid field can be demonstrated in a map of the relative dispersion, as shown in Fig. 20, which is the ratio of standard deviation to the mean value. This map was computed from the daily averages of the albedo in each grid field obtained from measurements during the same
four semi-monthly periods. The values include all temporal scales of variations between the annual cycle and day-to-day changes of temperature, cloud cover and height, and surface albedo. The partition of each of these components can be considered on an annual basis only with a more complete data set (Vonder Haar, 1972), while the variability on a monthly basis has been considered elsewhere (Raschke and Bandeen, 1970).

Patterns in this map reveal some of the changes due to traveling disturbances. Over the oceans very large relative dispersion of the albedo is due to the contrast in the albedo between clouds and the open sea.

In the map high values of the relative dispersion can be attributed to the varying cloud cover at the equator and to areas of preferred dynamical and convective activity over both hemispheres. Relatively low dispersions are found over the subtropics and over both polar regions. Also, those areas known to be covered with persistent but low stratus decks appear in these maps with small values of the relative dispersion. Such features have been discussed already in a preliminary study (Raschke and Vonder Haar, 1971).

e. Deviations from zonal means

Longitudinal variations of the radiation fields are heavily overshadowed by the equator-to-pole gradients in all maps of the annual radiation budget, especially of those quantities containing as one component the incoming solar radiation. The removal of this gradient, simply done by subtraction of the zonal average from each grid value, then clearly reveals the departures from a zonal structure, which are due to surface properties and cloud fields and may cause an additional (and comparatively weaker) longitudinal forcing of our atmosphere's circulation.

In the map of the outgoing longwave radiation (Fig. 21), the negative areas are those with comparatively large and high cloudiness. These are the major cyclonic tracks over the Southern Hemisphere, the monsoon cloudiness over the Indian Ocean and over Southeast Asia, and convective cloudiness over most tropical continental areas and the Malayan Archipelago. Apparently, Northern Hemisphere storms have a less persistent zonal component. The high-reaching ice fields of Greenland and the Antarctic continent are also considerably cooler than their surrounding areas.

Almost all continental areas and also the aforementioned fields of permanent cloudiness were found to have lesser surplus or higher deficit of radiative energy than adjacent ocean areas (Fig. 22) which is primarily due to their higher surface albedo. The highest relative deficits of more than 0.09 cal cm\(^{-2}\) min\(^{-1}\) were found over South America and the North African and Arabian deserts.

f. Minimum albedo

Estimates of the albedo of the ground and also locations of persistent cloud fields and of ice and snow cover can be made when traveling or otherwise changing cloud fields are removed by displaying only the lowest albedo value in each grid field. This approach is based on the simple assumption that the albedo of the earth-

**Fig. 21.** Deviation of the outgoing longwave radiation from zonal average.
atmosphere system is higher over each area in the presence of clouds than for a cloud-free atmosphere. Further, the instrumental noise should have been removed considerably by averaging of a sufficiently large number of single observations within each grid field. Made on an annual basis, as shown in Fig. 23, these maps will allow estimates of the effective surface albedo of continental areas, after the atmospheric interference has been removed properly. Note also the aforementioned areas of persistent cloud cover and that other regions over equatorial areas with apparently no cloud-free days can be located. Most ocean areas between 50N and 50S were found with minimum albedos <10%, but not smaller than 4%. At higher latitudes
the cyclonic activity prevents observations of completely cloud-free areas in this scale. Minimum albedos >40% belong to ice fields at their observed smallest extent during July over the arctic and during January over the antarctic, respectively.

6. Summary and conclusions

This paper has discussed results of measurements of the 1969-70 annual radiation budget of the earth-atmosphere system and its components. The data were obtained from a temporally incomplete but relatively accurate set of radiation measurements from the meteorological satellite Nimbus 3 during 1969-70. They are presented on global, hemispherical, zonal and high resolution scales.

Despite the errors introduced primarily by the evaluation method and assumptions, and by the incompleteness of the data set, these results provide a basis for checks of the local and global annual energy budget of numerical circulation models. The magnitudes of the global annual albedo of 28.4% and of the outgoing longwave radiation, which corresponds to an effective radiation temperature of about 255K, confirms previous results from satellite data of a darker and radiatively warmer planet Earth than was believed earlier on the basis of calculations using climatological data. These values nearly balance on a global scale the incident solar radiation computed for a solar constant of 1.93 cm² min⁻¹. The required poleward energy transport obtained was found smaller over the Southern than over the Northern Hemisphere during 1969-70 in contradiction to the earlier investigations summarized by London and Sasamori (1971). These results, however, cannot be considered to be representative for a typical annual cycle, basically due to lack of measurements during several months of this particular period. It is therefore concluded that further satellite experiments of similar or even better accuracy than the Nimbus 3 experiment are required to obtain measurements with a high relative accuracy over a period of more than 10-15 years, thus permitting radiation balance studies lasting over this entire period. These measurements should include observations of the important components of incident solar radiation since the sun's output of radiative energy may undergo variations of several percent as discussed by Kondratiev and Nikolsky (1970), although there is some doubt that the sun is at present such a variable star.

Once such observations are available, base lines can be established to permit subsequent observations of climatic trends that may result from natural causes on earth, human activities, and/or changes in the spectral energy radiated by the sun.

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