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Measurements of the Earth's Radiation Budget from Satellites During a Five-Year Period. Part I: Extended Time and Space Means

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ABSTRACT

This paper summarizes an extended time series of measurements of the earth's radiation budget from the first and second generation United States meteorological satellites. Values of planetary albedo, infrared radiant emittance, and the resulting net radiation budget are now available for 39 months during the period 1962–66. These measurements show a mean global albedo of 30%, and net radiation balance within measurement accuracy. The discussion treats global and zonally averaged values for the "mean annual" case, for "mean seasons," and includes a comparison of measurements during the same seasons in different years. The role of these radiation budget measurements in the total global energy balance is noted.

1. Introduction

Earth-orbiting satellites provide an ideal platform for measuring the energy exchange between earth and space. Until this platform became available about ten years ago, our knowledge of this energy exchange was based exclusively on theoretical and empirical calculations. The need for the information is fundamental, since the equator-to-pole gradient of energy transfer across the "top of the atmosphere" is the prime forcing function that drives our atmospheric and oceanic circulations. Measurements from satellites now allow us to study and understand our radiation budget. Regarding the future of our atmosphere, such measurements will allow us to consider the effects of natural or inadvertent changes within our atmosphere on the global radiation budget, and thus on global weather and climate.

TABLE 1. Available radiation budget measurements.

			Year			
Season*	1962	1963	1964	1965	1966	
MAM	X		X	X		→ $\overline{\text{MAM}}$
JJA		X	X	X	X	→ $\overline{\text{JJA}}$
SON		X	X	X		→ $\overline{\text{SON}}$
DJF		X	X		X	→ $\overline{\text{DJF}}$
						↓ Annual

* Months of the seasons are identified by initial letters.
Note: The DJF measurements are plotted under the year for the respective December. Arrows indicate the method of averaging to form mean seasonal and annual values.

a. Available satellite data

This paper presents a synopsis of measurements from the first generation (TIROS-type) satellites, together with the most recent radiation budget measurements from our second generation (Nimbus and ESSA) spacecraft. Only experiments that have measured both components (the infrared and reflected solar) of the radiation budget are included (see Table 1). The first of these were obtained from TIROS IV in 1962 (House, 1965). The most recent data available[2] are preliminary results from ESSA III in late 1966 and early 1967. Within this period, Vonder Haar (1968) presented measurements obtained during 33 months during 1962–65. [Part of his data were collected by Bandeen *et al.* (1965).] Raschke and Bandeen (1970) provide a detailed discussion of 2½ months of measurements from Nimbus II during 1966.

All of these data are considered in the present study. However, nearly 80% of all observations thus far have been acquired by the lower resolution, Wisconsin-type sensors (Suomi *et al.*, 1967); the remainder has been obtained from medium resolution scanning radiometers. A summary of results obtained through 1965 is discussed by Vonder Haar and Suomi (1969).

b. Description of the experiments

House and Suomi *et al.* describe the Wisconsin sensors in detail. A set consists of matched pairs of black and white sensors using thermistor detectors to measure sensor temperature. From these measurements, and others giving the sensors' mount temperatures, the gains of energy due to radiation from earth or sun are derived from balance equations which consider all

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[2] MacDonald, T. H., 1969: Private communication.

TABLE 2. Mean annual radiation budgets of the entire earth-atmosphere system, the Northern Hemisphere and the Southern Hemisphere, as measured from first generation meteorological satellites together with first results from the second generation spacecraft. (The latter were weighted into the average as shown in Table 1.) A solar constant of 1.95 cal cm^{-2} min^{-1} was used in the evaluation.

	Planetary albedo (%)			Infrared loss (cal cm^{-2} min^{-1})			Net radiation (cal cm^{-2} min^{-1})		
	Northern Hemisphere	Southern Hemisphere	Global	Northern Hemisphere	Southern Hemisphere	Global	Northern Hemisphere	Southern Hemisphere	Global
First generation satellites*	29	29	29	0.33	0.33	0.33	+0.01	+0.01	+0.01
Second generation satellites**	30	30	30	0.33	0.34	0.34	0.00	0.00	0.00

* March, April, May 1962 and June 1963–November 1965 (33 months).
** First generation satellites plus Nimbus II and ESSA III (39 months, 1962–66).

possible power gains or losses by the sensors. Viewing from horizon to horizon at satellite altitude, the sensors are self-integrating with greater weight being given to energy arising from the nadir. Aside from their simplicity and ruggedness, the most worthy feature of the Wisconsin sensors is their ability to self-calibrate against direct solar radiation twice each orbit as the satellite passes from day to night. This allows a check of prelaunch calibration and continuous compensation for any drift or degradation of the sensors during their experimental lifetime. Another feature allows direct measurement of planetary albedo along the orbit as a ratio of the energy reflected from the earth-atmosphere system to that measured by the sensor when exposed to direct solar rays. However, the sensors flown thus far could not be used to measure the absolute value of the solar constant to the required accuracy and thus, to derive net radiation values, a solar constant must be specified (Drummond, 1970).

The scanning radiometers flown on TIROS and Nimbus have been described fully in several manuals.[3] Ground resolution at nadir is less than 50 mi. Detectors are chopped thermistor bolometers fronted with appropriate filters to limit the spectral bandpass. Reflected solar and infrared radiance is measured. Choice of a solar constant affects derived values of planetary albedo and the resulting net radiation. Further information about the use of these data to study the earth's radiation budget is given by Bandeen *et al.* (1965) and Vonder Haar (1968).

The latter reference also includes a summary of time and space sampling of the satellite data used in the present study. Even though the sensors used for measurements had both low and medium ground resolution, the basic space scale is the least of the two, about 1000 km^2. Thus, maps and meridional profiles are formed from a 10° mesh and are smoothed accordingly. The temporal sampling problem is of more significance to this study. Beginning in June 1964, the radiation budget experiments were flown on sun-synchronous satellites. From that time until late 1965 measurements were made over most of the world at only two local times (0900 and 2100). This potential bias in the long-term averages is moderated slightly by use of Nimbus and ESSA data during 1966 (ascending nodes near 1130 and 1430 local time, respectively). Nevertheless, over zones or areas where a diurnal variation of the radiation budget may occur, the results of this paper must be considered with care.

2. Radiation budget measurements: The mean annual and seasonal time periods

a. Global and hemispheric results

Table 2 shows the "mean annual" average of the radiation budget parameters integrated over the entire earth and separately for the Northern and Southern Hemispheres. The parameters are related by

$$RN = I_0(1.0-A) - W_L, \qquad (1)$$

where RN is the net radiation; I_0 the incident solar radiation at the "top of the atmosphere" (derived from a solar constant of 1.95 cal cm^{-2} min^{-1} and astronomical parameters[4]); A the planetary albedo (ratio of total solar energy scattered and reflected by the atmosphere, clouds and earth surface, H_R, to the incident solar energy, I_0); and W_L the infrared radiant emittance of the earth-atmosphere system. All units are cal cm^{-2} min^{-1} except planetary albedo (percent). Eq. (1) may be applied to all time and space scales.

The table shows that both the first and second generation satellite measurements present a consistent picture of the mean annual global and hemispheric radiation budgets. The intial results from Nimbus III (during 1969) also agree on these space scales (Raschke *et al.*, 1970). Absolute measurement accuracy is estimated to be one unit of the least significant digits shown. Thus, the time and space mean values of Table 2 are measured with a relative accuracy of 2–3%.

Considering these accuracies and the possibility of time sampling bias already mentioned, we find essentially no significant change in the global and hemi-

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[3] NASA Staff Members, Goddard Space Flight Center, Greenbelt, Md.

[4] This value of the solar constant is used throughout this paper except where another (2.00) is explicitly noted.

Table 3. Mean annual and seasonal radiation budget of the earth-atmosphere system observed from meteorological satellites (1962–66).

	Global average					Northern Hemisphere					Southern Hemisphere				
	DJF*	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
I_0	0.50	0.48	0.47	0.49	0.49	0.34	0.55	0.63	0.42	0.48	0.67	0.42	0.32	0.56	0.49
H_a	0.34	0.33	0.34	0.35	0.34	0.24	0.38	0.45	0.31	0.34	0.46	0.30	0.25	0.40	0.34
H_r	0.16	0.15	0.13	0.14	0.15	0.10	0.17	0.18	0.11	0.14	0.21	0.12	0.07	0.16	0.15
A	31	30	26	28	30	30	31	28	27	30	32	30	23	29	30
H_L	0.33	0.33	0.34	0.34	0.34	0.32	0.33	0.35	0.34	0.33	0.34	0.32	0.32	0.34	0.34
RN_{EA}**	0.01	0.00	0.00	0.01	0.007	−0.09	0.05	0.11	−0.04	0.006	0.11	−0.03	−0.08	0.06	0.009

I_0=incident solar radiation (cal cm^{-2} min^{-1}) based on solar constant of 1.95 cal cm^{-2} min^{-1}.
H_a=absorbed solar radiation (cal cm^{-2} min^{-1}).
H_r=reflected solar radiation (cal cm^{-2} min^{-1}).
A=planetary albedo (percent).
H_L=emitted infrared radiation (cal cm^{-2} min^{-1}).
RN_{EA}=net radiation budget of the earth-atmosphere system (cal cm^{-2} min^{-1}).
* Months of the seasons are identified by initial letters.
** Probable absolute error of ± 0.01 cal cm^{-2} min^{-1}.

spheric radiation budgets as measured by the two data sets. New data from additional satellite experiments will allow continual updating of these results but a summary of the values obtained through 1966 indicates:

1) Over a 4–5 year period the net radiation budget of the entire earth, and of each hemisphere separately, is in radiative balance as well as we can measure such a balance. With both hemispheres in balance, there is no requirement for a net energy exchange across the equator.[5]

2) The entire earth and both hemispheres are darker (A=30% vs 35%) and warmer (W_L=0.34 vs 0.325) than earlier estimates had shown (London, 1957). The equivalent blackbody temperature difference is 3K (254K vs 251K). Being both warmer and darker indicates that the earth-atmosphere system must accomodate (and most probably transport) more energy than previously believed (~15% more in each hemisphere).

3) Each hemisphere has nearly the same planetary albedo and infrared loss to space on the "mean annual" time scale. This points out the dominant influence of clouds on the energy exchange with space, since the surface features of the two hemispheres are quite different.

On a global and hemispheric scale the mean values of the radiation budget parameters are shown by season in Table 3. All numbers are rounded to measurement accuracy save for the mean annual net radiation values. The grouping of months into seasons is arbitrary, but follows familiar convention in the atmospheric sciences.

For the global case we note a colder and brighter earth during the period December through May from a combination of snow and ice cover over the northern continents together with the highly reflecting southern polar regions. As we will note in later discussion, the two hemispheres are not mirror images insofar as their energy exchange with space is concerned. The low albedo during the Southern Hemisphere winter was not expected. It is not matched by exceptionally great infrared emittance, although the very cold Antarctic land mass may strongly influence the hemispheric average.

Net radiation gains in each respective summer exceed 15% of the incident solar energy on the hemispheres. This amount comprises about 65% of an average annual intake, implying that any modulation in the summertime exchange of energy to space might have significance beyond the relatively short time interval involved. Since it is always attractive to have a "target" with high signal, future measurements of the earth's energy budget might advantageously focus on the summer hemisphere energy gain.

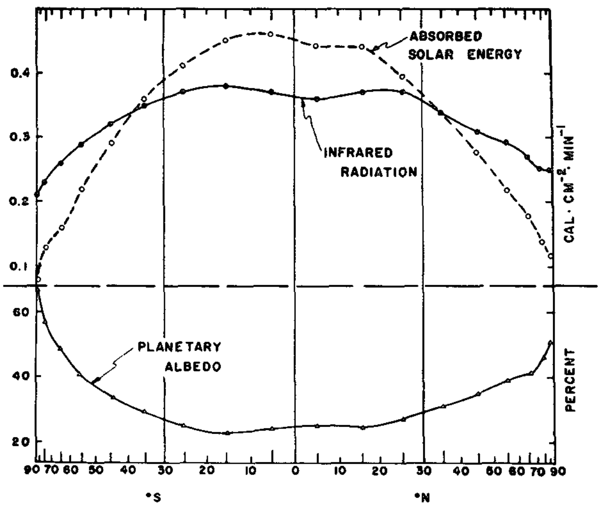

Fig. 1. Mean meridional profiles (averages within latitude zones) of components of the earth's radiation budget measured during the period 1962–66. The abscissa is scaled by the cosine of latitude.

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[5] A small portion of our data set (7.5%), from the ESSA III data by MacDonald (*loc. cit.*) were derived using the assumption of net global radiation balance. This does not alter the general result as stated.

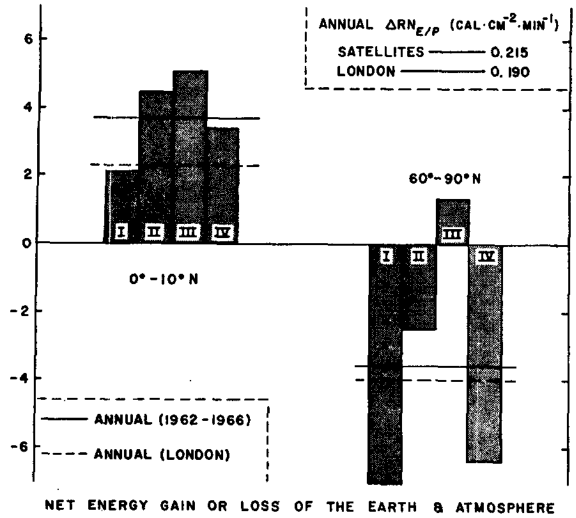


FIG. 2. Mean annual and seasonal energy exchange with space, measured from satellites during 1962–66, for two latitude zones. Bar graph represents seasonal values (I = Dec., Jan., Feb.; II = Mar., Apr., May; etc.). $\Delta RN_{E/P}$ is the net radiation gradient between equator and pole.

b. Zonal and geographical asymmetries of the radiation budget

Fig. 1 continues our view of the "mean annual" case. It shows the measured meridional profiles of planetary albedo, absorbed solar energy, and infrared loss. The classic picture of excess energy absorbed at low latitudes and net energy loss from mid-latitudes and polar areas is apparent. Note, however, the lack of equatorial symmetry, with more energy being retained in the southern subtropics than at the same latitudes in the north. This occurrence is offset by a difference in the polar radiation budgets. The arctic is observed to be warmer and darker than the antarctic. Latitudinal averages of planetary albedo are as low as 23% in the subtropics, ranging to 50% near the north pole and 70% at the south pole. These polar values are heavily weighted by the summertime conditions.

With the aid of Fig. 2 we take a closer look at the radiation budgets in two latitude zones of approximately equal area. For the regions 0–10N and 60–90N the "mean seasonal" energy gain or loss measured by satellites is shown by the bar graph, the "mean annual" average by the solid line. London's annual value for each zone is noted by a dashed line. On this space scale, smaller than that of the globe or a hemisphere, we find a wide range of departure between measurements and earlier computations. For the region 0–10N we find that the net annual gain of energy calculated by London is *35% less* than that measured from satellites. However, for 60–90N London's value falls much closer to the observed mean. Recall that the measurements have shown (and earlier calculations require) near hemispheric balance of gains and losses on this time scale. This occurs because zones not shown in Fig. 2, especially at mid-latitudes, have a measured net loss exceeding that computed (due primarily to the higher values of infrared loss already mentioned).

The departure of measurements from early estimates in the deep tropics is of special significance. Astronomical factors insure large amounts of available solar energy during the entire year. The large energy gain shown in Fig. 2 results primarily from a lower planetary albedo (Fig. 1). Thus, the tropics gain more energy because they are "darker." More than any other single factor, this result of satellite measurements contributes especially to the total global albedo being lower than previously believed. In addition, the greater energy input at low latitudes implies either greater poleward energy transport by ocean currents or greater air-sea exchange of energy and increased tropical convection. Vonder Haar and Hanson (1969) used the satellite measurements together with a summary of the few available observations of solar radiation received at the surface in the tropics (Quinn and Burt, 1967). The surface data show that 20% more energy arrives annually (in the region 0–20N) than was earlier estimated from climatic data and empirical relations (i.e., Budyko, 1963). Thus, the combination of recent measurements are in agreement and show that additional energy entering the earth-atmosphere system is primarily added to the oceans.

Fig. 2 also shows the wide seasonal range of net energy exchange with space over the arctic cap. From a large net loss in the winter, to a small but significant net gain during the summer season, the range is about 2½ times greater than that for 0–10N. Fig. 6 will show that the southern polar regions do not have this wide a

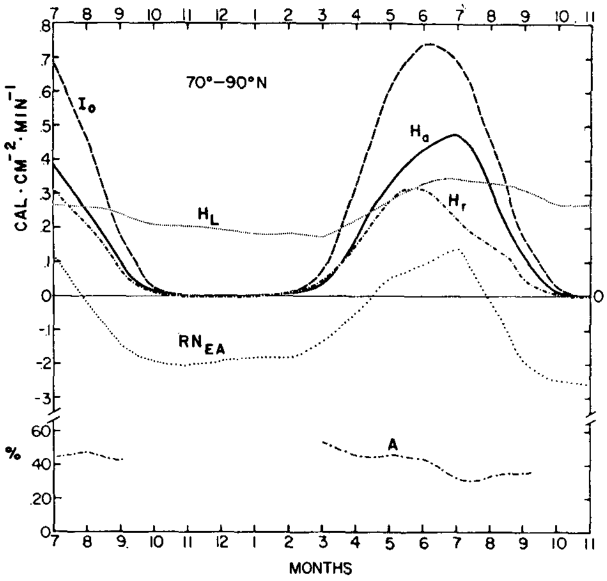
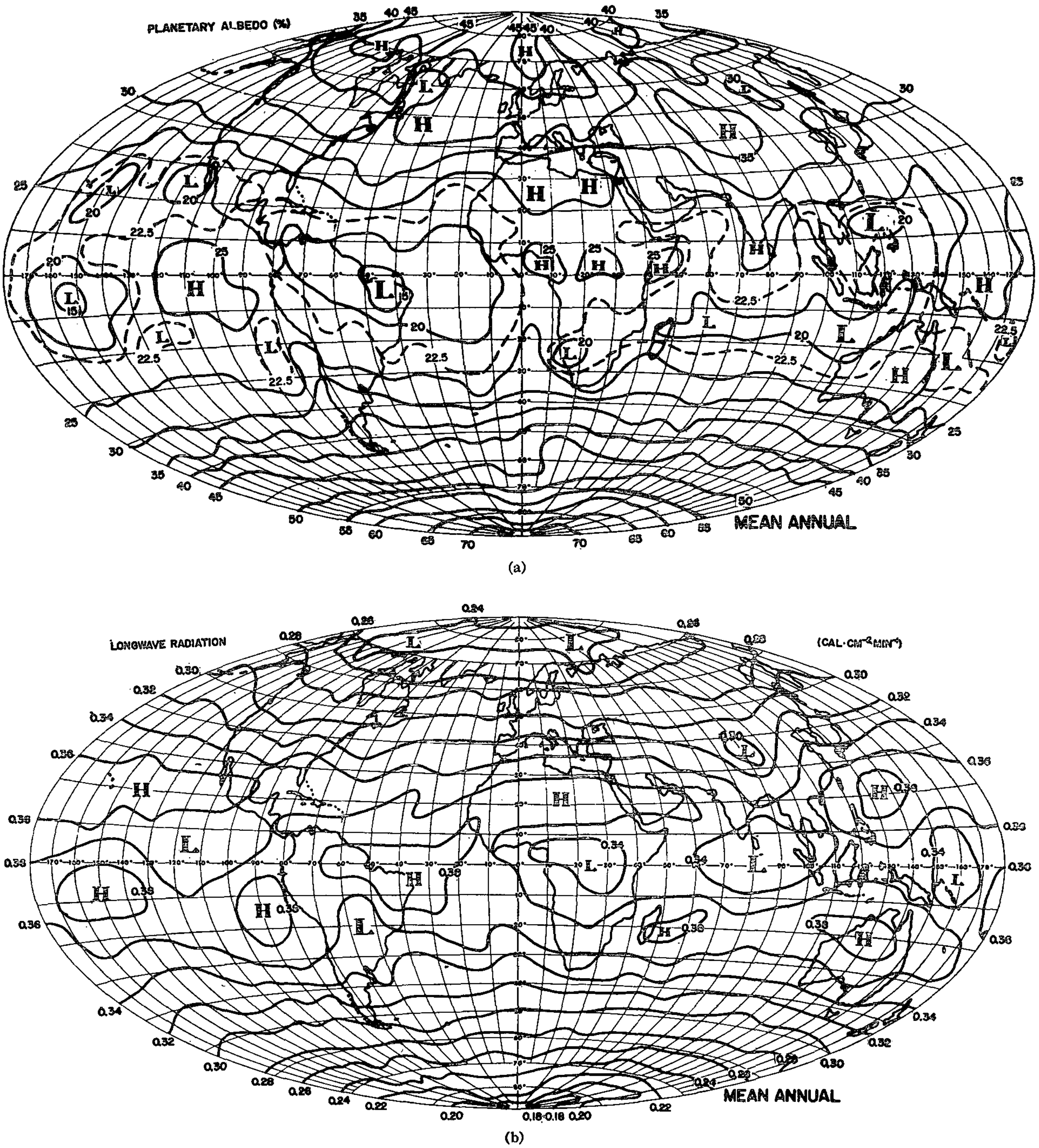


FIG. 3. Continuous time series of radiation budget parameters over the north polar region during 1964 and 1965. H_a and H_r are the portions of solar radiation absorbed and reflected by the earth-atmosphere system, and I_0 is the mean monthly insolation computed with a solar constant of 2.00 cal cm^{-2} min^{-1}.

seasonal range, pointing out again the lack of equatorial symmetry in the energy exchange with space.

An insert in Fig. 2 notes that the "mean annual" pole-to-equator gradient of net radiation measured from satellites is 10–15% greater than London's mean annual value for the Northern Hemisphere. This simple index is a measure of the planetary forcing function, the required poleward energy transport by the atmosphere and oceans. It indicates that our circulations are more "vigorous" than previously estimated.

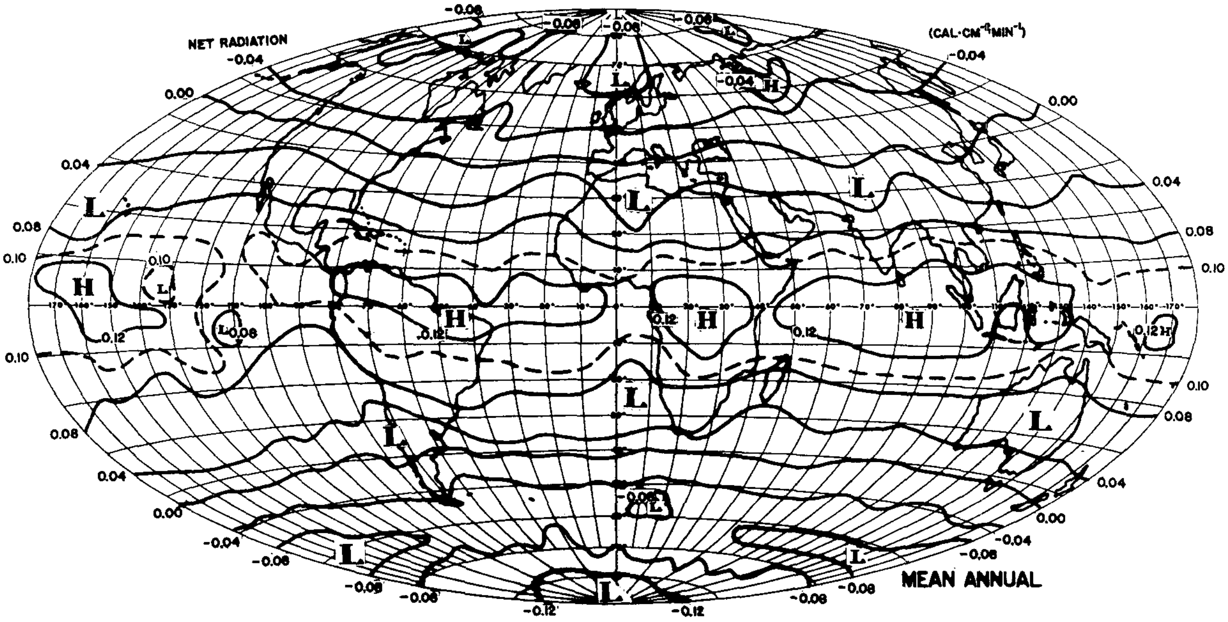
A closer look at time variations measured over the north polar cap is presented in Fig. 3. It shows a 17-month time series of the incident, absorbed and reflected solar energy, the infrared loss, albedo and net



(a)

(b)

FIG. 4. Mean annual geographical distributions of radiation budget parameters. Planetary albedo and longwave radiation were measured from satellites during 1962–1965. Net radiation values were derived using a solar constant of 2.00 cal cm^{-1} min^{-2}.



(c)

FIG. 4 (*continued*).

radiation. The earliest satellites (TIROS) had orbital inclinations such that they did not view this polar region. Thus, Fig. 3 shows our first long period of radiation measurements over the arctic. Second generation Nimbus and ESSA satellites, in near polar orbits, also returned measurements over the poles, but during shorter time intervals of our five-year period (Raschke *et al.*, 1968). An interesting feature in Fig. 3 shows that the absorbed solar energy maximum lags a month behind peak insolation. Several earlier studies had anticipated this observation based on information about the break-up and puddling on the arctic ice pack during the summer. Even though the infrared loss reaches a flat maxima in July, the total radiation budget of the earth-atmosphere system is slightly positive. The time period of net gain began in May and ends abruptly in August; it occurs primarily because of the features of the solar energy budget.

Thus far we have only discussed global and hemispheric averages and the mean radiation budget within latitudinal zones. This can be misleading, because an important result of the satellite measurements shows that significant changes in the earth's radiation budget occur within latitude zones, especially in the tropics. Fig. 4 presents mean annual maps of the radiation data. These geographical variations of planetary albedo, infrared radiation and net radiation will be discussed elsewhere in more detail (e.g., Part II of this report). Note, however, the zonal pattern of the isopleths at high latitudes in both hemispheres. This occurs in the region of migratory storms, where alternating clear and cloudy conditions occur over a given area. In the Northern Hemisphere a continental influence can be seen, especially in the map of planetary albedo. In the tropics semi-permanent features of the atmospheric circulation, terrain features, or the influence of special conditions in a specific season (i.e., the monsoon) cause significant

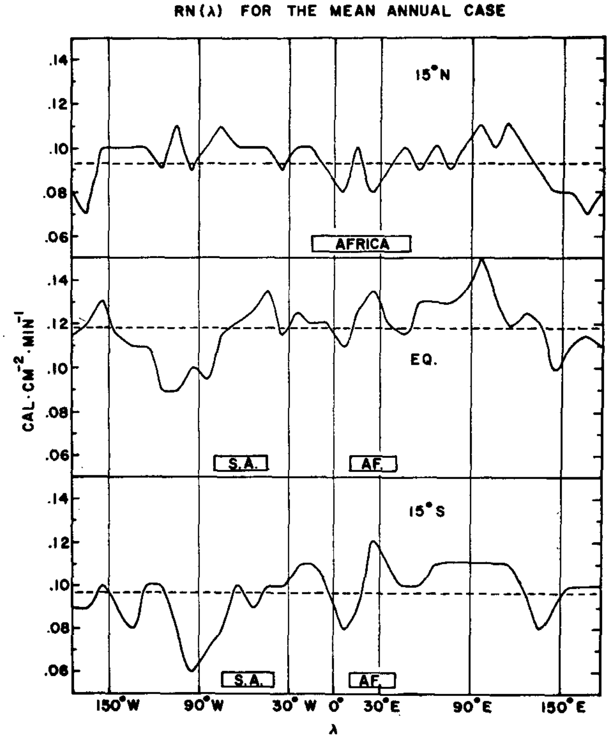


FIG. 5. The variation of net radiation with longitude λ extracted from Fig. 4c for three latitude circles. Dashed line is the zonal mean value; major land masses are shown schematically.

departures within the latitude zones. This is true even in the map of net radiation. Recall the maps are for the mean annual case, and thus all daily and even seasonal anomalies are smoothed a great deal. Even so we see a definite distribution of relative energy gain and loss areas within a zone. In higher latitudes (more zonal patterns) the range of variation is much smaller. These results show that a numerical model used to simulate the circulation of the atmosphere or ocean cannot add a forcing function only as a function of latitude over longer time periods (i.e., as a function of solar declination). Such an input may be valid for the higher latitudes but certainly not for the tropics. Variation in net radiation is shown in Fig. 5 for three tropical zones. Some of the greatest minima are found over the oceanic deserts west of South America and Africa. Here the low, bright, warm clouds reflect the solar energy well and also radiate strongly in the infrared. Maxima of net radiation occur over clear oceanic regions.

3. Mean seasonal budgets and interannual variations

Reference to mean and specific seasonal measurements has been included above for comparison with the mean annual case. Fig. 6 gives a more detailed view of the average zonal net radiation as it varies with latitude during each season of the year. As in Fig. 1, we note the departure from exact symmetry about the equator. For example, the north polar region has the wider range of net radiation with season. The net radiation reversal near the winter pole results from the absence of solar radiation at the highest latitudes combined with increasing infrared loss to space from the relatively warmer regions away from the poles.

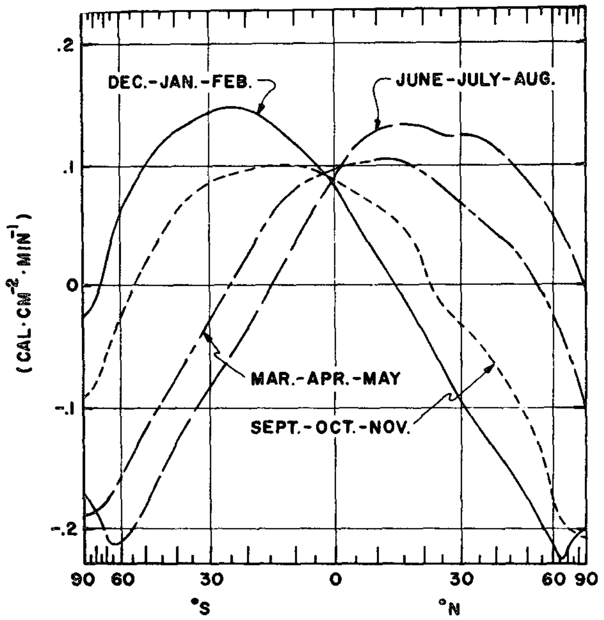


Fig. 6. Mean seasonal values of the meridional profiles of net radiation obtained from satellite measurements, using a solar constant of 1.95 cal cm^{-2} min^{-1}.

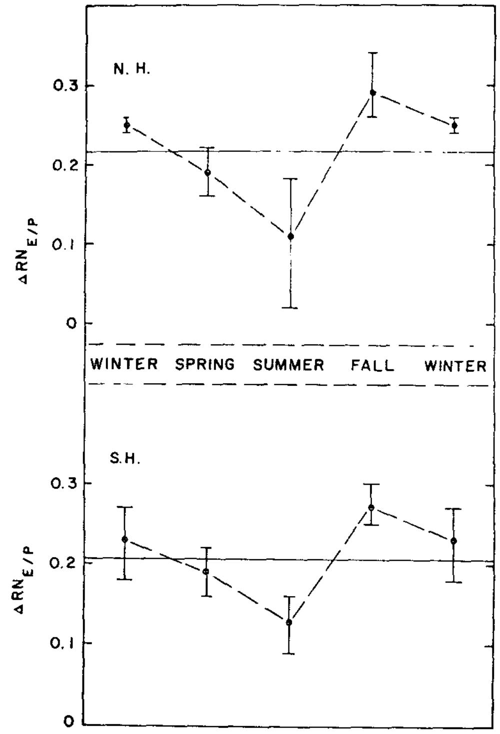


Fig. 7. Mean annual and seasonal values of the equator-to-pole gradient of net radiation and the range of interannual variation (all units cal cm^{-2} min^{-1}) measured from satellites. Table 1 shows the periods of measurement. Both Northern and Southern Hemisphere results are shown.

For a basic understanding of the energy exchange between earth and space, mean annual and seasonal averages provide the first step. Now that a relatively large sample of measurements is available we can proceed further, i.e., examine observed interannual variations of the radiation budget. We use a simple index ($\Delta RN_{E/P}$), the difference in net radiation between the equator and 90N or 90S. In Fig. 7, we see the change in the measured index during the same season of different years. The horizontal line shows the mean annual gradient, slightly larger in the Northern Hemisphere. Dots indicate mean seasonal radiation gradients and the bars note the range of values during the three or four years of data for each season.

We observe the largest gradient change between summer and fall in both hemispheres, a change toward a stronger gradient, a stronger forcing function. The greatest range within one season was observed during the Northern Hemisphere summer, the smallest range during winter of the same hemisphere. Absolute magnitudes of the gradient are largest during fall. However, the reversal of net radiation seen in Fig. 6 is not considered by our simple index. An upward adjustment for winter would make that gradient nearly the same

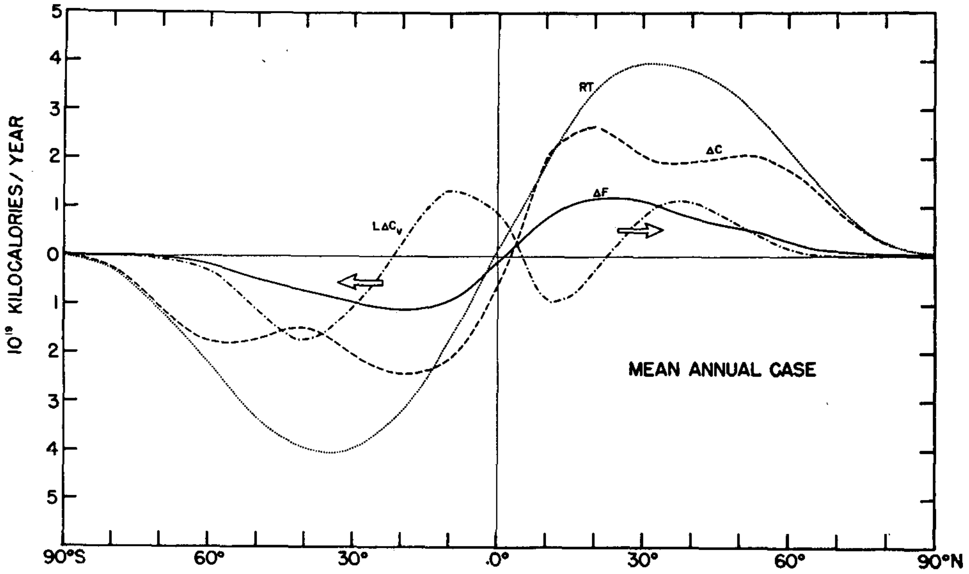


FIG. 8. Total poleward energy transport required by the radiation budget (RT) and its major components.

as for fall. As expected, summer gradients are small in both hemispheres.

A further step will be to study the response of our atmosphere to each season's measured gradient of net radiation. The measure of the forcing function used in this study (or another similar index) can now be obtained routinely by our meteorological satellites. Of course, we must consider the large thermal inertia of our oceans and thus expect the response and feedback to vary with both time and location. Some initial work in this area has been reported by Winston (1967, 1969).

4. The role of the radiation budget in the global energy balance

The energy exchange between the earth and space by radiative transfer is only one component of the total energy budget of the earth-atmosphere system. True, on a global scale and over long time periods, it is the overwhelmingly significant component, but we are very often concerned with higher frequency variations in space and time. In this section we shall use *measurements* of the earth's radiation budget together with *estimates* of the other major terms in order to present a simple depiction of the earth's total energy budget. We do this to illustrate the role of the radiation terms in the energy budget. Since much weight must be placed on climatological estimates of certain parameters, the absolute accuracy of results in this section is open to question. In addition, the illustrative exercise falls short of a thorough discussion of atmospheric energetics, i.e., the study of the generation, conversion and dissipation of various "forms" of energy in the atmosphere.

Fig. 8 shows, for the mean annual case, the total poleward energy transport (RT) required by the measured radiation budget. Vonder Haar (1968) and others have shown that for no net energy storage in the atmosphere, earth or ocean the net required energy transport across a parallel of latitude must equal the sum of several horizontal energy transport terms. These are: ΔF, energy transport by ocean currents; $L\Delta C_V$, the transport of energy in latent form as water vapor; and ΔC, the sensible heat plus potential energy transport by the atmosphere. To derive Fig. 8 we used estimates of ΔF and $L\Delta C_V$ from a recent compilation by Sellers (1965). Thus, using satellite measurements for RT we obtain ΔC as a residual. Note that values plotted above the zero line in Fig. 8 indicate northward energy transport; below the line, southward. We note a double maxima of ΔC in both hemispheres, very similar in shape to one derived by Holopainen (1965) from Northern Hemisphere radiosonde data. Note also the requirement for southward transport of sensible heat and potential energy across the equator, but northward movement of water vapor by the atmosphere.

It is possible to derive similar curves for the mean seasons (Rasool and Prabhakara, 1966). However, a major uncertainty in the transport terms arises from lack of knowledge about seasonal variation of energy storage in the oceans. It may be expected that within some latitude zones, during some seasons, that the radiative, latent heat (i.e., evaporation minus precipitation), and ocean storage terms may all be nearly the same magnitude. Newell *et al.* (1970) discuss new measurements of the atmospheric transport terms and satellite measurements will be available on a continuing basis. Thus, we may eventually be able to study oceanic transport and storage as a residual.

5. Conclusions

A summary of this first comprehensive study of measurements of the earth's radiation budget shows that:

1) The first generation meteorological satellite observations as well as the early results from our second generation spacecraft have independently shown a consistent picture of the earth's radiation budget. It is a *warmer and darker* planet than we previously believed. More solar energy is being absorbed, primarily in the tropics.

2) Although the tropics (30N–30S) as a whole gain energy from space during all seasons, significant longitudinal variations in the net input are noted.

3) Although the annual net radiation budgets of the Northern and Southern Hemispheres are both in balance (despite the difference in topography), we do not find exact equatorial symmetry in radiative exchange with space. This is especially true in subtropical and polar regions.

4) The prime forcing function, the equator-to-pole gradient of net radiation, has its greatest relative change between summer and fall in both hemispheres. In addition, there have been significant gradient changes measured between the same seasons in different years. Further study of atmospheric response is in order.

5) In like manner, even though the satellite measurements show no requirement for net energy exchange across the equator for the "mean annual" case, the measurements can be combined with independent observations to gain a better understanding of the global energy balance and the transport requirements of the atmospheres and oceans.

6. Further comments

The results of satellite measurements shown in this paper are the first of their kind. Like all new observations, final judgment of their relevance must rest primarily on confirmation by independent means. The first such confirmation is already on record, coming from sensors flown on the first of our second generation satellites. Of course, the absolute and relative accuracies of the measurements can be improved in future sensing systems. See, for example, error analyses included in the references dealing with the Wisconsin-type sensors (since these provide 80% of the measurements reported here).

The trend toward departure from the earlier computation studies of the radiation budget seems irreversible. The reason for the departure from previous estimates is still not completely resolved, although we strongly suspect that an overestimate of tropical cloudiness, especially as it affected computations of solar energy transfer, must have been a major failing of the early studies. In this regard, London and Sasamori (1971) have recently re-evaluated the earlier work by London (1957) and have computed a global planetary albedo somewhat lower[6] (33%) than given in the earlier study (35%). Thus, computations and observations seem to be coming closer to agreement with one another. The end results of computations which use satellite measurements as a control at the upper boundary should be improved estimates of the vertical profiles of net radiative cooling *in the atmosphere.* Such profiles are very important in atmospheric energetics studies and cannot be easily measured on a global scale.

Throughout this paper we have used London's 1957 study as representative of a great deal of extensive earlier computational work. It serves this purpose well and allows us to avoid repetitive comparison of the satellite measurements with the multitude of previous numbers computed by a like number of methods. In the same vein, to maintain some fluidity in this paper we have only discussed the great number of satellite measurements collectively via their time and space means. A great deal of research remains when the measurements of the radiation exchange between earth and space are applied to special studies. Our initial work on interannual variations is a small start in this direction. Indeed, further work on these kind of problems, not possible before, may be of more scientific interest than a polished description of mean conditions.

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[6] London (1970, personal communication) states that a value of 31% results if additional atmospheric absorption (i.e., due to dust) is included in the calculations.

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