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Radiation balance of the earth-atmosphere systems from satellite radiation measurements

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ABSTRACT. Satellite radiation measurements have given for the first time direct global measurements of the radiation balance of the earth-atmosphere system. The values of albedo, outgoing long wave radiation and the radiation balanc obtained from satellite measurements agree fairly well with ground based and airborne measurements but more extensive aircraft and balloon borne measurements are necessary to check the quality of the results, particularly the tropics.

1. Introduction

In studies of the net radiation of the earth-atmosphere system, we have to consider only two energy fluxes, the absorbed solar radiation and the re-emitted longwave radiation. The absorbed solar radiation $(S-R)$ is given by the difference between the incoming solar radiation S and the reflected shortwave radiation R, R/S being the albedo, while the radiation balance or net radiation Q is expressed as the difference between the solar radiation absorbed by the earth-atmosphere system $(S-R)$ and the outgoing radiation E,

$$Q = (S - R) - E \qquad (1)$$

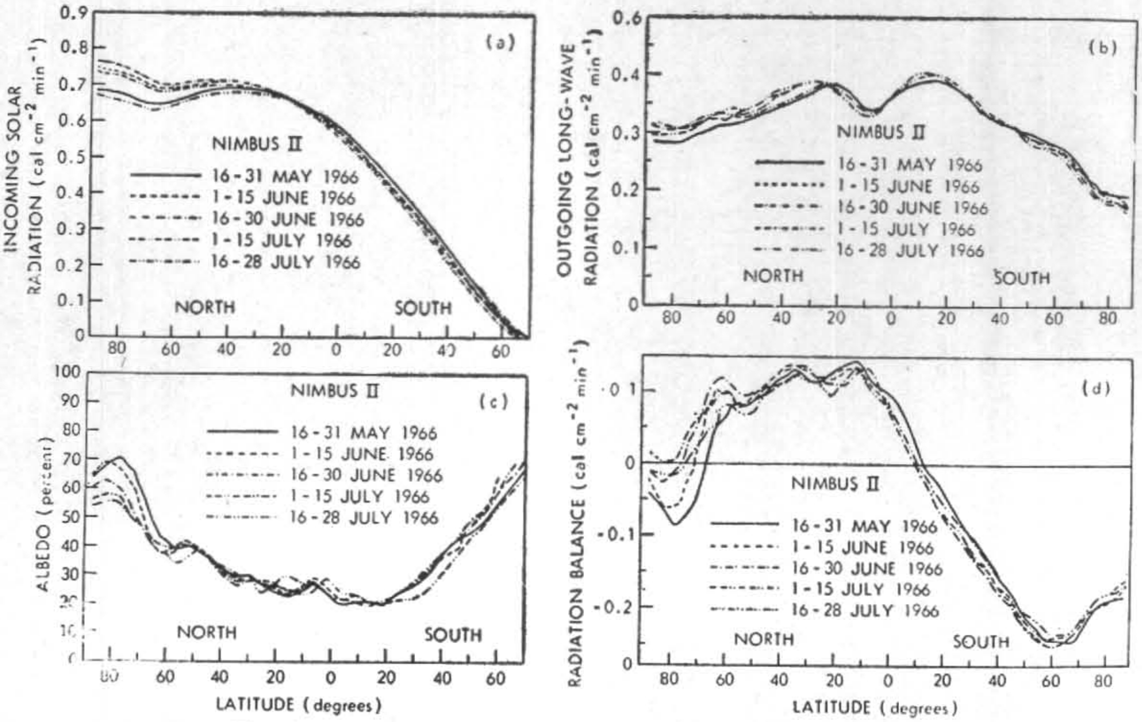
Of the shortwave radiation reaching the top of the atmosphere about 99 per cent lies within the spectral range $0\cdot2$–$4\cdot0\mu$. Shortwave radiation having wavelength less than $0\cdot3\mu$ forms only $1\cdot2$ per cent of the downward radiation and is almost completely absorbed in the atmospheric layers above 50 km above the earth's surface. Of the rest, about 60 to 70 per cent is absorbed mainly at the ground and in the troposphere, while 30 to 40 per cent is scattered and reflected from ground to space. Of the outgoing longwave radiation only about 5 per cent originates above the tropopause, the main part being emitted from the ground and the troposphere. Thus for any measurement of the radiative budget of the earth-atmosphere system we need consider only the radiation balance at a level less than 30-50 km above the surface. Changes in the net radiation at this level are closely related to all atmospheric processes below this level.

Theoretical computation of the radiation balance of the earth-atmosphere system, based mainly on climatological data, have been made for many years (London 1957). But actual measurements of all components of the radiation balance from aircraft and balloons have been made only at a few places (Kondratyev *et al.* 1960). Radiometer soundings provide experimental data but only on values of outgoing radiation in the free atmosphere (Mani *et al.* 1965). Satellite radiation measurements have given for the first time direct global measurements of the radiation balance of the earth-atmosphere system.

2. Satellite measurements of radiation balance

The first radiation experiment was flown on Explorer VIII (Weinstein and Soumi 1961) followed by those on TIROS Satellites II, III, IV and VII. TIROS VII obtained continuous data over the earth for more than a year and Bandeen *et al.* (1965) worked out a limited climatology of the spatial and temporal variations of the total outgoing longwave radiation and the planetary albedo. TIROS provided only data between 60°N and 60°S and reliable results were obtained only for outgoing longwave radiation. Results obtained of the reflected solar radiation showed large uncertainties due to post-launch degredation of instrumental response and the assumption of complete isotropic reflection characteristics of the earth-atmosphere system.

Nimbus II was the first satellite to measure the radiation balance of the entire globe. Raschke, Moller and Bandeen (1967) have calculated the outgoing longwave radiation flux, the reflected solar radiation flux and the radiation balance from the radiation measurements, after allowing for the



Figs. 1 (a-d). Zonal average of radiation at the top of the atmosphere

(a) Incoming solar radiation (b) Outgoing long-wave radiation (c) Albedo and (d) The radiation balance

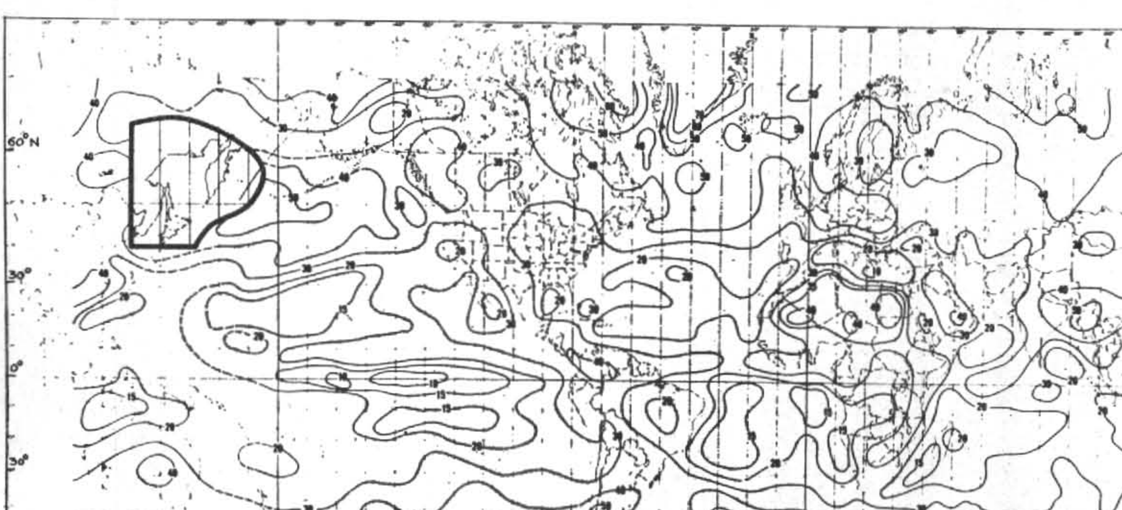


Fig. 2. Albedo of the earth-atmosphere system between 70°N and 60°S during the period 16-30 June 1966

(*After* Raschke)

anisotropic nature of the earth-atmosphere reflection characteristics. The solar constant was assumed to be $2 \cdot 0$ cal/cm^2/min.

3. Instrumentation

The radiation instruments used on meteorological satellites were wide-field low resolution radiometers and five channel scanning radiometers, sometimes referred to as medium resolution infrared radiometers. The name is, however, a misnomer since both shortwave and longwave radiation is measured by the MRIR.

The wide field radiometer carried on TIROS II, III and IV had two sensors to measure the total emitted and reflected radiation and the thermal radiation alone. The field of view was the same as that of the wide angle camera system and provided a direct measure of the heat balance of the area of the earth viewed.

The five channel radiometer has a much higher resolution and has five channels 6–$6 \cdot 5\mu$, 10–11μ $0 \cdot 2$–$4 \cdot 0\mu$, 5–30μ, and $0 \cdot 55$–$0 \cdot 75\mu$, designed to measure the water vapour, the surface and cloud top temperatures, and the earth's albedo and the total emitted thermal radiation.

The reflected solar radiation and the outgoing longwave radiation on Nimbus II were measured in the spectral bands $0 \cdot 2$–$4 \cdot 0$ and from $5 \cdot 0$–$30 \cdot 0\mu$. The field of view of the scanning was $2 \cdot 5°$ for Nimbus II enabling a spatial resolution of 50 km near the sub-satellite point. The outgoing radiation measurements were continuously controlled by on-board calibration and are accurate within ± 2 per cent. The reflected radiation measurements have no on-board calibration system and should be fairly accurate provided there was no deterioration of instrumental response after launch.

The radiometers are described in detail in the Nimbus II and III Users' Guide.

4. Radiation balance equation

The net radiation flux Q at a horizontal surface element outside the atmosphere of geographic longitude λ and altitude ϕ is the sum of the radiation fluxes crossing this surface —

$$Q(\lambda, \phi, d) = S(\lambda, \phi, d) - R(\lambda, \phi, d) - E(\lambda, \phi, d) \quad (2)$$

where, S and R are the fluxes of incoming and reflected solar radiation, and E is the emitted longwave flux; d designates the day of the year.

The derivation of Q involves considerable computational effort.

(1) Conversion of the 'filtered' radiance measured to 'unfiltered' radiance.

(2) Integration over all angles of measurement to convert beam measurements to total outgoing flux.

(3) Averaging over a 24-hour interval to obtain mutually comparable values.

Many generalized assumptions have to be made for all these conversion and integration procedures and the complex computations are described by Raschke (1968).

5. Zonal variations of albedo, outgoing longwave radiation and net radiation

The zonal averages of the incoming solar radiation, the outgoing longwave radiation, the albedo and the net radiation at the top of the atmosphere for May-July 1966 measured by Nimbus II is shown in Fig. 1 taken from Raschke's paper. Direct measurements of albedo from aircraft and of outgoing longwave radiation using radiometersondes, especially over the tropics would be extremely valuable in confirming these observations. The minima in outgoing longwave radiation over the equator and over the poles due to increased cloudiness and ice and snow cover have been observed from radiometer soundings. Longwave radiation to space is a function of temperature and cloudiness and is low over the equator and highest over the subtropics. Radiometersonde observations over India give values of the same order, $0 \cdot 30$–$0 \cdot 35$ cal/cm^2/min when cloudy, $0 \cdot 22$ when overcast and $0 \cdot 40$ cal/cm^2/min when clear (Mani *et al.* 1965).

6. Geographical distribution

The geographical distributions of the albedo, outgoing longwave radiation and net radiation are shown in Figs. 2, 3 and 4 taken from Raschke's paper.

6·1 *Albedo* — The geographical distribution of albedo for the period 16-30 June 1966 (Fig. 2) shows that albedos of more than 55 per cent are observed over snow-covered surfaces and over the poles. Towards the equator the albedo decreases rapidly with decreasing cloudiness, showing minima of less than 20 per cent over the subtropical oceans on both sides of the equator. High cloudiness, especially over Central Africa and the monsoon regions of Southeast and South Asia result in albedos of more than 20-30 per cent and 40 per cent respectively. The Sahara and Arabian deserts have albedos of more than 30-35 per cent. South of 30 °S, the albedo increases nearly zonally towards 60°S because of the increasing cloud cover and descreasing sun elevation.

6.2. *Outgoing longwave radiation* — The pattern of the outgoing longwave radiation (Fig. 3) is closely

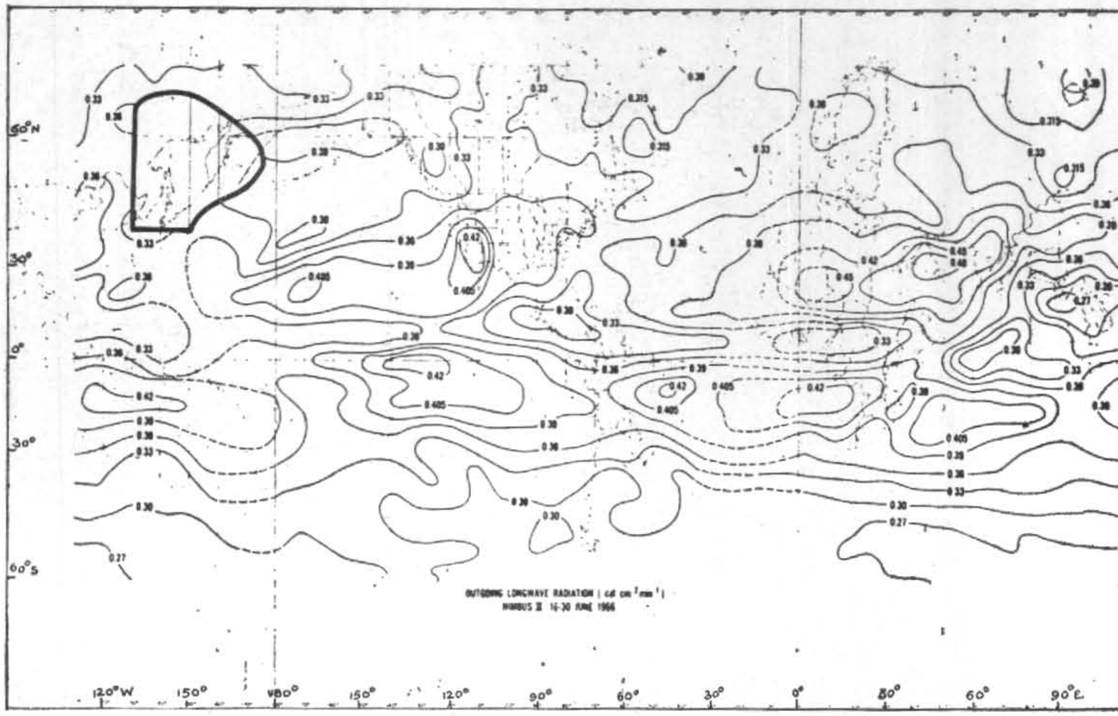


Fig. 3. Outgoing long wave radiation flux at the top of the atmosphere between 70° N and 60°S during the period 16-30 June 1966

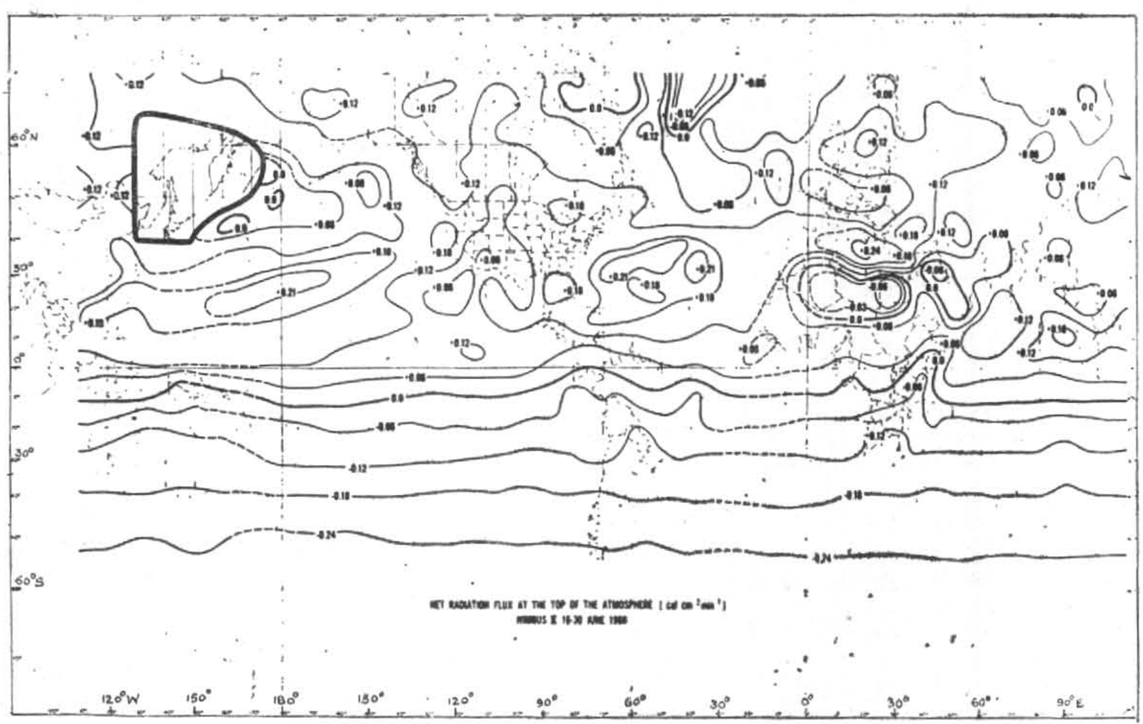


Fig. 4. Radiation balance of the earth-atmosphere system between 70° N and 60° S during the period 16-30 June 1966 (*After* Raschke)

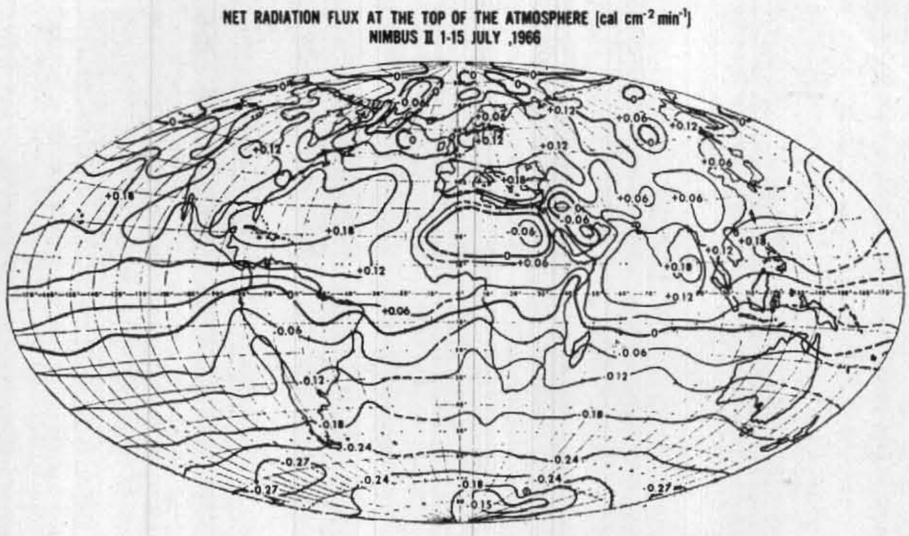


Fig. 5. Radiation balance of the earth-atmosphere system over the entire earth
The deficit over Greenland exceeds 0·12 cal/cm²/min
(*after* Raschke *et al.*)

correlated to the temperature of the underlying surfaces. At low latitudes, over cloudly areas the values are as low as 0·36 cal/cm²/min associated with cyclonic activity and the intertropical convergence zone. In the monsoon months, it is as low as 0·22 as is also seen from radiometersounding. The ITC is more pronounced in the outgoing longwave radiation than in the albedo, probably because of the large temperature difference between the high tropical cloud surfaces and the adjacent nearly cloud-free and warm subtropical ocean and land surfaces, regions of very high loss of longwave radiation to space.

6.3. *Net radiation* — The map of net radiation flux at the top of the atmosphere (Fig. 4) clearly shows the major regions of gain and deficit of radiative energy during June 1968. Owing to the sun's declination during this season, the northern hemisphere south of 70°N and the southern tropics absorb more radiation then they re-emit to space. Maximum energy gain areas are over the very low reflecting northern subtropical oceans. In contrast to these the large desert areas of North Africa and Arabia (both are highly reflecting and highly emitting areas) have only a small radiation surplus or even a small deficit. This was already predicted by Budyko (1963) and indicated in an earlier study of the net radiation of the Indian Ocean and its environments (Mani *et al.* 1967).

In all three maps the isolines over the southern hemisphere are almost zonal by latitude, because of the preponderance of the oceans in the southern hemisphere. This is particularly pronounced in the net radiation map, because the meridional gradient of incoming solar radiation is very strong over the southern hemisphere during this season. Over the northern hemisphere, the wide continental surfaces dissolve the zones in several maxima and minima.

Fig. 5 shows the radiation balance of the whole earth-atmosphere system, in July 1966 taken from Raschke *et al.*'s paper. There is an energy surplus at this time of absorbed solar radiation over emitted longwave radiation everywhere north of 10°S. Maxima of energy occur over the relatively cloudless northern subtropical ocean and a deficit over North African and Arabian deserts. This was again predicted by Budyko. The deficit is caused by high values of the albedo 30-40 per cent and high surface temperatures. Over the entire southern hemisphere the radiation balance is negative.

The global average values of albedo, absorbed solar, outgoing longwave and net radiation are of the order of—

Global albedo	29–30 per cent
Absorbed radiation	0·34 cal/cm²/min
Outgoing radiation	0·345 cal/cm²/min
Net radiation for July	—0·003 to 0·007 cal/cm²/min.

7. Conclusion

The global distribution of the albedo, the outgoing longwave radiation and the radiation balances has been obtained for the first time from meteorological satellite observations. They agree fairly well with ground-based and air-borne measurements of the same parameters. But more extensive aircraft and balloon-borne measurements, especially over the tropics are necessary to check the quality of the results obtained and confirm the satellite measurements of the various components of the radiation balance.

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