Some Geographical Variations of Terrestrial Radiation Measured by TIROS II

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ABSTRACT

Infrared radiation observations made by TIROS II during 27 days between 26 November 1960 and 6 January 1961 are used to obtain mean latitudinal profiles of outgoing long-wave radiation. The mean profiles revealed an insufficient estimate of limb darkening in the data. Consequently, only subsatellite observations are used to obtain mean latitudinal profiles for oceanic and continental areas. The distinct differences which are noted between the land and ocean profiles are discussed. Finally, the means obtained from the TIROS II data are found to agree well with estimates of the terrestrial radiation based on theoretical considerations and indirect quantitative estimates.

1. Introduction

Radiation data obtained from artificial earth satellites have provided the first direct measurements of the infrared radiation emitted from the earth. Such measurements will play an essential role in obtaining an accurate heat budget of the earth and will eventually provide a firmer basis for an understanding of the atmospheric circulation. In this study, mean meridional profiles of the outgoing long-wave radiation have been prepared for continental and oceanic areas from a 27 day sample of data obtained from the TIROS II satellite.

Prior to the advent of the meteorological satellite, knowledge of the outgoing terrestrial radiation was based primarily on theoretical considerations and indirect quantitative evaluations. For example, average seasonal values or meridional profiles have been computed by Simpson (1929), Baur and Philipps (1934, 1935), Lettau (1954), Houghton (1954), London (1957) and Davis (1963). The possibility of estimating the infrared flux from satellites has been discussed by Suomi (1958), and an analysis of the infrared radiation measurements made by Explorer VII has revealed large-scale radiation patterns associated with weather systems (Suomi and Weinstein, 1961). Recently, Winston and Rao (1962) related large-scale temporal variations in long-wave radiation as measured by TIROS II to temporal variations in kinetic energy and available potential energy.

2. Basic data

The data used in this study were extracted from 27 days of infrared radiation measurements made by the channel 4 radiometer aboard TIROS II during the period 26 November 1960 to 6 January 1961. (The other days in this period were not used because of large nadir angles.) Daily composite radiation maps of the channel 4 data were prepared by the Meteorological Satellite Laboratory of the United States Weather Bureau for the 27 days. The radiation maps, printed on a Mercator projection with a scale of 1:20,000,000, encompassed an area extending from 50N to 50S for all longitudes except for two regions—a portion of central Asia, and the high latitude region of South America with the adjacent southeastern Pacific and southwestern Atlantic Oceans.

Channel 4 of the TIROS II scanning radiometer measured radiation in the 7.2 to 32.6 micron region. With corrections made for the non-flatness response of the filters, these measurements essentially represent the total radiation emitted from the earth-atmosphere system. The radiometer was shielded by a cone which permitted the sensor a 5° angle of view. When pointing directly downward the cone subtended an area on the earth's surface of approximately 60 km in diameter. The radiometer had two views—one through the floor of the satellite at an angle of 45° to the spin axis and another through the wall of the satellite in an opposite direction. Thus, as the satellite rotated about its axis, one view swept across the earth while the other was directed toward space. In a single sweep the sensor scanned the earth with angles of view ranging from glancing to directly below. [For a more detailed discussion of the TIROS II radiometer see *TIROS II Radiation Data User's Manual* (1961).]

From the signal obtained during each sweep of the sensor, a number of discrete values were read. Average areal values were obtained by dividing the map into small areas, each equivalent to a $2\frac{1}{2}$ deg latitude square at the equator, and averaging the discrete values within each square. These averages were then used by the Meteorological Satellite Laboratory in preparation of contour maps of infrared radiation for each of the 27 days. Maps portraying the number of observations used in obtaining each average were also prepared. In general, sweeps near the horizon provided fewer observations than those which more closely followed the subsatellite path. In this study, only those averages which were obtained from 10 or more observations were used. These averages cover areas which lie within regions delineated by nadir angles of less than 56 deg. By using only these data, some of the difficulties which arise from the use of peripheral data were lessened. However, as will be shown in the next section, somewhat different results were obtained when the data were even more restricted.

3. Limb darkening effects

A mean meridional profile of outgoing long-wave radiation was computed from radiation values read from the maps. A total of 7,269 values were obtained, and means computed for each 5 deg of latitude from 50N to 50S. These means, together with the number of cases for each parallel, are presented graphically as curve B (and numerically at the top) in Fig. 1. As would be expected, the meridional profile described by curve B shows a general M-shape, with maximum values of outgoing radiation over the warm and relatively cloudless subtropics. Over the warm but cloudier tropics, and also over the cooler and cloudier areas at higher latitudes, the outgoing radiation is less.

The latitudinal means represented by curve B are lower than infrared means obtained from the radiometer aboard Explorer VII (personal communication from Mr. F. B. House, Univ. of Wisconsin) and from balloon-borne radiometers (Sabatini, 1962). This difference could result from an insufficient limb darkening estimation in the TIROS II data. With a scanning radiometer such as that used on TIROS II, observations made when the radiometer is scanning the horizon tend to be lower than those made directly below the satellite—i.e., there is limb darkening. An estimation of darkening, dependent only on the nadir angle, was added to the radiation values by the Meteorological Satellite Laboratory before the radiation maps were prepared. However, the actual limb darkening is dependent on the characteristics of the air mass through which the radiometer scans.

To test whether the limb darkening estimation used for TIROS II was sufficient, a reduced data sample consisting of only subsatellite observations was extracted from the original sample. These observations were made at nadir angles of less than 26 deg. This is a considerably more stringent restriction than the 56 deg limit when all data from regions of 10 or more observations are used. The means derived from the subsatellite data average about 3 per cent higher than those shown in curve B, indicating that, in general, the limb darkening estimation was not sufficient. However, it should be noted that even the means obtained from TIROS II subsatellite data are lower than those obtained from Explorer VII. This suggests that there exist calibration

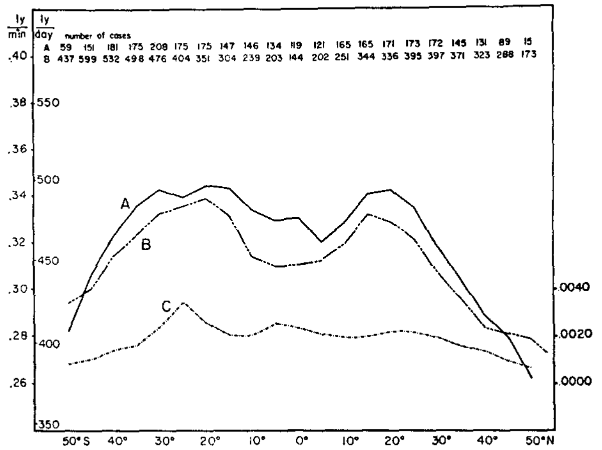

FIG. 1. Average latitudinal values of outgoing longwave radiation at 5 deg-latitude intervals from TIROS II. Curve A: means computed from subsatellite data. Curve B: means computed from areas having 10 or more observations. Curve C, variance of subsatellite values with units of ly^2 min^{-2} plotted on the right.

differences in the two instruments as well as limb darkening effects.

Curves A and B of Fig. 1 show that the apparent limb darkening may vary with latitude. Between 5N and 10S the difference in means exceeds 6 per cent, indicating that the limb darkening estimation was insufficient. Poleward of 45 deg there is a reversal and the subsatellite means are about 3 per cent lower than the curve B data, indicating that the limb darkening was overestimated at high latitudes. However, this overestimation may not be important because of the very limited number of cases at high latitudes. The variation with latitude apparently reflects the dependence of limb darkening on the presence of clouds and water vapor at high levels.

Using infrared estimates from selected stations for both clear and overcast conditions, Wark *et al.* (1962) found that high humidity aloft is an important factor in producing limb darkening. However, these authors point out that the presence of scattered clouds produces greater limb darkening than occurs with either clear or overcast conditions. Furthermore, the work of Wark *et al.* (1962) was based on the assumption of a uniform horizontal distribution of infrared emitters. If there are horizontal variations in the height of cloud tops or in the water vapor content, the limb darkening effect will also be increased. Thus, it seems that the relatively large difference in curves A and B between latitude 5N and 10S is the result of the presence of a greater amount of scattered and thin clouds at high levels over these latitudes. The relatively high moisture content at high levels over equatorial regions also contributes to this difference. Using data from the 5.6- to 5.7-micron channel on TIROS III, Nordberg *et al.* (1961) found a large increase in water vapor at high levels when the satellite passed from the subtropics to the equatorial region of Africa.

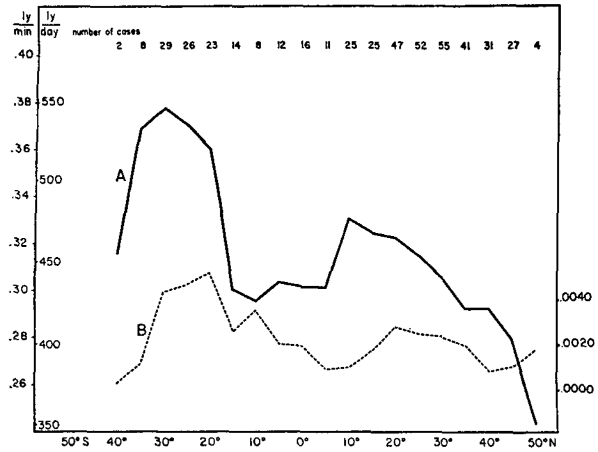

FIG. 2. Curve A: average latitudinal values of outgoing long-wave radiation for land areas. Curve B: variance with units of $ly^2\ min^{-2}$ plotted on the right.

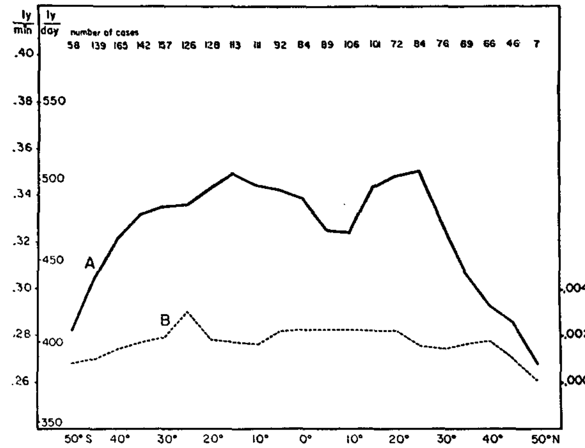

FIG. 3. Curve A: average latitudinal values of outgoing long-wave radiation for oceanic areas. Curve B; variance with units of $ly^2\ min^{-2}$ plotted on the right.

Thus the data sample presented in Fig. 1 suggests the desirability of using an empirically determined limb darkening estimate which varies with latitude. Equatorward of 45 deg the estimates should be larger than those used in modifying the TIROS II data. Poleward of 45 deg the data indicate that the estimate should be less, although here it is difficult to draw conclusions concerning the nature of the limb darkening estimation since the data are limited and extend only to 50 deg.

4. Mean profiles of infrared radiation

Because of the greater reliability of the subsatellite data, the discussion of the meridional profiles will concentrate on those derived from subsatellite data. Although curve A of Fig. 1 has the same general shape as curve B, the reduced limb darkening of the subsatellite data produces a somewhat flatter minimum over equatorial regions.

The subtropical maxima presented by curve A exceed 480 ly day^{-1} between 15N and 25N and between 10S and 35S. The greater latitudinal extent of the zone of maximum terrestrial radiation south of the equator is probably due to greater solar heating in the Southern Hemisphere during the data period (Nov.–Jan.). The high values over the subtropics and the low values over the equatorial region are the result of the distribution of water vapor and clouds in these latitudes. In the subtropics fewer clouds and lower water vapor content are the significant factors which allow a high outward flux of radiation. In the equatorial regions a strong depletion of infrared flux by extensive cirrus layers and a higher water vapor content result in the lower values of outward flux (London, 1957; Sabatini, 1962). The decrease of terrestrial radiation poleward from the subtropics is consistent with the poleward decrease in the heating of the earth by solar radiation and by the increased cloudiness associated with middle latitude cyclones.

Figs. 2 and 3 present the meridional profiles that were obtained by partitioning the subsatellite data (nadir angles less than 26 deg) into continental and oceanic observations. As in Fig. 1, the number of observations used to obtain each latitudinal mean are indicated at the top of the figures. In both cases the radiation profiles reflect the climatic patterns of land and ocean areas.

The profile for land cases (Fig. 2) shows a minimum of long-wave radiation between 5N and 15S while the oceanic profile (Fig. 3) shows a minimum between 5N and 10N. The relative southward displacement of the radiation minimum over the continents is most likely produced by the cloudiness associated with the intertropical convergence zone. This zone assumes a more southerly position over the continents than over the oceans during the Southern Hemisphere summer, and the latitudes of minimum long-wave radiation agree very well with the mean position of the intertropical convergence zone for December as presented by Trewartha (1961). Over Africa the intertropical convergence zone migrates southward to about 15S during the southern summer, while over the Eastern Pacific it is located near 5N. These latitudinal differences are clearly reflected in the meridional profiles for land and ocean areas.

Another difference between the profiles for land and ocean is noted in the subtropics. Here the radiation flux over the oceans reaches a value of about 500 ly day^{-1} in both hemispheres, while the maximum values for subtropical land areas are 540 ly day^{-1} in the summer hemisphere and only about 475 ly day^{-1} in the winter hemisphere. Since the subtropics of both hemispheres are relatively cloudless and dry, the outgoing radiation of these areas is significantly influenced by the surface temperatures. The uniform flux from the oceanic areas of both hemispheres reflects the relatively uniform ocean temperatures, while the lower values over the subtropical land areas of the winter hemisphere compared with those of the summer hemisphere point up the stronger seasonal variation of land temperatures. The fact that over land areas the maximum in the summer hemisphere occurs at 30S while in the winter hemisphere it occurs at 10N is likely related to the southward displacement of the subtropical highs and the intertropical convergence zone during the data period.

The variances for the subsatellite data are shown as dashed curves in Figs. 1 to 3. In general the variances over the land areas show more variation with latitude than do those over oceanic areas. The greater variances over the Southern Hemisphere land areas probably result from the pronounced contrasts in outward flux of radiation which exist between the warm daytime land surfaces of clear areas and the cold radiation temperatures associated with high clouds. For a large part of this data, daylight observations were from the Southern Hemisphere, and nighttime observations were from the Northern Hemisphere. This factor, together with the high soil temperatures associated with the longer daylight hours in the Southern Hemisphere, are significant in contributing to the contrast of outward flux between clear areas and cloudy areas. The lower variances over the equatorial land areas indicate a more uniform cloud cover and water vapor distribution over this region.

5. Comparison with other studies

Although the data sample used here was for only 27 days, the mean outgoing long-wave radiation computations compared favorably with those based on indirect quantitative estimates. In a heat budget study for the Northern Hemisphere, London (1957) calculated latitudinal averages for winter (Dec., Jan., Feb.) which were within 3 per cent of the averages calculated here. Houghton (1954) used mean soundings and the Elsasser chart, and obtained a value of 485 ly day^{-1} for the annual mean of outgoing radiation between 0 deg and 50N. This compares well with the 465 ly day^{-1} obtained by averaging the Northern and Southern Hemisphere data from TIROS II. Other studies (Baur and Philipps, 1934, 1935; Simpson, 1929) do not agree as closely. Differences in the estimation of cloud cover appear to be the most important factor in the disparity of the outgoing radiation means.

Although the curve B data was lower than the balloon-borne radiometer measurements, the curve A data (nadir angles less than 26 deg) were consistent with the radiometer measurements. From 170 wintertime radiometersonde ascents made at seven United States stations, Sabatini (1962) obtained a mean net flux of 0.29 ly min^{-1} at 30 mb. The radiometersonde values at this level should be nearly the same as those existing at the top of the atmosphere. The TIROS II data also gave a mean of 0.29 ly min^{-1} for land observations at 40N, which was the mean latitude of the seven radiometersonde stations. The exact correspondence of the means is encouraging even though the data samples are relatively small.

The computation of a mean albedo from the TIROS II data provides an interesting comparison with other estimates. The solar constant was taken as 2.01 ly min^{-1} for December and the incoming radiation was assumed to balance the outgoing radiation for this period. The amount of reflected radiation was then estimated from the difference between incoming solar radiation and the measured outgoing terrestrial radiation (*Smithsonian Meteorological Tables*, 1958). Since TIROS II measurements only covered the area between 50N and 50S, it was necessary to estimate the infrared radiation at higher latitudes. This was done by using London's values (1957) to extrapolate the means to the poles. The resulting global average of 0.311 ly min^{-1} corresponds to an albedo of 0.38. This is higher than the generally accepted value of 0.34 and is also higher than a value of 0.33 which F. B. House and W. Shen (personal communication, Univ. of Wisconsin) calculated from Explorer VII data. Because of the very limited sample of data employed in this study these differences are not surprising. Furthermore, significant temporal variations in albedo on a planetary scale may exist. Nordberg *et al.* (1962) and Takasugi (1962), for example, have found large variations of the albedo in preliminary studies of localized regions. More satellite observations will have to be made over extensive areas before any firmer conclusion can be drawn, however.

6. Conclusions

The direct measurements of infrared radiation by TIROS II agree quite well with previously obtained indirect calculations. The data do suggest, however, that a latitudinally varying correction for limb darkening is desirable.

The consistency of the radiation data with respect to geographical and climatological features indicates that the date will be of value in obtaining a better understanding of the planetary controls of the general circulation. Future studies employing more extensive satellite data should provide a better estimation of the spatial and temporal variations of outgoing radiation.

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REFERENCES

Baur, F., and H. Philipps, 1934: Der Wärmehaushalt der Lufthülle der Nordhalbkugel. *Beitr. Geophysik*, **42**, 160–207; 1935, **45**, 82–132.

Davis, P. A., 1963: An analysis of the atmospheric heat budget. *J. atmos. Sci.*, **20**, 5–22.

Houghton, H. G., 1954: On the annual heat balance of the northern hemisphere. *J. Meteor.*, **11**, 1–9.

Lettau, H., 1954: A study of the mass, momentum, and energy budget of the atmosphere. *Arch. Meteor. Geophys. Bioklim.*, Ser. A, 7, 133–137.

List, R. J., 1958: *Smithsonian meteorological tables.* Washington, D. C., Smithsonian Institution, 527 pp.

London, J., 1957: A study of the atmospheric heat balance. Final Report, Contract AF 19 (122)-165, Research Division, College of Engineering, New York University, 99 pp. (Available from OTS, no. PB 129551. mf. $5.70, ph $16.80.)

Nordberg, W., W. R. Bandeen, B. J. Conrath, V. Kunde and I. Persano, 1962: Preliminary results of radiation measurements from the TIROS III meteorological satellite. *J. atmos. Sci.*, **19**, 20–29.

Sabatini, R. R., 1962: Wintertime atmospheric infrared cooling over the Caribbean and the United States. Master's thesis, University of Wisconsin. (Available at Memorial Library, University of Wisconsin, mf. $2.00.)

Simpson, G. C., 1921: The distribution of terrestrial radiation. *Mem. Roy. meteor. Soc.*, **3**, 53–78.

Staff Members, 1961: *TIROS II radiation data user's manual.* Greenbelt, Md., Goddard Space Flight Center, 57 pp.

——, 1961: *TIROS II radiation data user's manual supplement.* Greenbelt, Md., Goddard Space Flight Center, 13 pp.

Suomi, V. E., 1958: The radiation balance of the earth from a satellite. *Ann. Internat. Geophys. Year*, **6**, 331–340.

Takasugi, S., 1962: Methods of albedo determination from Explorer VII satellite radiation data. Master's thesis, University of Wisconsin. (Available at Memorial Library, University of Wisconsin, mf. $2.00.)

Trewartha, G. T., 1961: *The earth's problem climates.* Madison, University of Wisconsin Press, 334 pp.

Wark, D. Q., G. Yamamoto and J. H. Lienesch, 1962: Methods of estimating infrared flux and surface temperature from meteorological satellites. *J. atmos. Sci.*, **19**, 369–384.

Weinstein, M., and V. E. Suomi, 1961: Analysis of satellite infrared radiation measurements on a synoptic scale. *Mon. Wea. Rev.*, **89**, 419–428.

Winston, J. S., and K. Rao, 1962: Preliminary study of planetary-scale outgoing long-wave radiation as derived from TIROS II measurements. *Mon. Wea. Rev.*, **90**, 307–310.