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Distribution of global and net solar radiation over the Indian Ocean

A. MANI, O. CHACKO, V. DESIKAN and V. KRISHNAMURTHY

Meteorological Office, Poona

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ABSTRACT. Annual and monthly maps showing the distribution of global solar and net solar radiation over the Indian Ocean and its adjoining land areas have been prepared from available observations, supplemented by calculations based on observations of albedo, duration of sunshine and cloudiness. The annual distribution of global solar radiation shows minima over the equatorial belts and the monsoon regions and maxima over the sub-tropical high pressure areas. The geographical distribution is mainly zonal except in the low latitudes, where areas of higher or lower radiation are distributed according to regions of higher or lower amounts of cloudiness.

The net solar radiation is naturally smaller than global radiation but its distribution pattern is very similar to that of global radiation, with maxima along the subtropics and minima along the equator. The major differences arising from the different values of surface albedo over land and sea, are the location of maxima over sea in the subtropics, with the highest values in north Arabian Sea, and breaks in the isolines between sea and land.

Over the Indian Ocean itself, the latitudinal variation of both global and net solar radiation is small during the southern summer but large during the northern summer. The pattern shifts with the movement of the sun, the most prominent feature being the distortion of the basic distribution pattern during the monsoon season over India and southeast Asia, during the northern summer.

1. Introduction

Global solar radiation, or the downward flux of shortwave radiation from sun and sky on a horizontal surface, is the principal component of the radiation balance and the most important, determining as it does the amount of solar energy received by a unit area of the earth's surface and used later by various natural processes originating near the surface.

It is also the most commonly measured component of the radiation balance. Maps depicting the spatial distribution of global solar radiation over various land areas, have been prepared on the basis of observations and estimates, by Fritz and MacDonald (1949), Mateer (1955), Berliand and Efimova (1955), Drummond and Vowinckel (1957) and Mani, Swaminathan and Venkiteshwaran (1962). Ramdas and Yegnanarayanan (1956) and Ramdas (1961) have given estimates of global solar radiation for various stations in India based on duration of sunshine data. World-wide radiation charts showing the geographical distribution of the downward flux of solar radiation have been prepared by Budyko (1956), Black (1956), Landsberg (1961), and recently by Ashbel (1961) and Schulze (1963), who have summarised IGY measurements of global solar radiation in a series of maps of the monthly and annual mean values. Robinson (1964) has also critically reviewed the mean values of global solar radiation obtained during the IGY and IGC on a global scale. All these maps, however, show little or no detail over the Indian Ocean and its adjacent areas. Global solar radiation maps for the world contained in Budyko's Atlas of Heat Balance (1963), based partly on direct observations and partly on the application of empirical formulae to sunshine duration and cloudiness data, remain the most exhaustive published so far.

One of the meteorological objectives of the International Indian Ocean Expedition was to obtain a better understanding of the energy exchange between the sea and the atmosphere and of energy transport and transformation in the atmosphere over the oceans. For this, it was necessary to have extended measurements of the energy input, *i.e.*, separate measurements or critical estimates of the upward and downward fluxes of shortwave and longwave radiation over the whole Indian Ocean, both at the earth's surface and in the atmosphere. All nations taking part in the IIOE had programmes large or small, for the measurement of one or more components of the net radiation. India had 14 stations for measurement of shortwave and longwave radiation. The University of Michigan organized a network of 13 coastal and island stations in the Indian Ocean for the measurement of global solar radiation and total radiation. Some of the oceanographic ships taking part in the IIOE also made global radiation measurements over the sea. The first such observation had been made by Albrecht (1952) in 1949, during a voyage through the Indian Ocean. Despite the co-ordinated effort of many nations which took part in the IIOE the data actually obtained were too meagre for any climatological studies.

This should have been anticipated from the sheer magnitude of the problem itself and the difficulty of making reliable, accurate, large-scale observations over the oceans. Even on land, measurements of all components of the radiation balance are not easy. Fairly precise instruments for the continuous measurement of global solar radiation were, however, available and values of global solar radiation were recorded regularly at 111 stations in and around the Indian Ocean before and during the IIOE. Although most of the stations were located on the mainland and the distribution over the whole region very uneven, in view of the vital importance of radiation data in meteorological investigations, an attempt has been made to prepare annual and monthly maps, showing the geographical distribution of shortwave radiation over the Indian Ocean region. A critical evaluation of the available data on shortwave radiation over the Indian Ocean and its adjacent areas has been made, and where such data are not available, estimates have been made from sunshine and cloudiness data using empirical relationships. Annual and monthly maps showing the geographical distribution of global solar and net solar radiation over the Indian Ocean and its adjoining continents have been prepared and are presented.

2. Data used

For Indian stations, mean monthly and annual values were taken from regular radiation measurements made during 1957–1965. For other stations in the area, global radiation data were taken from the IGY/IGC Radiation Data (WMO 1962) and the Actinometric Reference Book (Berliand 1964). IIOE data from the Michigan University radiation stations at six island and coastal stations in the Indian Ocean were made available through the courtesy of Prof. Donald J. Portman.

3. Computation of global radiation

Wherever actual observations were not available, estimates were made using empirical formulae correlating global radiation, duration of sunshine and cloudiness. The methods have their limitations since they do not consider changes in the transparency of the atmosphere and of the heights and types of clouds.

At stations, where duration of sunshine data was available, values of global radiation were calculated using Ångström's well-known formula—

$$T = T_0\ [k_1 + (1-k_1) S] \qquad (1)$$

in which T_0 is the global radiation with clear skies, S is the ratio of observed sunshine hours to the given period, and k_1 is a constant determining the portion of the possible radiation which consists of actual radiation with overcast sky conditions. Sunshine data were taken from IGY/IGC publications. k_1 as a first approximation was taken as 0·35. Calculation of k_1 from known values of T, T_0 and S at stations in India where these are directly measured, gave values for Indian stations varying from 0·31 to 0·41 and averaging approximately 0·35. For South African stations Drummond and Vowinckel (1957) had obtained an average value of 0·49. The application of a uniform constant value of k_1 for stations differing widely in their radiation climate cannot, however, be justified except as a first approximation. Computed values have been corrected to be commensurate with observed values at neighbouring stations and careful attention has been paid while preparing the charts to variations in latitude, altitude and cloudiness.

At 214 locations in and around the Indian Ocean, where neither radiation nor sunshine data were available, T was computed from data on cloudiness using the Ångström–Savinov formula (Budyko 1956),

$$T = T_0\ [1-(1-k_2)\ n] \qquad (2)$$

in which n is the cloud amount in tenths, and k_2 is a coefficient indicating the effect of clouds on radiation. The coefficient k_2 representing the ratio between the actual radiation under overcast conditions and the possible radiation, depends on the mean altitude of the sun, the characteristics of the clouds and the value of albedo. Thus the mean values of k_2 vary from region to region and also show annual and diurnal variations. Values of k_2 were taken from tables prepared by Berliand and given in Budyko's book on the Heat Balance of the Earth's Surface (1956).

Data on cloudiness were taken from the monthly charts of the Indian Ocean published in Germany (1960) and USA (1957) marine climatic atlases. Observations made during 28 scientific cruises of the Indian oceanographic ship INS *Kistna* during 1962–1965 have also been used, wherever available.

The measurements and computations are summarised in a series of maps of the monthly and annual values of global solar radiation T. The maps are based on actual observations of T at 111 stations and estimates of global solar radiation at 227 locations on land and sea.

4. Computation of net solar radiation

Net solar radiation Q_1 represents the shortwave energy absorbed by the earth and is the difference between the downward short wave flux $R_s\downarrow$ and the reflected solar radiation $R_s\uparrow$ is given by $T.\alpha$, where α is the surface albedo.

$$Q_1 = R_s\downarrow\ (1-\alpha) \qquad (3)$$

Budyko (1956) has given the following mean values of albedo for various underlying surfaces—

Desert	0·30
Dark soil	0·05—0·15
Moist grey soil	0·10—0·20
Dry, clay or grey soil	0·20—0·35
Dry, light sandy soil	0·25—0·45

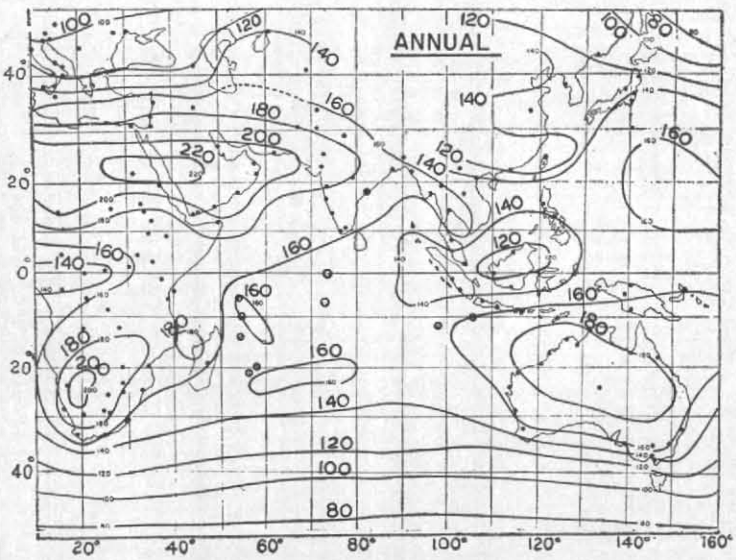

Fig. 1. Global solar radiation in kcal/cm²/year — Annual

Albedo of the desert sand is the highest for a natural surface, excluding snow and ice. Values of surface albedo change from day-to-day and during the day, being greater when the sun's altitude is low. It also varies with the cloud amount. The albedo of water surfaces is very low, compared to that of natural land surfaces. It depends on the altitude of the sun and varies from a few per cent at noon to 100 per cent with the sun near the horizon for direct solar radiation. For diffuse radiation, the albedo is fairly constant and about 8–10 per cent. The albedo for global radiation thus shows definite diurnal and annual variations.

Direct observations of albedo were available at only seven stations in the region. For the remaining locations, albedo was calculated from tables given in Budyko's Heat Balance of the Earth's Surface (1956). The procedure involves (*i*) calculation of albedo for direct radiation at a number of stations and (*ii*) assuming albedo for diffuse radiation as 0·10 and estimating the mean relationship between direct and diffuse radiation at various latitudes, calculation of α for global radiation for water surfaces. Using formula (2), annual and monthly values of Q_1 for 61 stations in the Indian Ocean area were then obtained. The data are presented in the form of maps showing the annual distribution of the net solar radiation and monthly values for four representative months, January, April, July and October.

5. Distribution of global solar radiation

5.1. *Annual* — Fig. 1 shows the annual values of global solar radiation in kilocalories/cm²/year for the region lying between 10°E to 160°E and 50°N to 50°S. Isolines are drawn every 20 kcal/cm²/year. The total shortwave radiation flux varies from 100–220 kcal/cm²/year over the region with high values of T over the sub-tropical high pressure belts of the northern and southern hemispheres and low values along the equator. Over the deserts of West Asia, Africa and Australia, the radiation received is a maximum, with yearly totals exceeding 200 kcal/cm². Extensive areas of North Africa and West Asia in the northern hemisphere receive over 200–220 kcal/cm²/year, compared to the southern hemisphere. The particular distribution of the land masses in the two hemispheres is clearly associated with the greater radiation input in the northern sub-tropics compared to that in the southern sub-tropics.

Very low amounts of global solar radiation are received over the monsoon regions of Asia and central Africa. The equatorial zone in general receives less than 140 kcal/cm² annually; and in southeast Asia, it is as low as 120 kcal/cm². There is also a rapid poleward decrease in global radiation below 140 kcal/cm² north and south of both the subtropics.

Over the major parts of the Indian Ocean, global radiation received is low and fairly constant. It is of the order 120–160 kcal/cm²/year, except over the north Arabian Sea and the sea to the northwest of Australia, where radiation received exceeds 180–200 kcal/cm².

The distribution of global radiation on the whole follows a zonal pattern, except in the low latitudes where areas of lower or higher radiation are distributed according to higher or lower amounts of

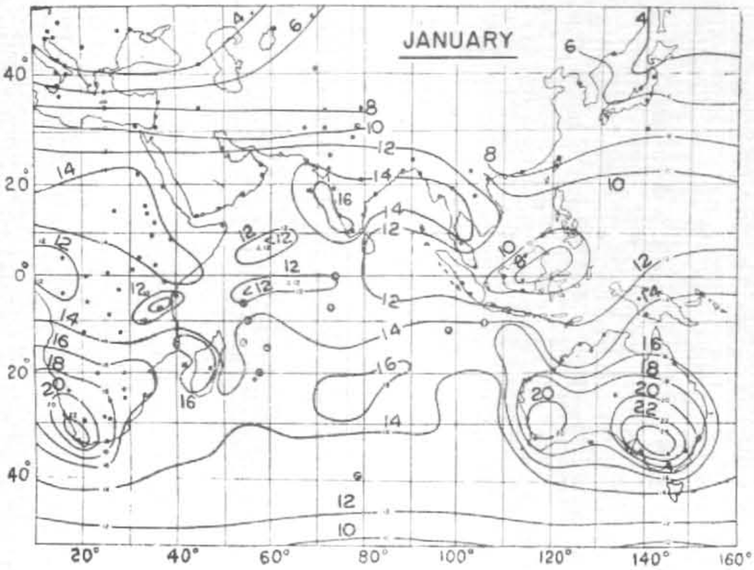

Fig. 2

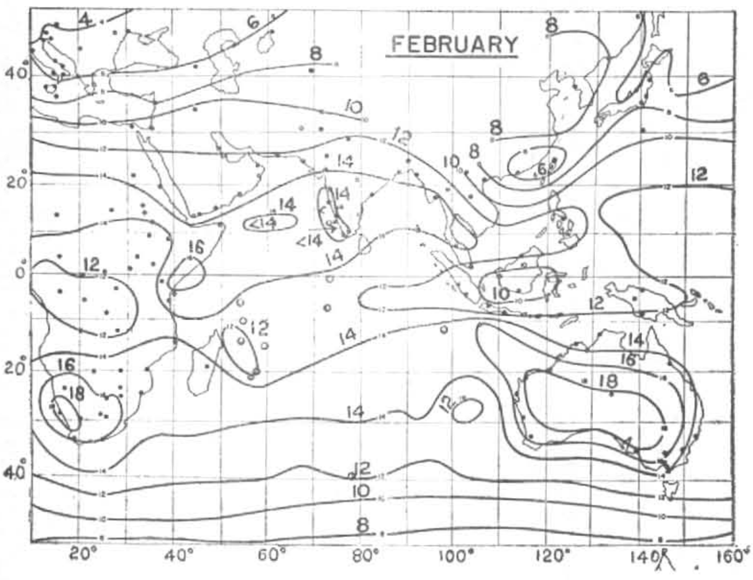

Fig. 3

Figs. 2-3. Global solar radiation in kcal/cm²/month

cloudiness. In the southern hemisphere, it increases with decreasing latitude till maxima are reached about 20°-30° S with markedly higher values over land; it decreases near the equator, increasing again with latitude northwards, reaching a maximum about 20°-25°N except over the monsoon-influenced areas of southeast Asia, and decreases again with latitude. Cloud amount is the main control of global radiation, although it is affected to a lesser extent by atmospheric aerosols (haze and dust) and by atmospheric absorption, the main variable absorber being water vapour.

5.2. *Monthly* — Figs. 2-13 show the distribution of global solar radiation during the twelve months, January to December. Isolines are drawn every 2 kcal/cm²/month. The basic annual pattern appears in all the monthly maps also, with maxima along the subtropics and minima along the equatorial belts. But their position shifts with the apparent northward and southward movements of the sun. The basic pattern is also distorted with the arrival of the monsoon in June till its withdrawal in September.

During the southern summer November to

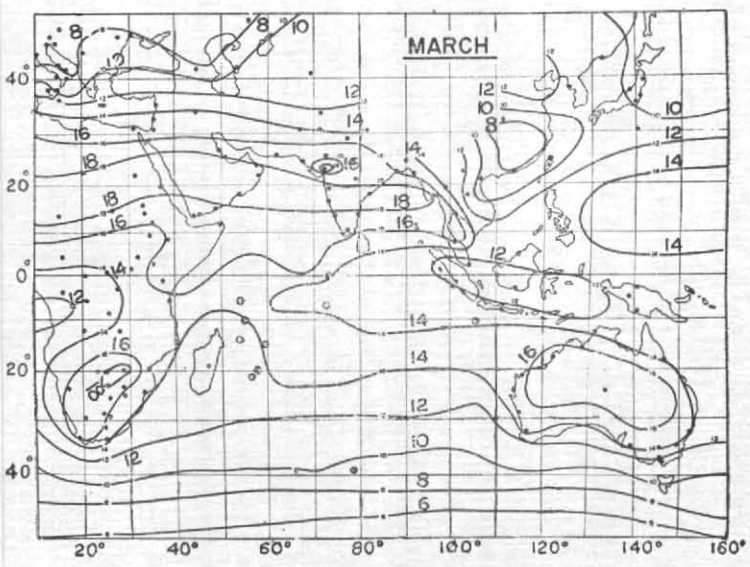

Fig. 4

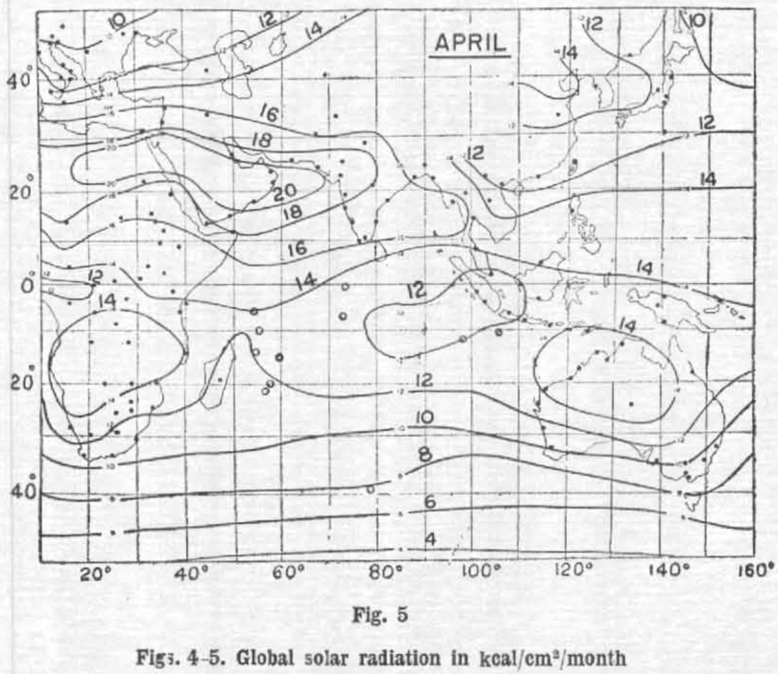

Fig. 5

Figs. 4-5. Global solar radiation in kcal/cm²/month

February, maximum values of the order of 18–24 kcal/cm²/month are received along 30°–35°S, over the deserts of South Africa and Australia. Minima occur over the low pressure areas near the equator, where clouding is large. Secondary maxima are present over land along 10°–20°N. Over the Indian Ocean itself, global radiation shows very little zonal change, being of the order of 12–14 kcal/cm². It does not decrease with increasing latitude in the southern hemisphere because of the compensating effect of the increasing length of the day in the southern latitudes.

The pattern changes gradually as the sun moves north, till in April—May, the pattern is reversed with the highest values of incoming solar radiation over the northern subtropics. Minima are again present over the equator and secondary maxima over 10°–20°S. In June the pattern abruptly changes with the arrival of the monsoon and corresponding marked minima in radiation occur in the monsoon areas along the west coast of India and southeast Asia. The increased moisture content of the air and the density of clouds also reduce the radiation amounts received in the monsoon regions.

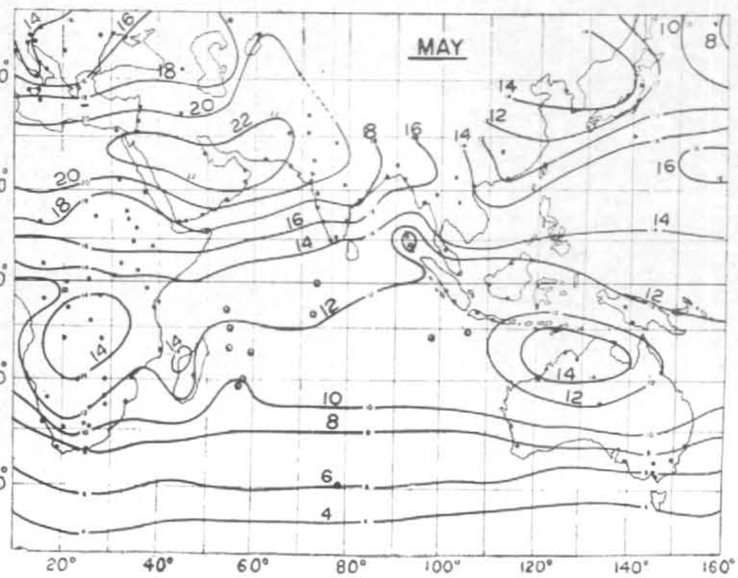

Fig. 6

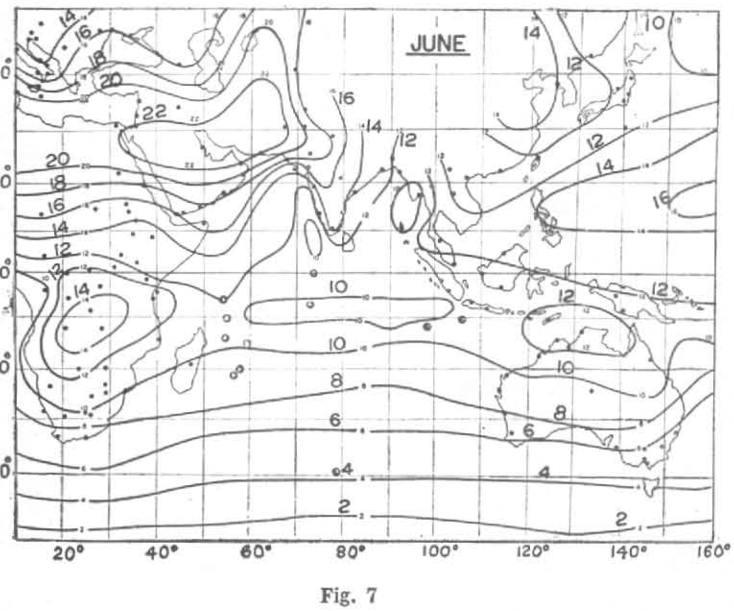

Fig. 7

Figs. 6-7. Global solar radiation in kcal/cm²/month

Over the oceans, the distribution of global solar radiation in the northern summer is quite different from that during the southern summer; radiation values range from 2–16 kcal/cm² and decrease rapidly with increasing latitude in the southern hemisphere. The gradient is particularly large in the Arabian Sea.

The distribution of global radiation during the equinoxes resemble qualitatively the annual pattern and other months have intermediate patterns of distribution between those described earlier.

5.3. *Factors affecting global solar radiation* — The major portion of the Indian ocean lies in the southern hemisphere and over the ocean, in the southern winter radiation values are low, when the solar trajectories are low and high during the southern summer when they are high. During winter there is a relatively great change from south to north, while during the southern summer there is relatively small latitudinal variation in the global solar radiation.

The over-riding controls on the spatial distribution of T are the latitudinal factor and cloud

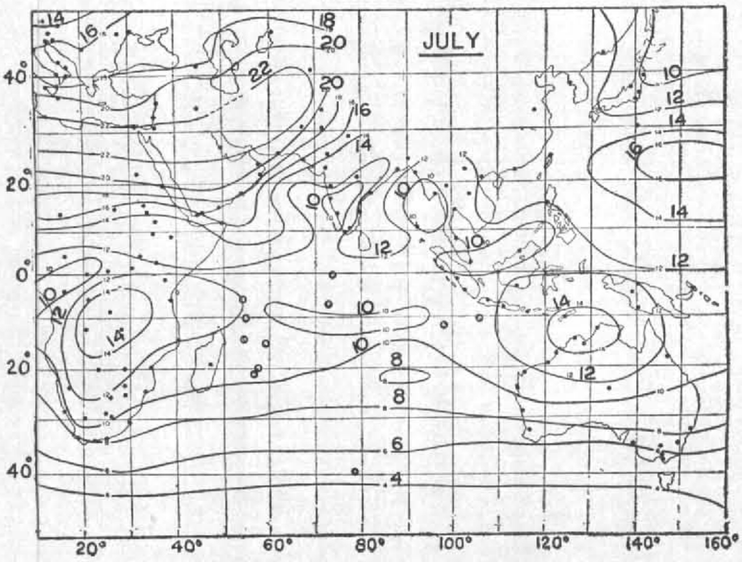

Fig. 8

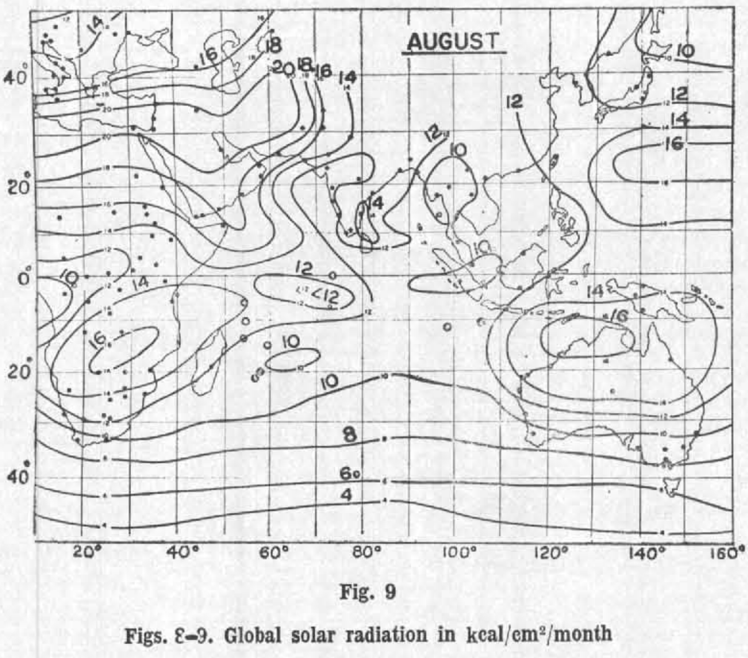

Fig. 9

Figs. 8–9. Global solar radiation in kcal/cm²/month

amount. Several factors like elevation of the land, duration of sunshine, cloud cover and type, moisture and dust content also influence the amount of global radiation received at a place. Local variations occur due to atmospheric pollution and ground reflection. Thus large local variations occur over large cities, mountainous areas and deserts, in regions having abrupt changes of snow cover and on the shores of large bodies of water. The influence of dust content is of great importance in the arid zones of the two hemispheres, as well as smoke raised by extensive grass fires in the savanna lands in south and central Africa. During the cloud-free seasons, the main agency responsible for reducing the incoming radiation is the particulate matter in suspension in the atmosphere.

6. A meridional cross-section

Fig. 14 shows the meridional variation along 73°E of global solar radiation throughout the year over the Indian Ocean between 25°N and 40°S. The three main climatic zones are the equatorial, tropical and subtropical regions. Along the equator, two maxima occur, as the sun crosses the equator

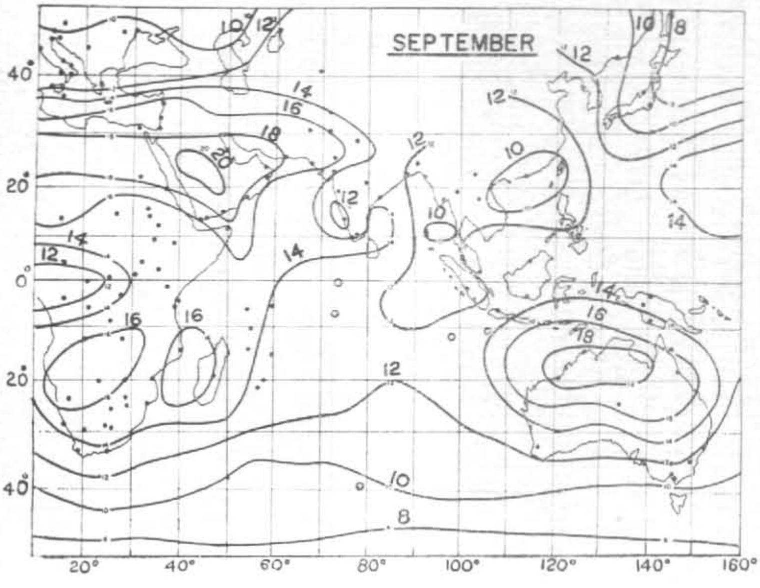

Fig. 10

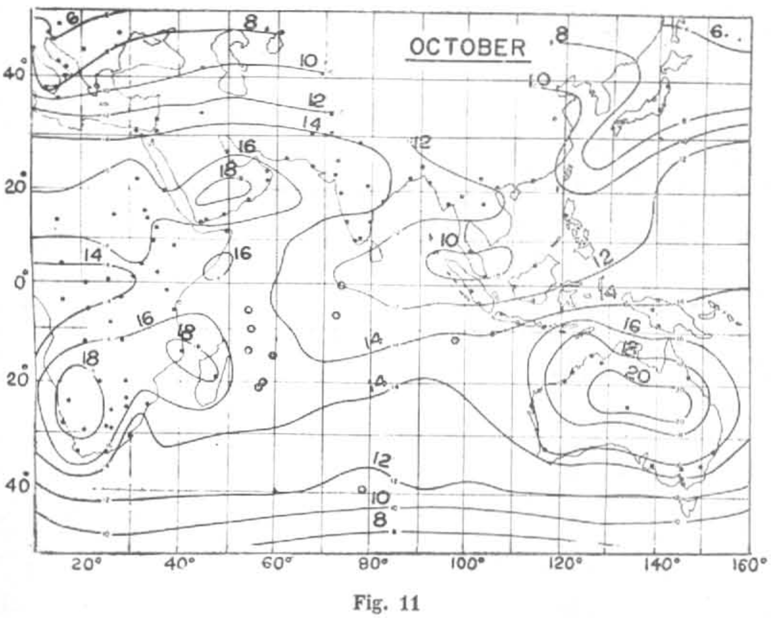

Fig. 11

Figs. 10–11. Global solar radiation in kcal/cm²/month

northwards in March and southwards again in September. Minima occur during the summer and winter solstices. The maxima are, however, not very pronounced, heavy cloud cover preventing high values being reached, during the periods of maxima. The maximum in March is only 15 kcal/cm²/month and in September only 13 kcal/cm²/month. The minimum in December 10 kcal/cm²/month is the lowest along the longitude from 25°N to 40°S.

In the tropical regimes north and south of the equator the pattern is different, with only one maximum during summer and one minimum during winter. The maximum is not very pronounced in the southern tropics, with only values of 15–16 kcal/cm²/month during the southern summer and minimum of 10 kcal/cm²/month during southern winter. In the northern tropics, the pattern is quite different from that in the southern tropics, the minimum occurring during the summer months

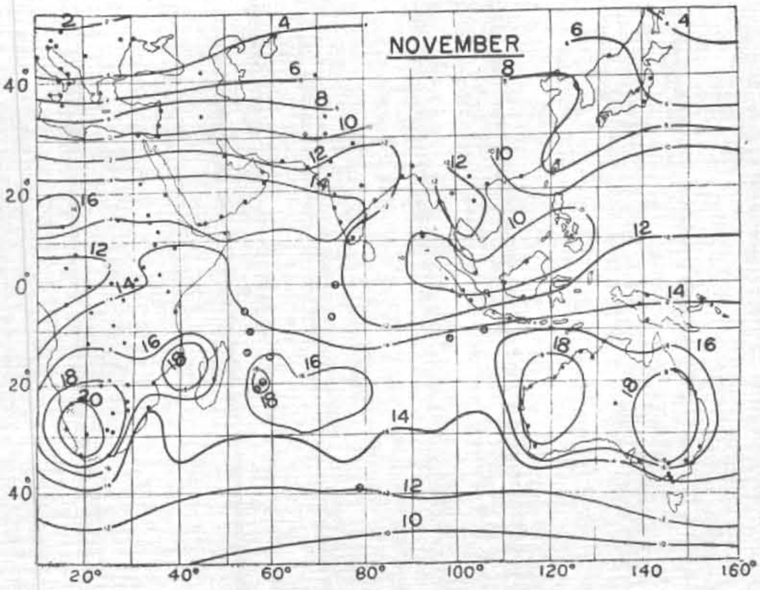

Fig. 12

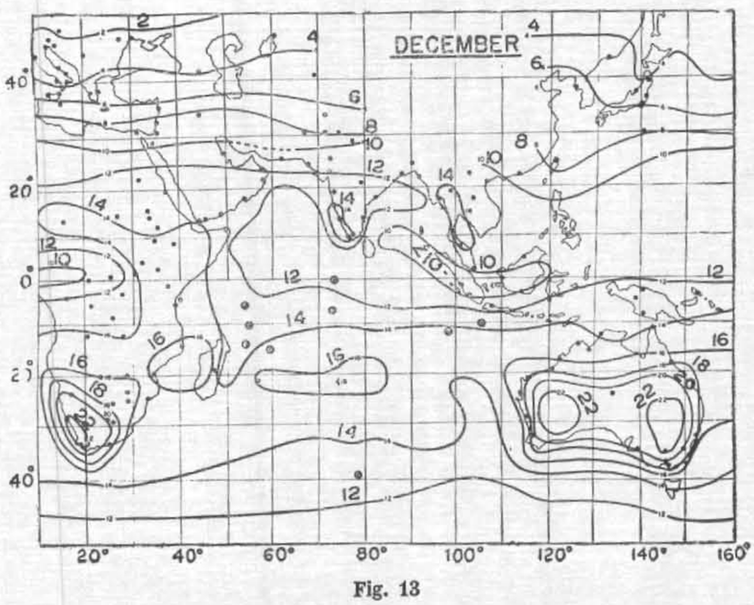

Fig. 13

Figs. 12-13. Global solar radiation in kcal/cm²/month

and values exceeding 14 kcal/cm² occurring during the rest of the year. Maximum values of 20 kcal/cm² are received during April–May.

The most radiation rich regions are, however, the subtropics 20°–30° N during April-June and 20°–30°S during November–February. The most pronounced minima also occur in the subtropics, during June–July in both northern and southern hemispheres. The northern hemisphere minimum is caused by the summer monsoon and the southern hemisphere by the smaller amount of radiation received in this season. Both subtropics are characterised by rapid changes in radiation with latitude, with the increasing influence of extra-terrestrial intensity. Both northern and southern subtropics are also characterised by rapid changes in radiation from season to season.

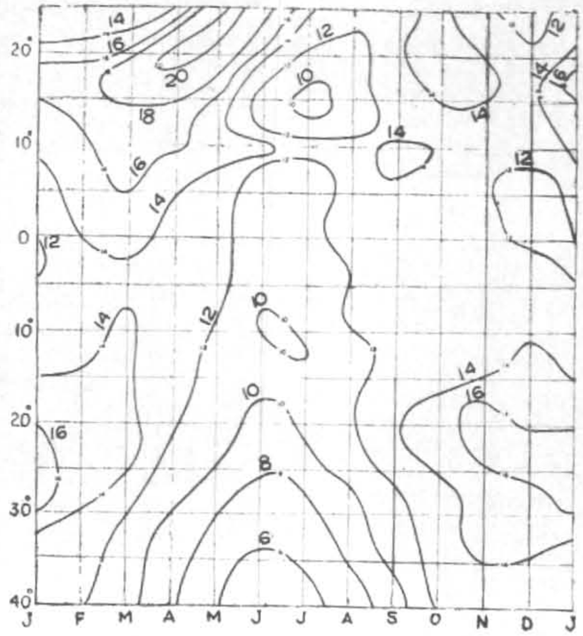

Fig. 14. Meridional cross-section of global solar radiation in kcal/cm²/month along 73°E

7. Distribution of net solar radiation (shortwave radiation balance)

Fig. 15 shows the annual distribution of net solar radiation over the Indian Ocean and the adjacent continents. Isolines are again drawn every 20 kcal/cm²/year. The net solar radiation is naturally smaller than global radiation but its distribution pattern is very similar to that of global radiation, with maxima along the subtropics and minima along the equator. The major differences are the larger values over sea than on land in the subtropics and the break in the isolines between sea and land.

The surface has a profound effect on the shortwave radiation balance, since value of surface albedo range from 0·8 or more for fresh snow to 0·08 or less for smooth deep water. As a result of the albedo over the ocean being very much less than on land, net solar radiation is higher over sea than on land, despite the larger global solar radiation received over land at the same latitudes. The isolines are not continuous, particularly on the border of continents and water bodies, as a result of the abrupt change in the albedo of the underlying surface.

The difference between global and net solar radiation is very small but significant over the major part of the land and oceans and is about 5–30 per cent. This difference is more over deserts and particularly so over regions covered with snow and ice. It will be seen from Figs. 1 and 15, that while global solar radiation is maximum over the desert regions along the tropics of Cancer and Capricorn, net solar radiation is maximum over the north Arabian Sea and the ocean to the northwest of Australia where it is of the order of 170 kcal/cm²/year. Almost all of the global radiation received is absorbed in this area.

Over North Africa where about 220 kcal/cm² are received the albedo being much higher over the desert, less than 140–160 kcal/cm² is absorbed. The same is true over the South African and Australian deserts where over 40–60 kcal/cm² are reflected. Minima occur over the equator and over southeast Asia as for global radiation, only 20 kcal/cm² being lost from here as reflected radiation.

Monthly maps for the four representative months January, April, July and October are shown in Figs. 16–19. The seasonal variations during the summer and winter solstices and the two equinoxes are similar to those of global radiation. Maxima during the southern summer occur on land, over the South African and Australian deserts and minima over the equator. During the northern summer, the maximum is over North Africa and Arabia with minima over south and southeast Asia, as the monsoon has already set in this area. The pattern during the equinoxes are midway between those of the solstices. The maxima during April are over North Arabian Sea and over the sea to the northwest of the Australian mainland. In October the maxima lie over the deserts of South Africa and Australia.

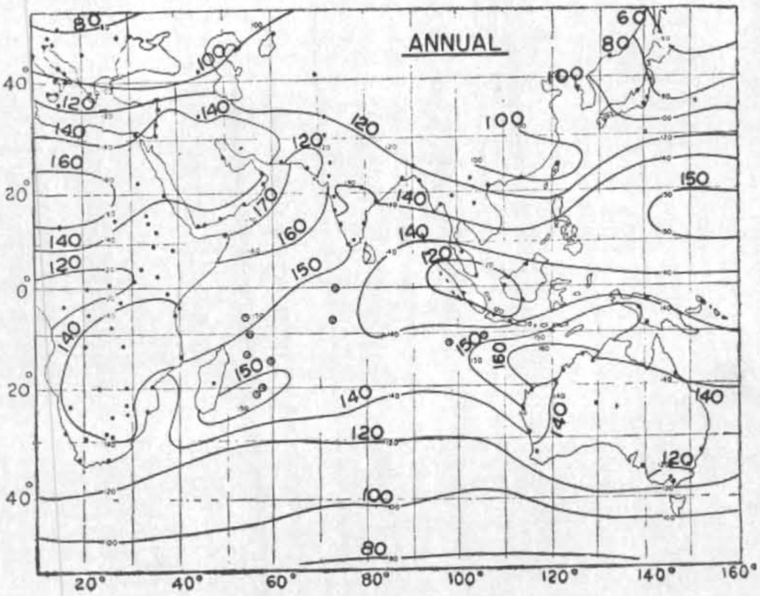

Fig. 15

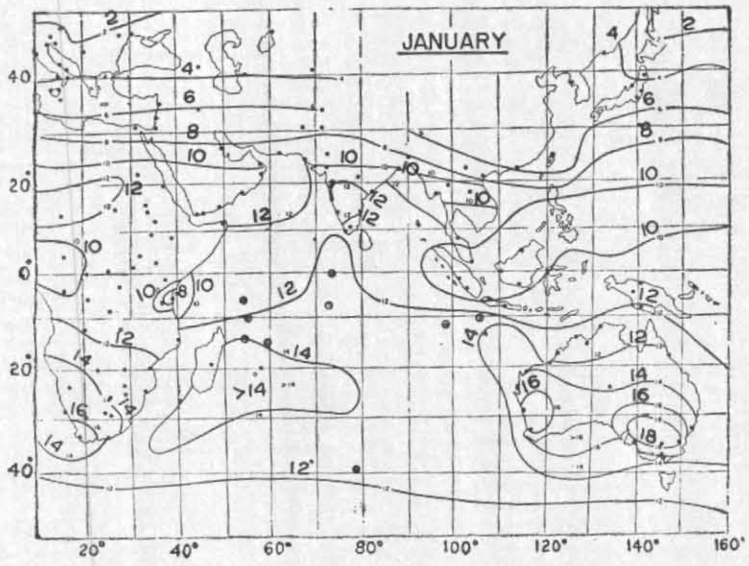

Fig. 16

Figs. 15-16. Net solar radiation in kcal/cm²

8. Errors in observation and computation

Moll-Gorczynski thermoelectric pyranometers are used for global solar radiation and albedo measurements at Indian radiation stations while Eppley 180° pyranometers are used at the Michigan University stations in the Indian Ocean. Thermoelectric pyranometers and bimetallic pyranographs are in use at the other stations, the latter being more common. The unreliability of radiation measurements with bimetallic pyranographs is well known (Robinson 1964). As with all instruments, the results obtained from bimetallic pyranographs depend on the care with which they are treated, the traces read and the trace readings reduced to the published values. An accuracy of ± 5 to 10 per cent is all that can be expected from bimetallic pyranographs. Errors up to ± 10—20 per cent are, however, not uncommon in the long-term sums in the tabulations derived from these instruments.

Thermoelectric pyranometers are much more

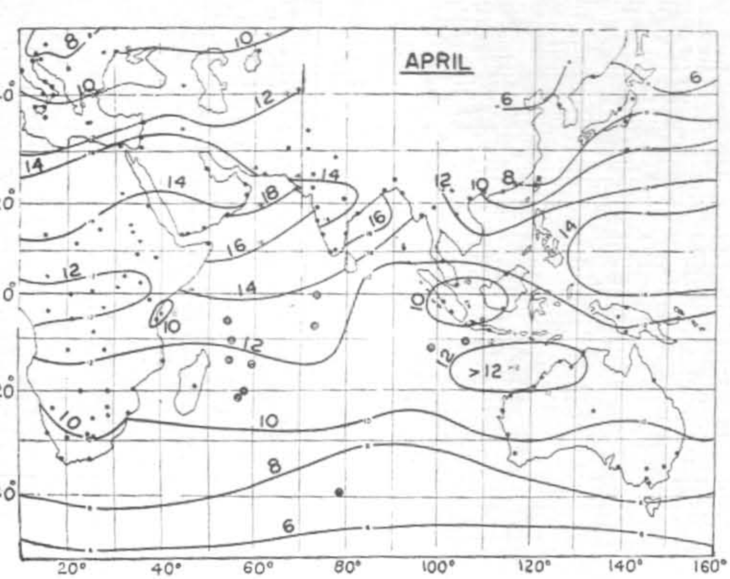

Fig. 17

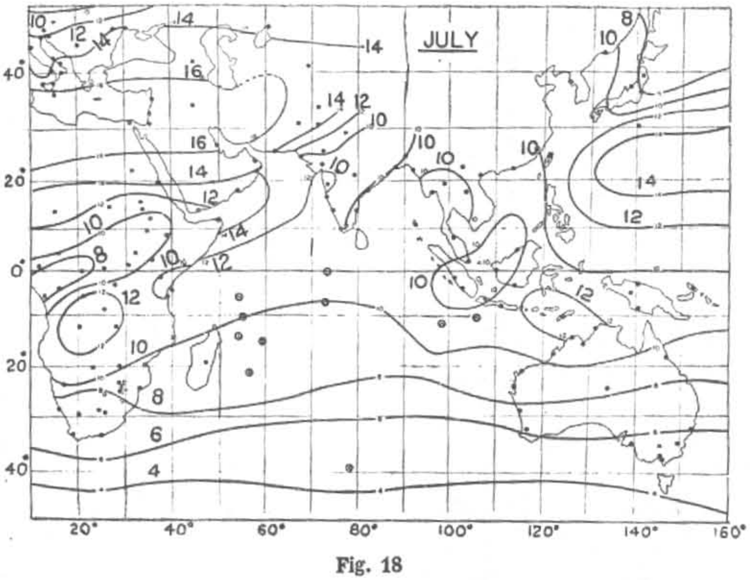

Fig. 18

Figs. 17–18. Net solar radiation in kcal/cm²/month

satisfactory than bimetallic pyranographs but the sensitivity of these also vary with solar elevation and azimuth. They also show a temperature coefficient of sensitivity. Errors in the monthly means are of the order $\pm$ 5 per cent.

Another source of difficulty is the absence of a uniform basis of reference in radiation measurements in the region. Large variations are noticed in *T* from country to country and errors of the order of 20 per cent or more exist. The inter-comparisons of reference standards used in various countries for the calibration of pyranometers and a common basis of reference for the reduction of the data to a common level is an urgent necessity.

In computations of *T*, Budyko (1956) has concluded that errors of the order of 5 per cent can occur for annual values and 10 per cent for monthly values. Obvious inaccuracies of a higher order exist

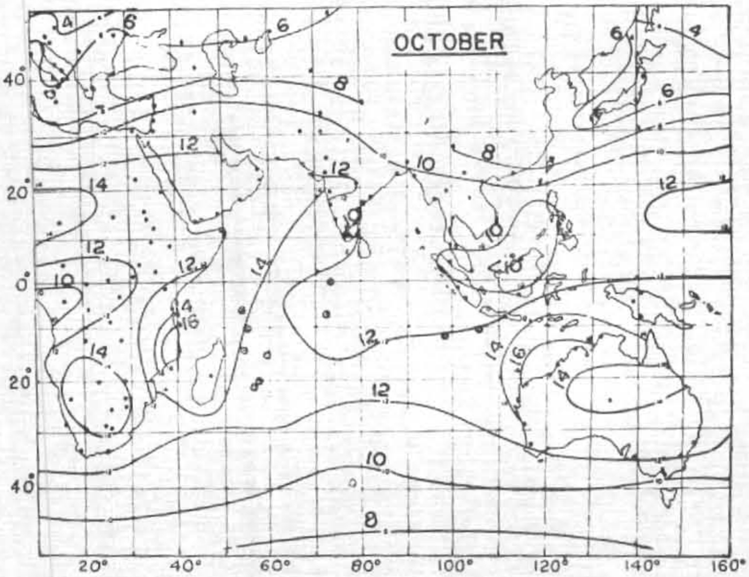

Fig. 19. Net solar radiation in kcal/cm²/month

in estimates of global radiation over the oceans, since measurements of meteorological parameters like temperature and humidity from ships are themselves not representative of actual conditions over the sea. Wüst (1950) found air temperature values given in the climatic atlases to be 1·5°—2·5°C lower between 0—20° N in the Atlantic. Albrecht (1952) found similar differences over the Indian Ocean. Allowing for the various inherent inaccuracies, ± 20 per cent seems to be a good estimate for the errors in the computed values over the oceans.

9. Conclusion

The need for strengthening the network for radiation stations in the Indian Ocean area, for systematic recording of all components of the radiation balance, particularly over the sea, remains urgent. Radiation measurements from weather ships and automatic weather stations at sea are difficult and expensive. Systematic measurements at island stations are simpler than observations over the ocean. Instrumental and organizational problems in carrying out even such a project are many and complex. Even on land, problems arising from remoteness of the stations, transportation of equipment, climatic influence on instrumentation and the varied jurisdictions in and around the Indian Ocean add to the complications. The periodic calibration of the instruments and the use of a common reference is another problem. Regional Radiation Centres exist at Tokyo (Japan), Aspendale (Australia), Poona (India), Leningrad (USSR), Leopoldville (Congo) and Pretoria (South Africa) with sets of working standards and facilities for instrument calibration. But all radiation instruments in the region have not been standardised or intercompared with working standards at these centres. Radiation measurements from satellites should be expected to contribute in some measure towards a solution of this basic problem.

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