Measurements of the Energy Exchange Between Earth and Space from Satellites During the 1960's

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ABSTRACT

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The net radiation budget of the earth-atmosphere system can be obtained from satellite measurements of the infrared radiant emittance and reflected and scattered solar radiation along with a knowledge of the solar constant. During the 1960's experimental and operational meteorological satellites carrying thermistor bolometer sensors designed for this task were in orbit during about 60 months. Our paper presents a synopsis of results from these measurements including: a global planetary albedo of 30%, long-term global radiation balance within measurement accuracy (2-3%), the net equator-to-pole radiation gradients (and their variation) that drive our atmospheric and oceanic circulations, as well as selected measurements of radiation budget terms over particular geographical areas. Future satellite experiments are planned to allow measurements of higher precision and with better space and time sampling. However, the results thus far have provided a solid descriptive base for more detailed diagnostic studies, especially regarding the significance of observed interannual radiation budget variations and also the separate consideration of energetics of the atmosphere and the ocean.

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I. Introduction

While atmospheric scientists have been interested in the global radiation budget for more than 100 years, measurements have been available only in the last twelve years. Earth-orbiting satellites provided the platform for radiation budget measurements; first experiments were flown on Explorer VII in 1959.

As in earlier days, our desire to study the radiation budget is high because:

a) global climate is a result of the total energy exchange (by radiation) between our planet and space,

b) the large-scale atmospheric and oceanic circulations are forced fundamentally by the gradient of radiation exchange with space between pole and equator,

and

c) local area radiation budgets at the "top of the atmosphere" are in an important boundary condition for local and regional energetics that affect both the physical and biological processes in the region of interest.

In recent years, radiation budget measurements from satellites have also been recognized as important controls for checking the performance of numerical models of the atmosphere's circulation on a global scale.

Invited Paper M-70 presented at the Joint Meeting of the German Physical and Meteorological Societies, Essen, Sept.-Oct. 1971. To be published in _Annalen der Meteorologie_, 1972.

Figure 1 shows a schematic diagram of the terms of the radiation budget of the earth-atmosphere system. Three terms are shown, with the net radiation or radiation budget, Q_n, as the residual of:

H_S (λ, ϕ, t) - the direct irradiance of solar energy at p = 0 (computed from an assumed value of the solar constant, I_0, 1.95 $cal \cdot cm^{-1} \cdot min^{-1}$)

minus W_S (λ, ϕ, t) - solar energy reflected and scattered from clouds, atmospheric gas and aerosol, and the surface (measured from the satellite)

minus W_L (λ, ϕ, t) - the infrared radiant emittance from clouds, atmospheric constituents and the surface (measured from the satellite)

All dimensions (as the solar constant) are energy per unit area and unit time. The functionals λ ,ϕ, t) refer to longitude, latitude and time. They serve to note the time and space scale dependence of the radiation budget; our schematic box could apply to a unit area at some location or to the entire global envelope. Note that the planetary albedo, A, is the ratio W_S/H_S.

Two basically different types of radiation budget experiments have been flown on U.S. satellites [SUOMI, et al. (1967), McCULLOCH (1969)]. They are shown in Figure 2 as:

a) the medium resolution infrared radiometer; it has a narrow angle (5 degree) field of view, scanning capability by rotating a mirror, four infrared channels and one to measure the radiance of reflected solar radiation.

and b) omnidirectional (2π sterdian) sensors named the Wisconsin hemisphere or Wisconsin plate radiometers (cones provide special checks for these omnidirectional sensors); they always consist of matched pairs of black and white sensors, the former to measure all radiation (solar and infrared), the latter only the infrared.

Both types of experiments use the same radiation detectors, thermistor bolometers. All other experiment parameters (field-of-view, time constant, spectral response, and method of data reduction) differ. Furthermore, the basic radiation measurement (of the radiation budget parameters shown in Figure 1) for the scanning radiometer is <u>radiance</u>, while the omnidirectional sensors measure <u>radiant power</u>. Data reduction techniques (more complex for the scanning radiometer data) are employed to derive the desired values of W_S (λ, ϕ, t) and W_L (λ, ϕ, t). From the viewpoint of scientific use, either system should be acceptable for studying the earths radiation budget. However, the more complex scanning radiometer system does provide radiation budget measurements at one order of magnitude finer on the space scale. Both experiments undergo absolute calibration before launch into space. In addition, the omnidirectional sensors are checked against the direct solar energy during each orbit; the scanning radiometer views a reference source of known temperature on the satellite. In this way, relative calibration in space is provided for all measurements by the Wisconsin experiment and for the infrared measurements from the scanning radiometer. Reflected solar radiance measurements from the latter are checked against regions on the earth such as deserts.

II. Results for the Entire Earth and for Latitude Zones

VONDERHAAR and SUOMI [1971] have discussed results from satellite experiments in orbit before 1967. RASCHKE and BANDEEN [1970] have discussed two-and-one-half months of 1966 scanning radiometer data in detail. Both of these references cite numerous previous papers dealing with both the methods of data reduction and special studies using the radiation budget measurements. The present paper discusses all of the measurements available thus far, including those acquired from NIMBUS-III in 1969 and 1970.[1]

Table 1 summarizes the measurements of the annual and seasonal radiation budget of the entire planet. First value is infrared radiant emittance, W_L; followed by planetary albedo (A). Accuracy estimates for the results of the U.S. experiments are plus-or-minus one unit of the least significant digits shown; this yields relative measurement accuracies of about 3%.

For the annual case, both the earliest satellite data set (1962-66) and the most recent (1969-70) show that our earth-atmosphere system has a planetary albedo of 29-30%, outgoing infrared radiation to space averaging 0.34 $cal \cdot cm^{-2} \cdot min^{-1}$, and net global radiation balance (within measurement accuracy) when the solar constant is 1.95 $cal \cdot cm^{-2} \cdot min^{-1}$. The infrared emission is equivalent to a black-body temperature of (255°K), higher than the value estimated by LONDON [1957] before the

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[1] See also Raschke, et. al. (1971), Vonder Haar, et. al. (1972, and Raschke, et. al. (1972) for a more detailed discussion of the Nimbus III measurements.

TABLE 1

GLOBAL RADIATION BUDGET

	SATELLITES 1962-1966	NIMBUS-III 1969-70	METEOR-II 1969-70
M A M	.33 (30%)	.35 (29%)	.37
J J A	.34 (26%)	.35 (28%)	.37
S O N	.34 (28%)	.35 (28%)	.37
D J F	.33 (31%)	.34 (29%)	.35
ANNUAL	.34 (30%)	.34 (29%)	.36
ANNUAL NET RADIATION	.00	.00	—

satellite experiments. Also, our planet is darker than was previously believed; it has a lower albedo than the early value of 35%. Recall that these results have now been obtained from two different types of satellite experiments, thus giving further assurance of the accuracy of both data sets.

Seasonal variation of the planetary radiation budget is small. A very small tendency for a brighter and colder planet during the period December - May is seen in both sets of U.S. data. Infrared experiments on METEOR satellites in 1969-70 (BOLDYREV and VETLOV [1970]) also detected a slightly colder earth during the Northern Hemisphere winter.

The annual case is especially interesting when we relax the space scale and consider the satellite measurements gathered into averages for each specific latitude zone. Figure 3 shows the resulting mean meridianal profiles for (a) the satellite measurements, 1962-66, (b) NIMBUS-III results and (c) the estimates by LONDON in pre-satellite days[1]. As in the global case (Table 1) the satellite sets show general agreement even though they were not obtained during the same years. All measurements differ strikingly from the estimates of planetary albedo in the tropics. The darker planet noted previously is due primarily to a lower albedo in the region 0 - 30°N than was previously believed. Apparently, the calculations of LONDON and others more than ten years ago used over-estimates of opaque (reflecting) cloud amount in the tropics. Separate evidence for this has been noted by VONDERHAAR and HANSON [1969]. They found that the measured solar radiation reaching the surface in the tropics is greater than all previous estimates.

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1 BOLLE [1971] compares the satellite measurements of VONDERHAAR and SUOMI [1971] ((a) above) with very recent, new estimates by LONDON and SASAMORI [1970]. The new estimates are now in much better agreement with the measurements.

Infrared radiation to space is measured to be slightly greater than was calculated at all latitudes. The significance of the overall differences between measurements and earlier calculations is seen in Figure 4. Here, the net energy gain or loss of two earth-atmosphere zones is shown for the annual time period (horizontal lines) and for mean seasonal conditions (shaded bar, I=DJF). LONDON's results for the annual case are also shown. In the region 0 - 10°N much more energy (1.5×10^{16} $cal \cdot min^{-1}$) is gained during the year than was previously estimated. At polar regions the old and new values are much closer, giving the same depiction as would have been inferred from Figure 3: more energy gained by our atmosphere and oceans at low latitudes, the need for increased poleward energy transport, slightly increased energy loss to space throughout the mid-latitudes.

Most of the energy gain is to the tropical oceans. Thus, the required increase in poleward transport must be accomplished by either direct sensible heat flux by the oceans, or increased air-sea energy exchange followed by energy transport in the atmosphere through some combination of the sensible, potential and latent energy mechanisms. On a seasonal basis, the energy gain and loss shown in Figure 4 varies in the expected relative pattern. Note, however, that a small net energy gain is measured over the North polar cap during summer. This energy, together with that advected from lower latitudes combines to allow the warming of air and melting of surface snow and ice characteristic of that season.

III. Measured Variation of the Radiation Gradient from Equator to the Poles

In the previous section we have seen the results and hypotheses that are based on consideration of the satellite radiation budget measurements over a long time scale (5-6 years). Of special interest also are the measured values in specific seasons and their interannual variation. Figure 5 displays a simple index, $\Delta RN_{E/P}$, used as a first look at the fundamental net radiation gradient between equator and pole. On the very longterm this gradient depicts the thermal forcing of our earth-atmosphere system; values of the mean annual gradient for both the northern and southern hemispheres are shown as horizontal lines in Figure 4. They are nearly the same, with the northern hemisphere slightly larger.

The same figure shows mean seasonal values (dots) and the range of gradients measured from satellites in specific seasons (range bars). In both hemispheres the gradient is least in summer and greatest in fall, with the most abrupt change between these two seasons. Mean winter values are less than those of fall due to a gradient reversal in polar regions not considered by our simple index. Therefore, the fall and winter values should be considered practically the same in the mean.

Measured variation had been the least in Northern Hemisphere winter, greatest in Northern Hemisphere summer during the 1962-66 period shown in Figure 5. Recent values of this same gradient measured from NIMBUS-III during 1969-70 fell within the range bars in all seasons and in both hemispheres except during Northern Hemisphere winter. This re-emphasizes the need for a continuing program of radiation budget measurement so that we may measure and study the full natural variation of the radiation gradient.

On the time scale of a specific season, one cannot expect a direct relation between the radiation gradient measured from satellites and the resulting atmospheric circulation. Whereas, this would be the case on Mars, our oceans and hydrologic cycle provide other mean to release energy into the atmosphere and often operate out of phase with each other and with the radiative forcing from space.

Nevertheless, as an illustration of the potential equivalent variations of radiation gradient we have constructed the simple linear example shown in Figure 6. Here the mean summer and winter values of the thermal wind (V_T)[1] are used with the corresponding mean values of radiation gradient index (from Figure 5) to derive the linear relation. Mean values of gradient measured over the southern hemisphere are noted by the arrows, they would indicate a lesser range of the mean V_T in that hemisphere. Shaded areas denote the range of measured gradient in all summers and winters and the equivalent range of circulation activity. Research now underway will study the actual physical and dynamical relations between the satellite measurement of radiation resulting from atmospheric conditions and the subsequent circulations forced, in part, by the radiative energy exchange. The grossly oversimplified illustration in Figure 6 serves as a reminder that this application of the satellite measurements can proceed in parallel with an increasingly polished description of "mean" conditions.

IV. High Frequency Time and Space Changes in the Earth's Radiation Budget

This section is included to present the reader with examples of the radiation budget measurements from satellites on time and space scales sufficient to consider the local and regional energetics. The higher frequency data from the scanning radiometer is emphasized. Most results

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[1] Northern Hemisphere from 20°-70°N between the levels 1000 and 300mb.

are recent ones from NIMBUS-III; they are described in detail in RASCHKE et al [1972] .

Figures 7a, 7b, and 7c denote time-latitude sections from pole-to-pole during April, 1969 - February 1970. They show the monthly course of outgoing infrared radiation, W_L; planetary albedo, A; and net radiation, Q_N, in each latitude zone.

Geographical variations of the same radiation measurements are shown for the period 1-15 July 1969 in the set of figures 8a, 8b and 8c. Here the high area resolution of the NIMBUS-III experiment can be used to examine radiation patterns characteristic of the tropical convergence zone, sub-tropical desert regions and special areas of cloudiness in mid-latitudes during these 15 days.

A final example of the geographical variation of radiation to space is seen in Figure 9 . Based on measurements from nine seasons with the low area resolution Wisconsin sensors, we see here the natural range of the seasonal values of infrared emittance to space. As in the case of the interannual radiation gradients, more study of these results is now in order. Some features, such as the large range of values over the Indian monsoon sector, can be interpreted with little difficulty. Questions are posed, however, by the maxima of range in the tropical eastern Pacific and by the minima near the British Isles. The latter might be due to persistent cirriform cloudiness.

V. Summary

During the 1960's, radiation budget measuremnts from satellites have allowed quantitative study of the global energetics of our atmosphere-

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ocean system. A continuing program is planned, including independent measurement of the solar constant. Thus far, the measurements returned from two basically different types of satellite experiments are in agreement on the longterm global scales where they are most comparable. This fact, together with independent estimates of the accuracy of measurement from each system, shows that we now measure the energy exchange between earth and space better than it can be calculated.

Examples of application of the radiation budget data were shown. They can be related to the age-old problem of climate change, to the basic question of the thermal forcing of our circulation systems, and to the contemporary problems of local area energetics and computer modeling of the atmosphere.

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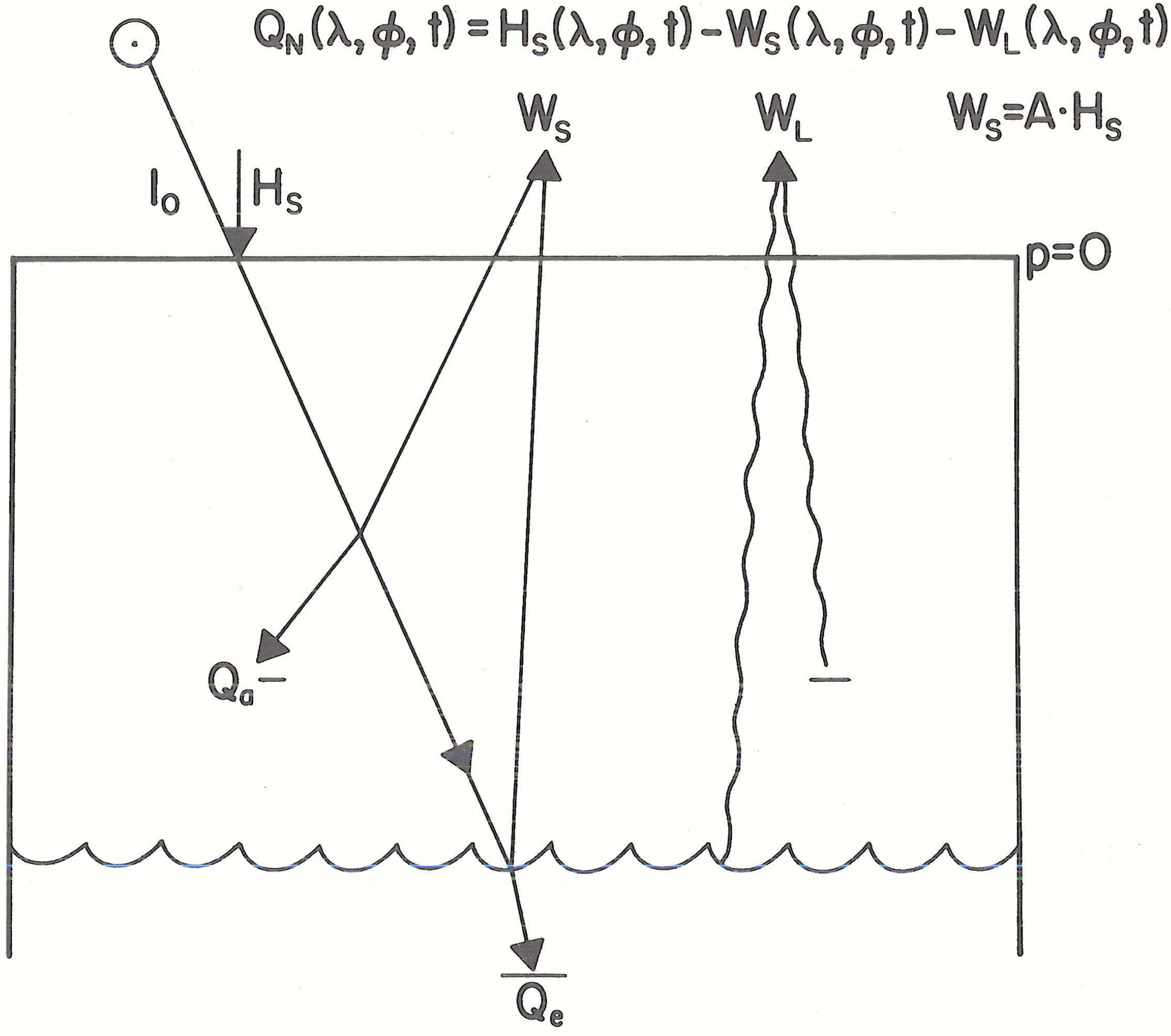
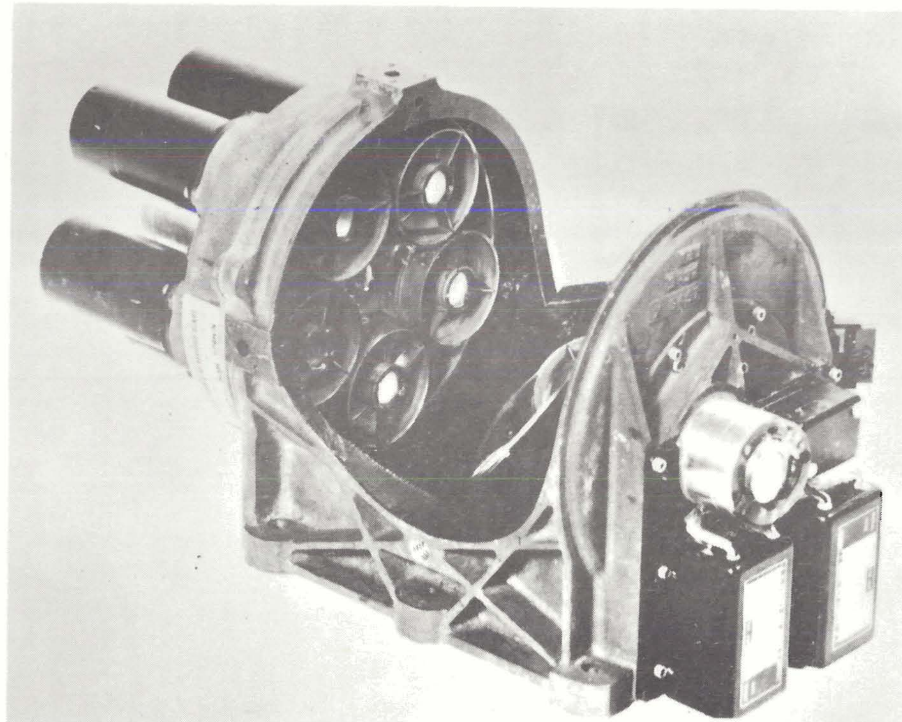
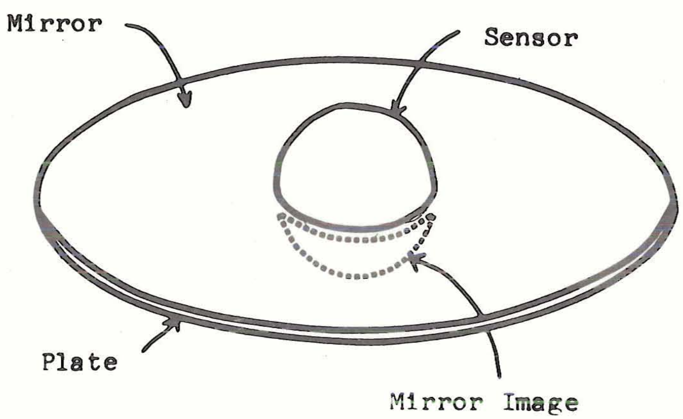
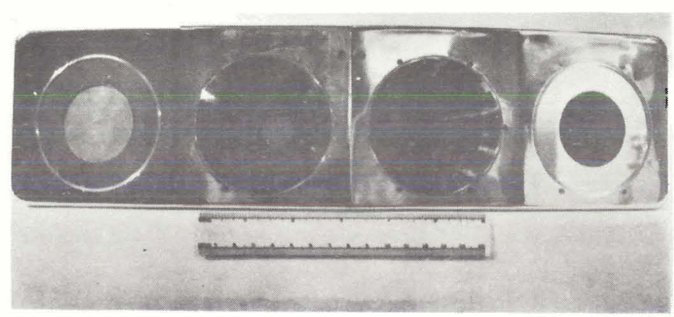

$Q_N(\lambda, \phi, t) = H_S(\lambda, \phi, t) - W_S(\lambda, \phi, t) - W_L(\lambda, \phi, t)$
W_S
W_L
$W_S = A \cdot H_S$
I_0
H_S
p=O
Q_a
Q_e



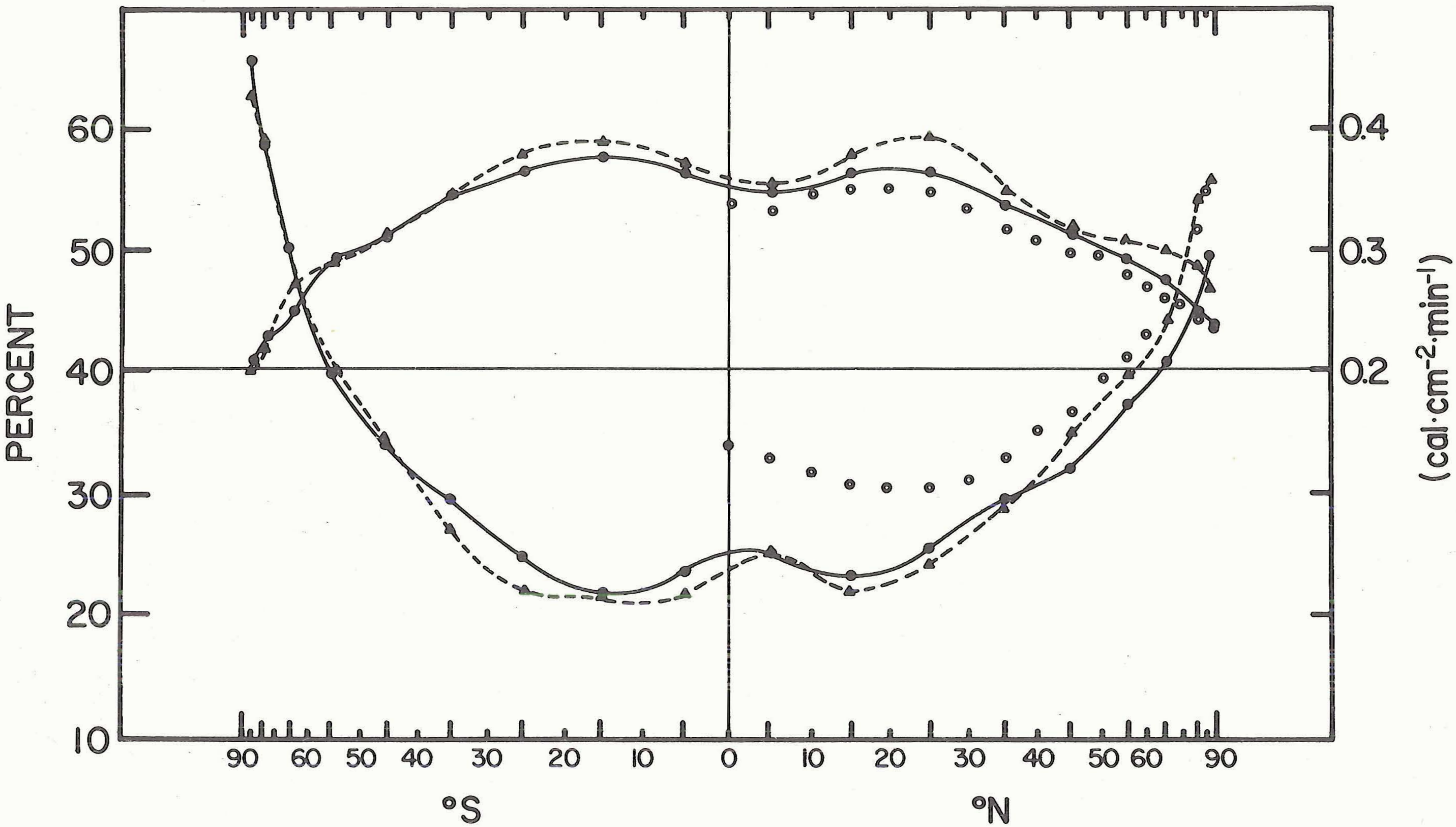
THE MEDIUM RESOLUTION INFRARED RADIOMETER



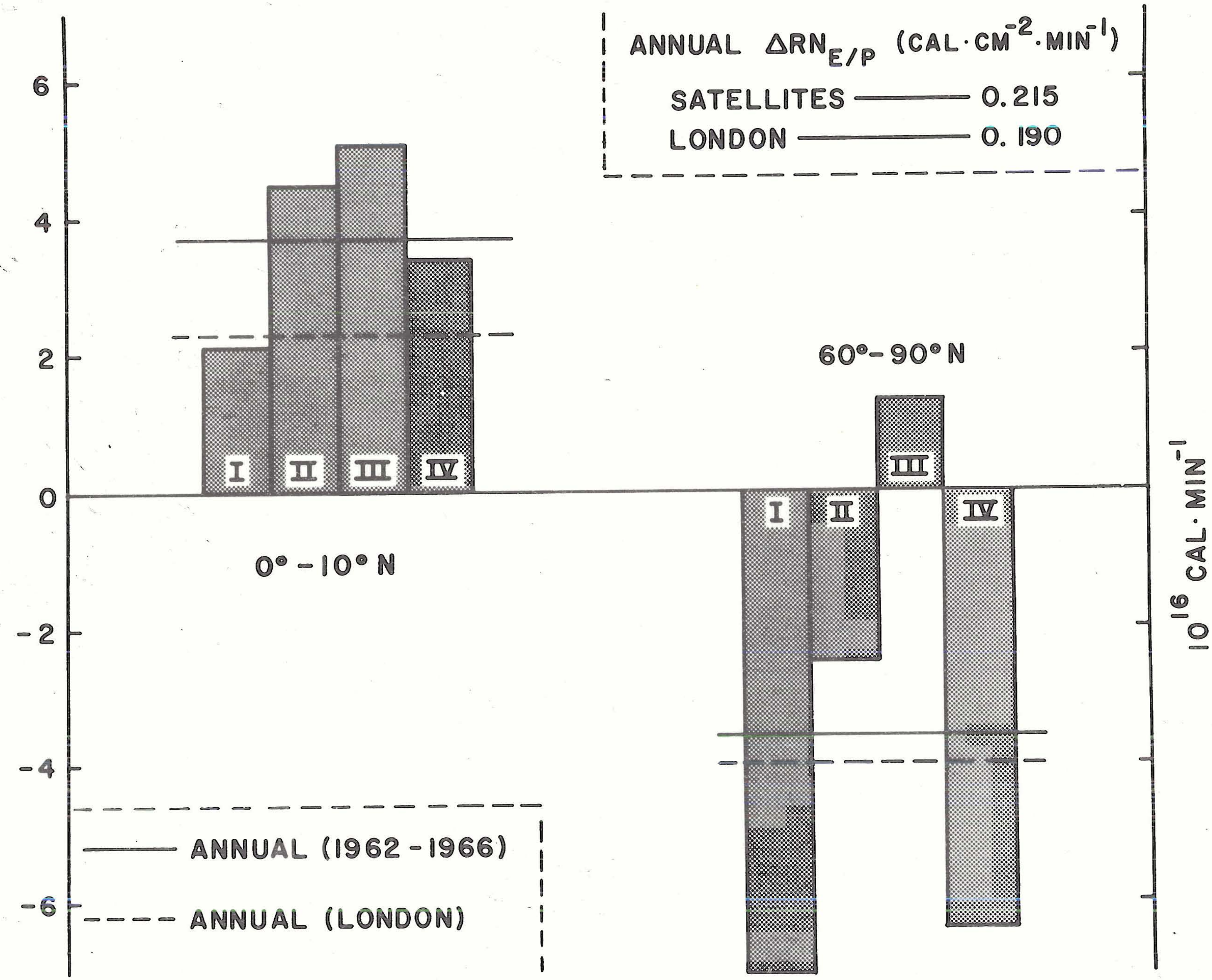
WISCONSIN HEMISPHERE RADIOMETER



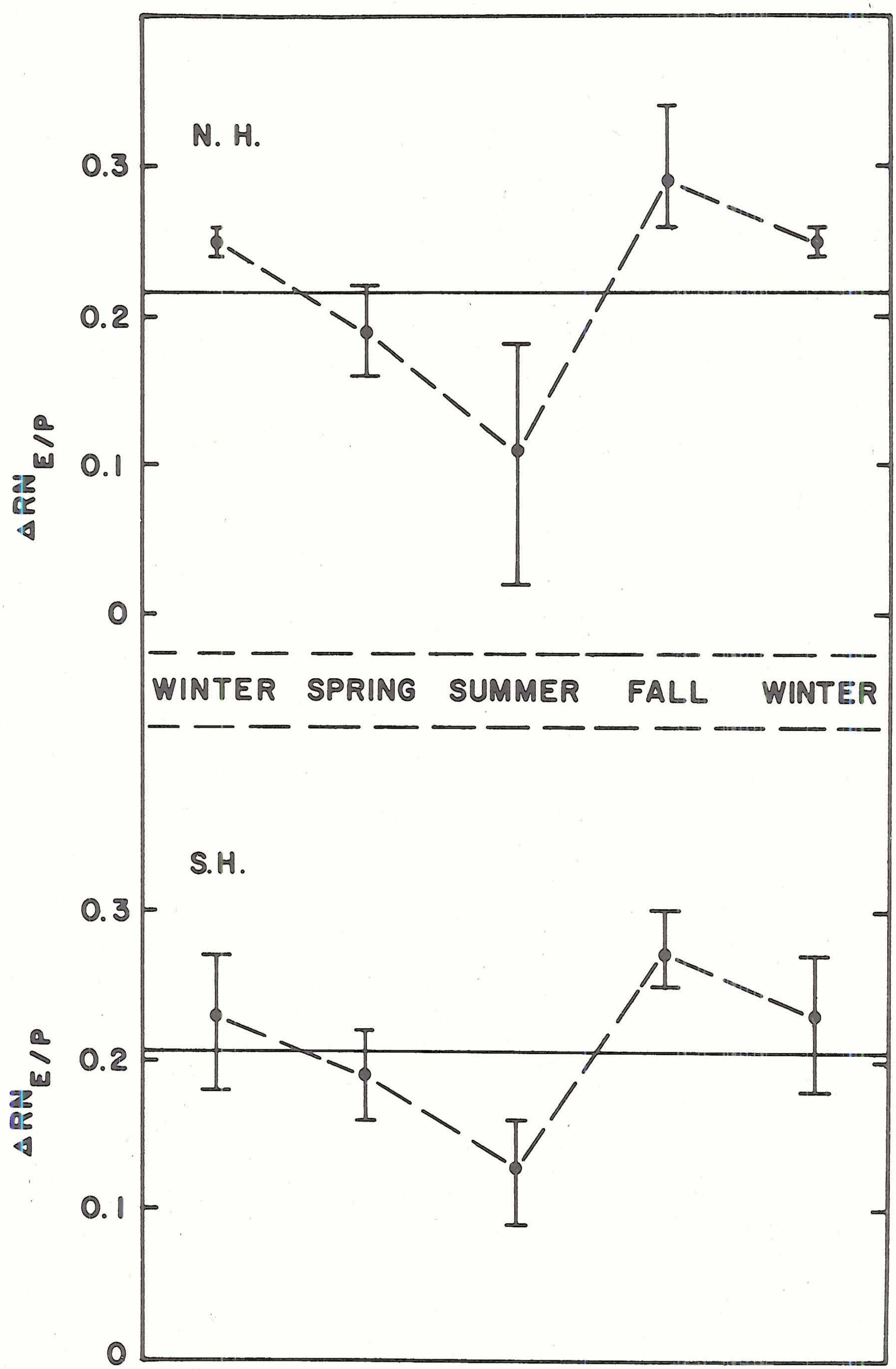
WISCONSIN FLAT-PLATE AND CONE RADIOMETERS

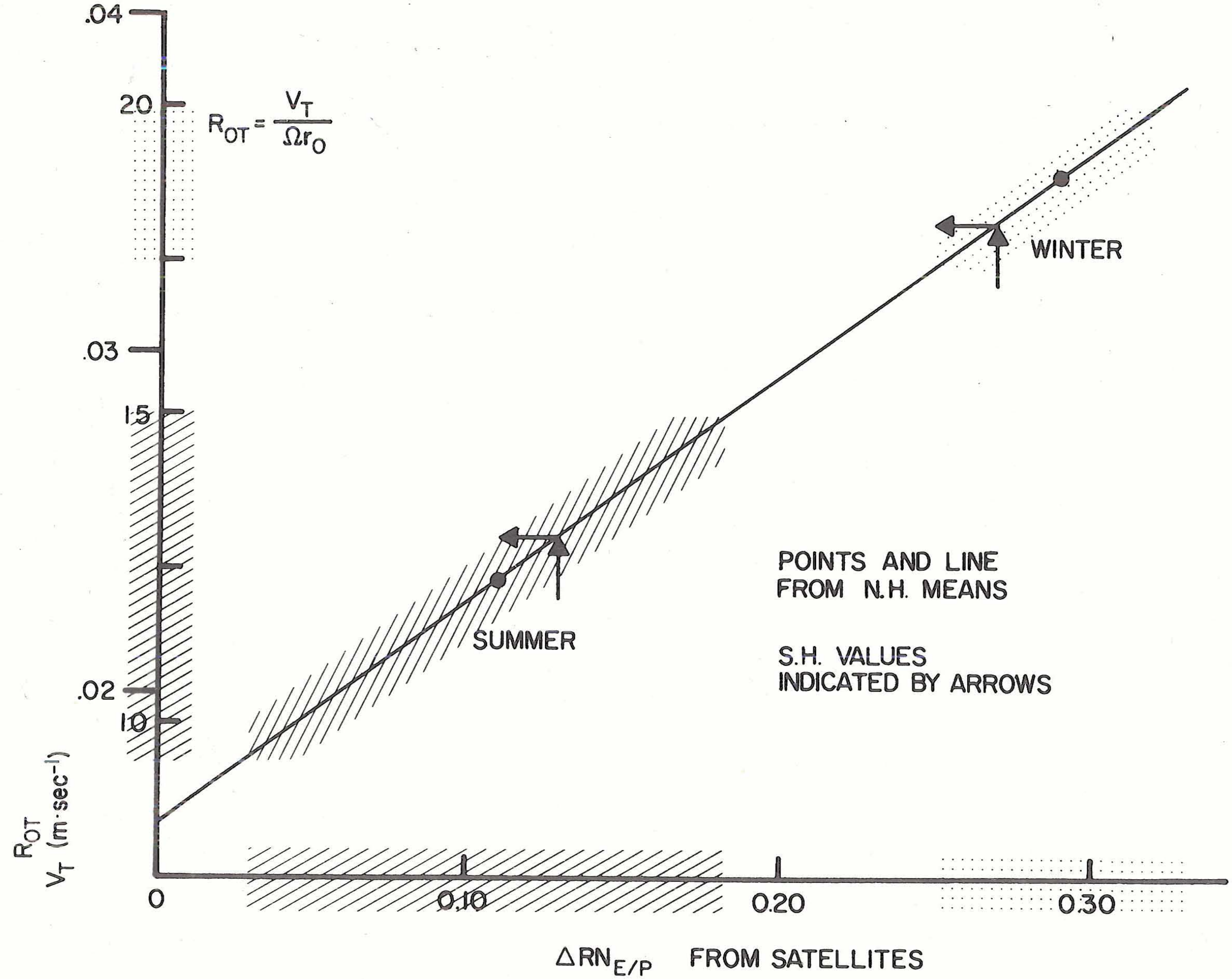


PERCENT
60
50
40
30
20
10
0.4
0.3
0.2
(cal·cm⁻²·min⁻¹)
90 60 50 40 30 20 10 0 10 20 30 40 50 60 90
°S
°N



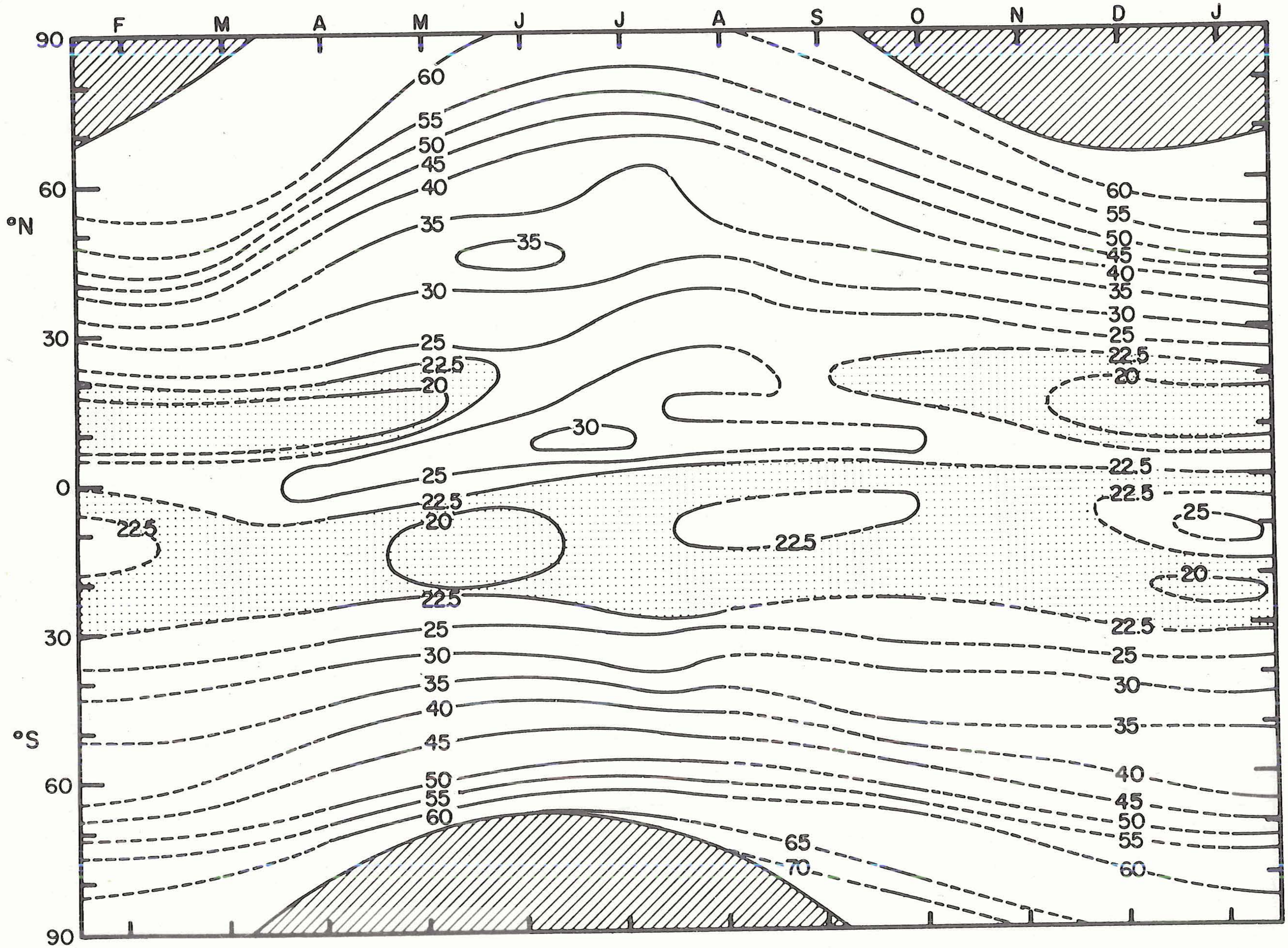
NET ENERGY GAIN OR LOSS OF THE EARTH & ATMOSPHERE


N. H.
S.H.
WINTER SPRING SUMMER FALL WINTER
ΔRN E/P
ΔRN E/P
0.3
0.2
0.1
0
0.3
0.2
0.1
0

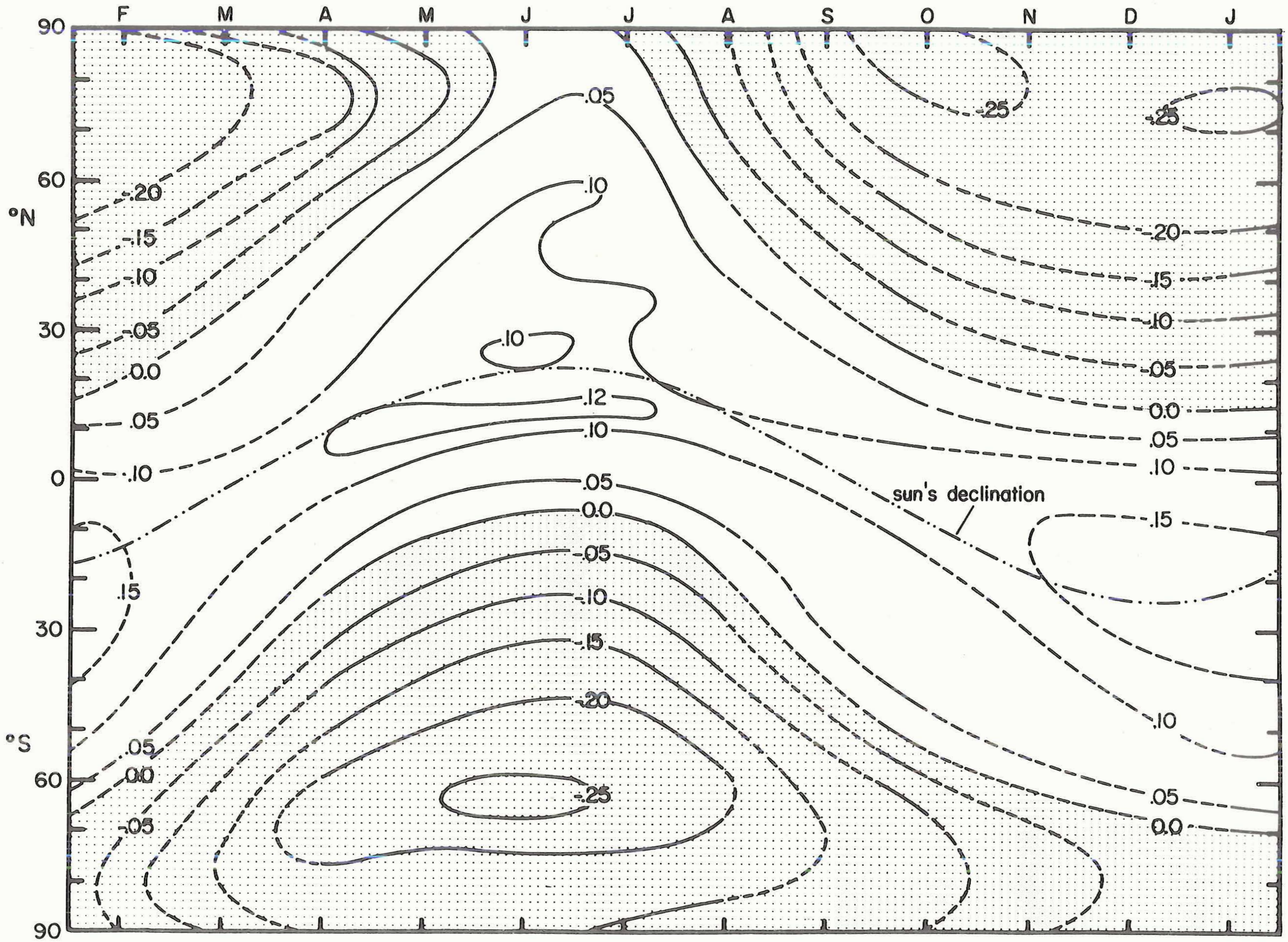


.04
20
$R_{OT} = \frac{V_T}{\Omega r_0}$
.03
15
.02
10
R_{OT}
V_T (m·sec^{-1})
0
0.10
0.20
0.30
$\Delta RN_{E/P}$ FROM SATELLITES
WINTER
SUMMER
POINTS AND LINE
FROM N.H. MEANS
S.H. VALUES
INDICATED BY ARROWS

ALBEDO (percent)

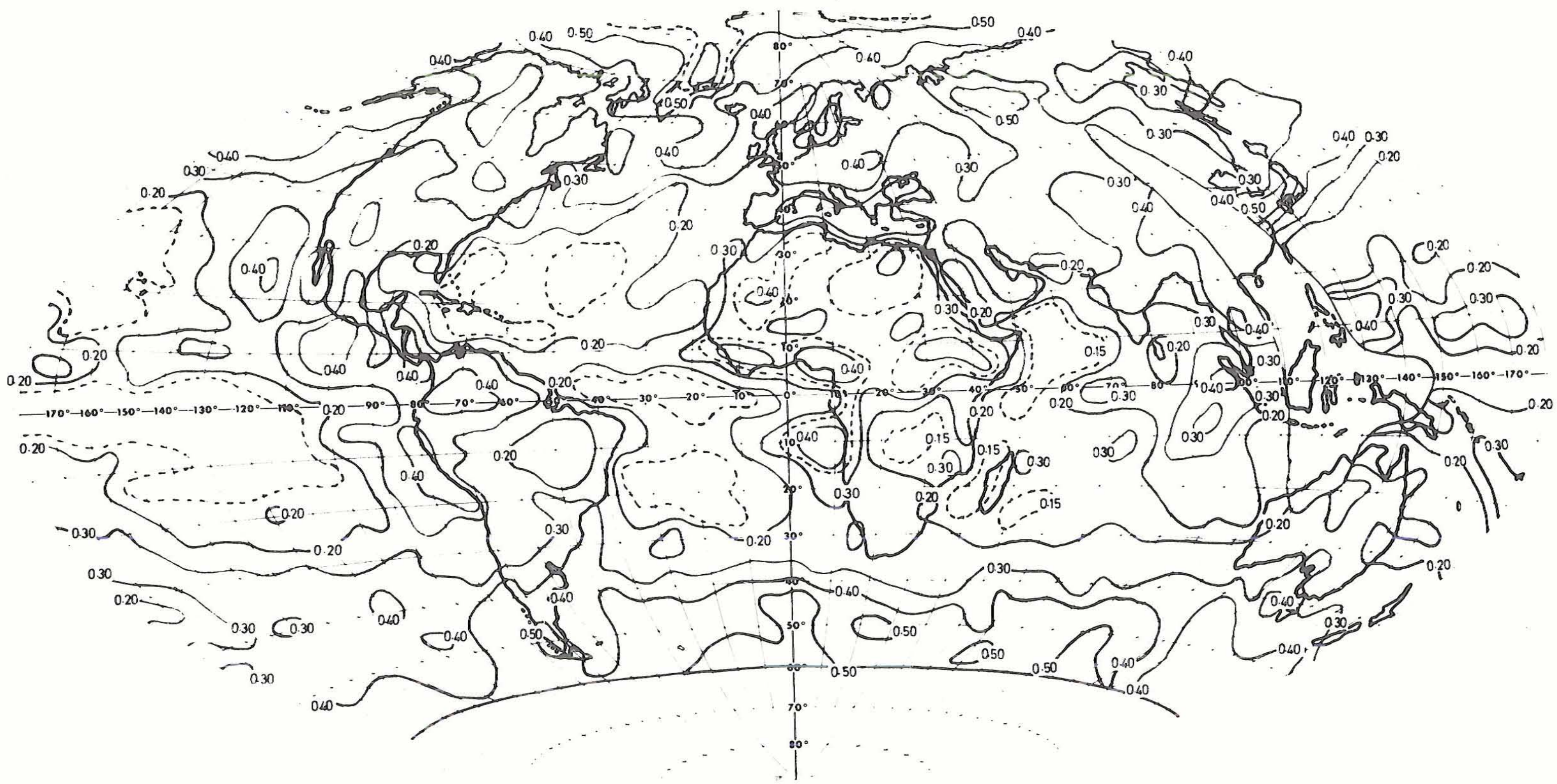


NET RADIATION (cal · cm^{-2} · min^{-1})



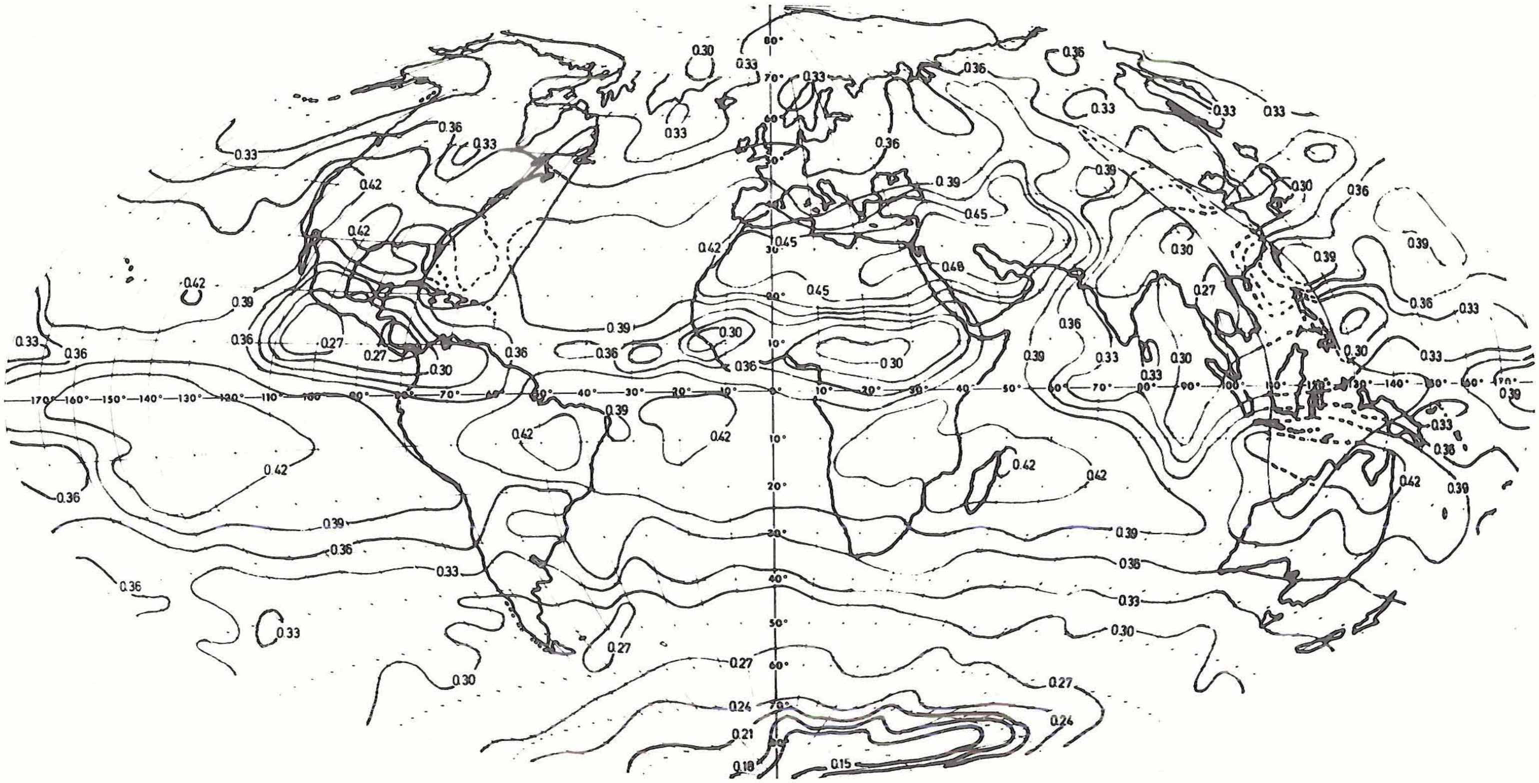
ALBEDO

NIMBUS III: 1.-15. JULY 1969



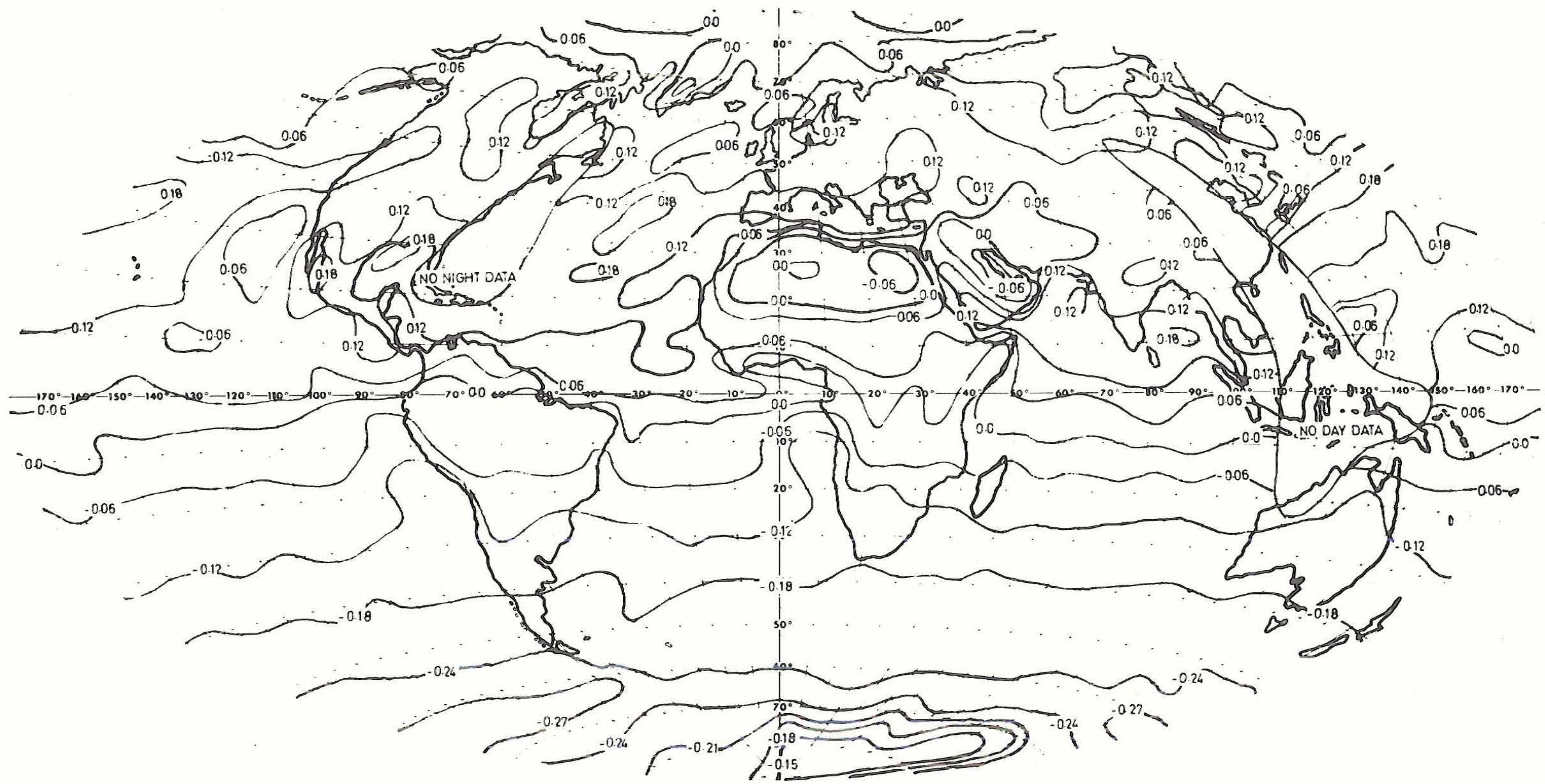
OUTGOING LONGWAVE RADIATION
(cal $cm^{-2} min^{-1}$)

NIMBUS III: 1-15. JULY 1969



RADIATION BALANCE (cal cm^{-2} min^{-1})

NIMBUS III: 1-15 JULY 1969



RANGE OF TOTAL INFRARED RADIATION MEASURED FROM SATELLITES (1963-1965)