For Milt Beards with compliments Herbert Riehl

Atmospheric Science Research Report Number 2

RADIATION MEASUREMENTS OVER THE CARIBBEAN DURING THE AUTUMN OF 1960

by

Herbert Riehl

A report on research conducted under contract No. CWB-9918 between the U. S. Weather Bureau and Colorado State University

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

March 1962

CER62HR13

RADIATION MEASUREMENTS OVER THE CARIBBEAN DURING THE AUTUMN OF 1960

by

Herbert Riehl

Abstract

Observations made over the Caribbean Sea with the Suomi-Kuhn infrared radiometer during 1960 are analyzed. About 120 soundings released at five stations ascended to the 100-mb level or beyond. Compared to Elsasser-chart calculations, they show greater cooling below 800 mb and much smaller cooling higher up. In the high troposphere a radiational heat source due to long-wave radiation alone is found. It follows that vertical heat transport requirements from the surface by convective means, for heat balance, are much less than previously estimated.

Fragmentary observations above 100 mb indicate that the outward radiative flux increases above the tropopause and gradually approaches the values obtained from Explorer VII measurements. Strong cooling of the air above the tropopause is computed, as much as five times that of the troposphere.

Day-to-day fluctuation of net radiation from the troposphere was large, as was the range of observed fluxes. Statistical analysis indicated

that the control of the net radiation from the troposphere lies mainly in the high troposphere, in the layer of maximum wind. It is shown that a cirrus hypothesis of this control is at least plausible, and that differential radiation can be sufficiently strong to be of considerable possible importance for the growth and evolution of daily weather systems.

Introduction

In most computations involving daily weather, radiation either has been neglected or been treated as a constant. Lack of synoptic radiation observations has been at least partly responsible for this approach. With the advent of satellites carrying radiation sensors, and with introduction of the Suomi-Kuhn radiometer (Suomi and Kuhn, 1958; Suomi, Staley and Kuhn, 1958; Tanner, Businger and Kuhn, 1960), it has become possible at last to examine long-wave radiation and its vertical distribution with respect to the instantaneous weather picture (Kuhn and Suomi, 1960).

Since such examination may prove helpful toward understanding tropical weather processes, the U. S. Weather Bureau and the University of Wisconsin undertook a joint observation program in the Caribbean during October and November 1960. At the five stations shown on fig. 1 radiometers were attached to radiosonde balloons released at 00 GMT (at or after sunset in the area of the experiment). The recorded signals subsequently were converted to radiative flux (units of ly/min); upward, downward and net flux were tabulated in the form of computer output from the vicinity of the surface to the top of each sounding. The data were kindly placed at the author's disposal for analysis of those aspects of the soundings which are of interest to him, the results of which are discussed in this report. It should be emphasized at once that this discussion is by no means intended to cover all aspects of the long-wave radiation flux picture which can be studied with the observations.

Climatic Radiation Values

At each station 30 soundings were scheduled. Of these, 116 soundings reached at least the 100-mb level, averaging 23 per station. Only these soundings will be considered.

Regional differences between averaged soundings at the five stations proved to be small, and they may have been due to random selection factors; hence combination of all ascents into one mean sounding of net outgoing long-wave flux appeared permissible (fig. 2). This mean sounding was extended linearly from the lowest computed point (950 mb) to the surface, which yields an approximate value of net radiation from the earth. This value, .07 ly/min, agrees closely with Houghton's (1954) estimate; it is a little lower than London's (1957) autumn value for latitude 20N. Most remarkable are the facts that the outward flux attains a maximum near 250-200 mb, close to the level of maximum wind; that it decreases from there to the vicinity of the tropopause (100-80 mb); and that above the tropopause it increases again. The layer of decreasing flux, noted by Kuhn and Suomi (1960), was present on almost all individual soundings; the level of maximum flux varied from 500 to 150 mb.

At the top of the troposphere--taken as 100 mb--the flux covered the range from .13 to .32 ly/min, mean and median .25 ly/min (fig. 3). This value is rather low as compared with a mean of about .35 ly/min observed, for instance, on several traverses of Explorer VII at latitude 20N (House and Blankenship, 1961). The latter value is almost identical with previously computed net emission to space from the tropics. For reference purposes, we shall treat .35 ly/min as a first approximation to the net emission at 20N. The satellite and radiometer information together yield a net tropospheric heat loss of .18 ly/min, and a net heat loss of the layer 100-0 mb of .10 ly/min (fig. 4). This computation, of course, is approximate and preliminary. It suggests, however, that the mass in the stratosphere and beyond cools at a much faster rate than the troposphere over the region considered; from fig. 4 we note that the ratio is 5:1.

It would have been interesting to compare the measured flux with that computed from the Elsasser radiation chart. Since the cloud layers intercepted by the balloons during their ascent could not be observed with sufficient accuracy, however, this computation was not feasible. Instead, the Caribbean data were compared with London's (1957) emission computation for latitude 20N in autumn for which he used climatic cloud information. At that time of year the Caribbean has no special cloud characteristics which would render comparison obviously unrealistic. Hence the comparison was made, though reservations about its full validity must remain. The measured upward flux exceeds the computed flux in the lowest 200 mb (fig. 5), a result previously obtained by Clarke (1961) using radiation measurements made on five flights by aircraft from the Woods Hole Oceanographic Institution east of Trinidad. Higher up, the measured emission is much lower than London's; the net flux through 100 mb differs by about 25 per cent. In terms of cooling, the Caribbean experiment shows almost constant cooling near 1.7 C/day up to 500 mb, with rapid decrease and change to warming above this level (fig. 6). Net infrared cooling for the troposphere is 1.1 C/day. London found maximum cooling near 500 mb and net tropospheric cooling of 1.6 C/day. Fig. 6 indicates that requirements for upward heat transfer by convective processes in heat balance computations are considerably lower than previously thought necessary.

Fluctuations of Radiative Cooling

Variations in cooling between successive soundings were very large at times. Thus, at Miami, maximum flux occurred at 500 mb on October 18 (fig. 7); net flux from the troposphere was only .05 ly/min (cooling of 0.3 C/day).

One would probably observe that the troposphere experienced no net cooling at all after inclusion of short-wave absorption. The possibility suggested here--that the troposphere can be a transient radiational heat source over limited areas--is a very interesting one from the viewpoint of understanding circulation changes, and it deserves broad further investigation. In contrast to October 18, strong cooling of 2 C/day to 200 mb occurred at Miami on the following day (fig. 7). If this difference in cooling rates persisted at two neighboring stations for 24 hours, a surface pressure difference of 5 mb would develop, given hydrostatic balance, unchanged height of the 100-mb surface and all other conditions equal. This demonstrates that we are dealing with a potentially important effect for growth and decay of weather systems, especially in the tropics.

Since the atmosphere above the tropopause was not a main objective for study, only a frequency distribution of cooling in several layers above 100 mb is presented here (Table 1). It shows mainly that cooling rates were far from uniform, which suggests that the atmospheric constituents determining the net radiative flux were variable. Further, emission was small in the layer 100-50 mb, and it increased from there upward. The top of the soundings considered in the table was mostly between 10 and 20 mb. It is seen that for the layer 100 mb to top of sounding the modal value approached, though it did not quite attain, the value of total infrared emission from the atmosphere suggested by the Explorer VII data.

Table 1

Radiative flux difference (ly/min) between 100 mb and the indicated pressures. In per cent of all observations (N).

mb	N	Radiative flux difference (10^2 ly/min)								
		+5 +4	+3 +2	+1 0 -1	-2 -3	-4 -5	-6 -7	-8 -9	-10 -11	-12 -13
100-50	89		3	55	33	9				
100-25	65	2	0	18	34	32	11	2	1	
100-top	50		2	12	20	26	34	0	4	2

Numerous attempts to correlate the fluxes at different tropospheric levels with total moisture and moisture in various layers failed. Correlation with pressure and wind changes at low levels also proved unsuccessful. A slightly better, though still unconvincing, result was obtained at 200 mb. Fig. 8 shows the best of the time sections relating pressure and wind variations with tropospheric emission at Gran Cayman. In this figure, successive radiation fluxes have been connected by straight lines; it is unknown, however, whether this interpolation is permissible. The radiometer, as distinct from the satellite which sees large areas, is sensitive to the cloud structure in the immediate area of ascent, so that there may be small scale fluctuations in emission--in space and time--with magnitudes comparable to the 24-hour fluctuations. This subject awaits further experimental exploration. If we set these doubts aside, with proper reservation, Fig. 8 shows the following:

25-30 October: An upper trough approached the station from the east, then became stationary. A minimum of emission coincided with the period of active westward trough displacement.

5-10 November: Another trough approached from the east, and this time it passed the station. Radiation dropped to a minimum in and east of the trough line.

13-19 November; A third trough passed from the east, associated with strong winds east of the trough line. No systematic variation in radiation was detected.

Discussion of a possible cause of these radiation variations will be offered later. At this time we should note merely that the time sections at the other stations indicated a predominant lack of obvious correlation between synoptic weather changes and radiation as during the third period at Gran Cayman.

Statistical Analysis

As noted initially, the data printout contained values of upward, downward and net radiative flux. In the mean, both upward and downward flux decrease with height (fig. 9). The difference between them varies so as to produce the net emission curve of fig. 2. It is of interest to investigate the variability of the upward and downward currents separately. For this purpose, standard deviations of the up and down currents were first computed at 100, 300, 500 and 700 mb. As the possible significance of this calculation became apparent, all the other levels denoted by dots in figs. 9-11 were added.

The standard deviation of both currents was nearly uniform up to 300 mb (fig. 10), followed by rapid change through the level of maximum intensity of high-tropospheric synoptic disturbances. In this layer, the variability of the downward current increased strongly downward, and that of the upward current increased strongly upward. This pattern was found at all stations individually except at Curaçao, where a more gradual variation of standard deviation through the troposphere was observed. In terms of variance, the fluctuations range from very small values near the ground to 10-15 per cent in the high troposphere (fig. 11).

Fig. 10 suggests that the primary interference with steady radiation occurs in the layer of maximum wind. The atmospheric constituents, or aerosols, producing such sharp changes of standard deviation have not yet been observed directly. Lacking such knowledge, we shall try to formulate a hypothesis which would at least give a possible explanation of the variations of the radiative fluxes. The hypothesis consists in postulating either presence or absence of cirrus sheets spread above the lower cumulus sky. Given such a sheet, the upward current from below would be intercepted and partly turned back. Emission from the top of the layer would approximate the black body emission at the temperature of the cirrus, in case of thick cirrus. Thin cirrus may not intercept fully the radiation current from below; but this does not affect the principle of the present discussion. It follows that--in the presence of cirrus--the downward current would increase more rapidly downward in the high troposphere than in the average shown on fig. 9; further, the upward current would decrease more rapidly upward than in the mean. During clear conditions the reverse should hold.

This model may be tested by preparing a scatter diagram of the change in downward flux from 100 to 300 mb against the change in upward flux from 300 to 100 mb (fig. 12). A correlation in the sense described above is indicated. Though not perfect, it suggests that the cirrus model is a plausible one, although the presence or absence of other aerosols with similar radiation properties is not ruled out.

We may note that, because of the low absolute values of mean flux and standard deviation of the downward current at 100 mb, the net emission from the troposphere should be correlated with either of the variables of fig. 12. In fig. 13, the change in upward flux from 300 to 100 mb has been plotted against net tropospheric emission. This diagram brings out the expected relation. Fig. 14 shows that only slight additional improvement is obtained by considering the change in upward flux from 500 to 100 mb. With this, the main control of net tropospheric heat loss through long-wave emission is localized near the level of maximum wind.

Pursuing the cirrus hypothesis one step further, it can now be seen why various correlations of net emission with tropospheric moisture content failed. At times cirrus is derived from cumulonimbus, and then high total moisture of the troposphere is implied. At other times cirrus forms independently of lower cloud decks, and in fact it is often found above dry air with trade wind inversion at low levels. Thus cirrus correlates poorly with total moisture, and the same should be true for radiative emission if the latter is controlled by the cirrus. Returning to fig. 8, since deep convection occurs mostly east of troughs, the low radiation on November 7-9 at Gran Cayman is readily understood. But cirrus also occurs frequently west of trough lines, especially when regular progression or retrogression is interrupted. Hence the low emission on October 26-28 also fits the model. This reasoning cannot be applied to the third period. We should note, however, that cirrus varies not only normal to troughs, but also along trough lines, depending on the location of the strongest wind belt and the horizontal shear of the basic current. This shear cannot be ascertained from individual time sections. A survey of the upper-air charts drawn by the Weather Bureau proved inconclusive. Further pursuit of the subject at this time appears unwarranted, since there is a question whether the radiation variations shown in fig. 8 really represent the synoptic course of events.

Conclusion

This study has shown that the mean cooling of the troposphere due to long-wave radiation is lower than previously computed for the region studied, except in the layer 1000-800 mb. Hence the requirement for vertical heat transfer by convective process to the high troposphere for heat balance is considerably lower than assumed in earlier calculations. Also, stratospheric cooling is large and variable, in the mean perhaps five times as large as the tropospheric cooling, which is slightly in excess of 1 C/day.

Variability of emission from the troposphere is large; at the lowest values measured, there may be no net radiational heat loss at all when absorption of short-wave radiation is taken into account. The variations in net emission can produce large differential pressure changes at the ground, other conditions being equal. These variations are controlled primarily in the high troposphere near the level of maximum wind. A model involving the presence or absence of cirrus sheets gives a possible interpretation of the radiation fluctuations. If valid, dynamic effects in the high troposphere can have a considerable impact on future weather developments through establishment of radiation gradients; these in turn will affect the field of motion.

For further progress in this subject, a new experiment is required in which the cloud layers present during the ascent of the radiometer are carefully observed and samples of high-tropospheric air are collected and analyzed.

Acknowledgements

This research was performed under a contract between the U.S. Weather Bureau and Colorado State University. Special thanks are due to Drs. V. E. Suomi and P. M. Kuhn for making the arrangements under which the author was enabled to participate with them in the design of the experiment and which permitted him to make the analysis. The effort made by the Weather Bureau in executing the operation of the program, and that of the Dutch Meteorological Service in participating, must be specially mentioned. Mr. Russell Elsberry performed most of the computations.

References

Suomi, V. E. and P. M. Kuhn, 1958. An economical net radiometer. Tellus, 10, 160-3.

Suomi, V. E., D. O. Staley and P. M. Kuhn, 1958. Measurements of infra-red radiation divergence to 160 mb. Quart. J. Roy. Meteor. Soc., 84, 134-141.

Tanner, C. B., J. A. Businger and P. M. Kuhn, 1960. The economical net radiometer. J. Geoph. Res., 65, 3657-67.

Kuhn, P. M. and V. E. Suomi, 1960. Infrared radiometer soundings on a synoptic scale. J. Geoph. Res., 65, 3669-77.

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

London, J. A., 1957. A study of the atmospheric heat balance. Dep. Meteor., New York Univ.

House, F. B. and J. R. Blankenship, 1961. Applications of infrared measurements in meteorology. Tech. Rep. 157, Air Weather Service, Scott AFB.

Clarke, D. B., 1961. Measurements of radiative flux and cooling over the ocean east of Trinidad. Marine Meteor. Tech. Rep. 46, Woods Hole Oceanogr. Inst.

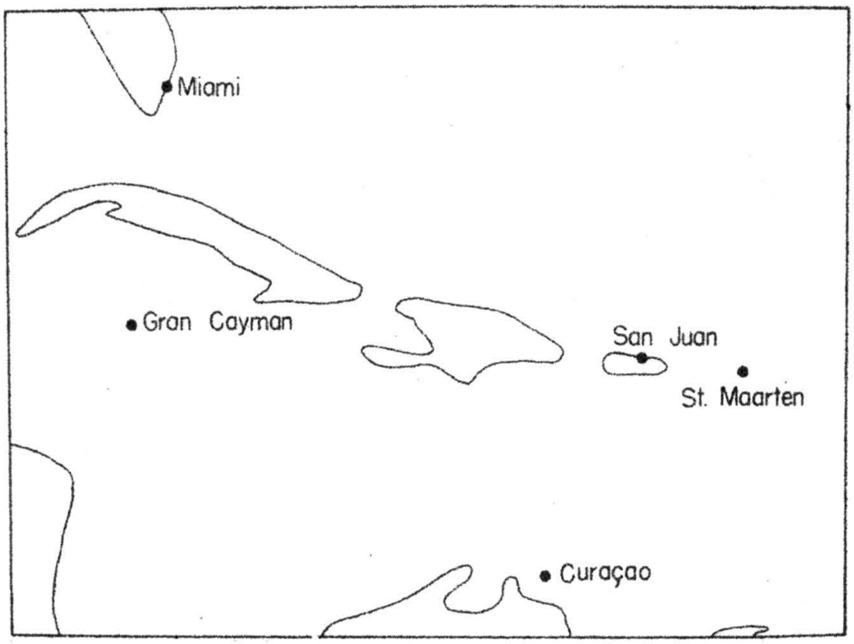

Fig. 1. Stations making ascents in radiometer program.

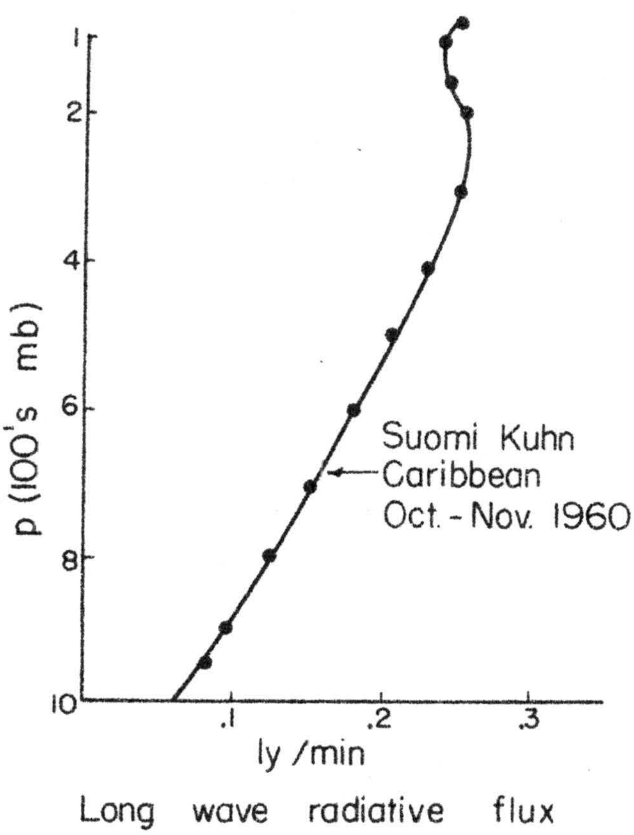

Fig. 2. Long wave radiative flux, mean of all soundings, to 75 mb.

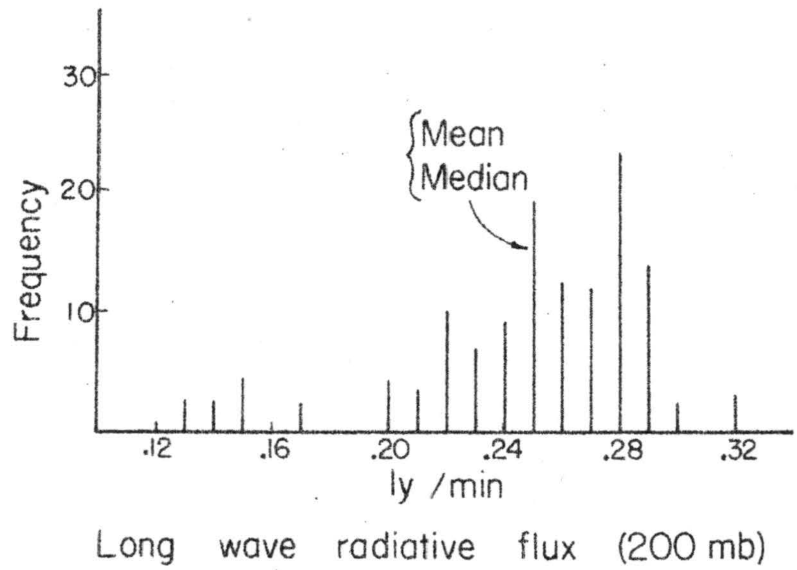

Fig. 3. Frequency distribution of net upward flux at 200 mb.

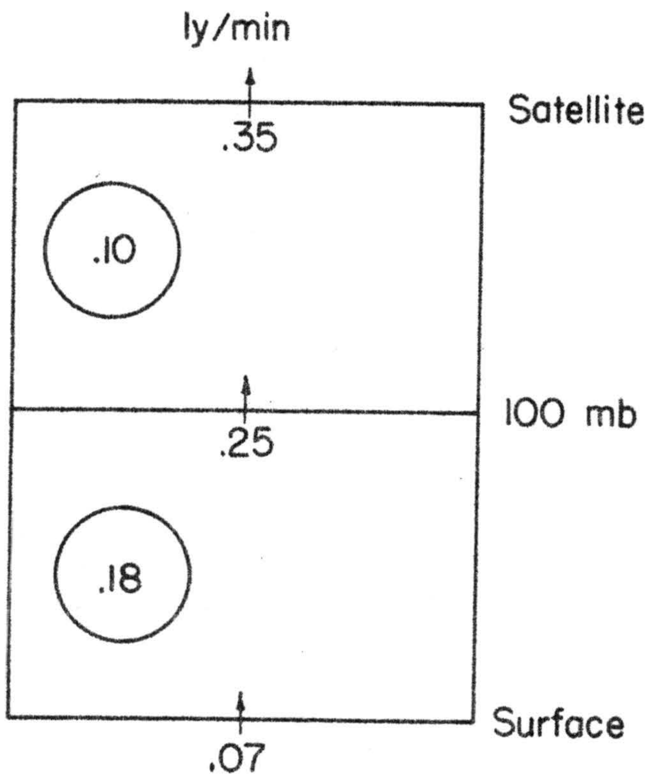

Fig. 4. Schematic diagram indicating net long wave radiative flux from ground, from 100 mb surface and as seen by satellite. Circled: computed cooling in troposphere and in layer above 100 mb.

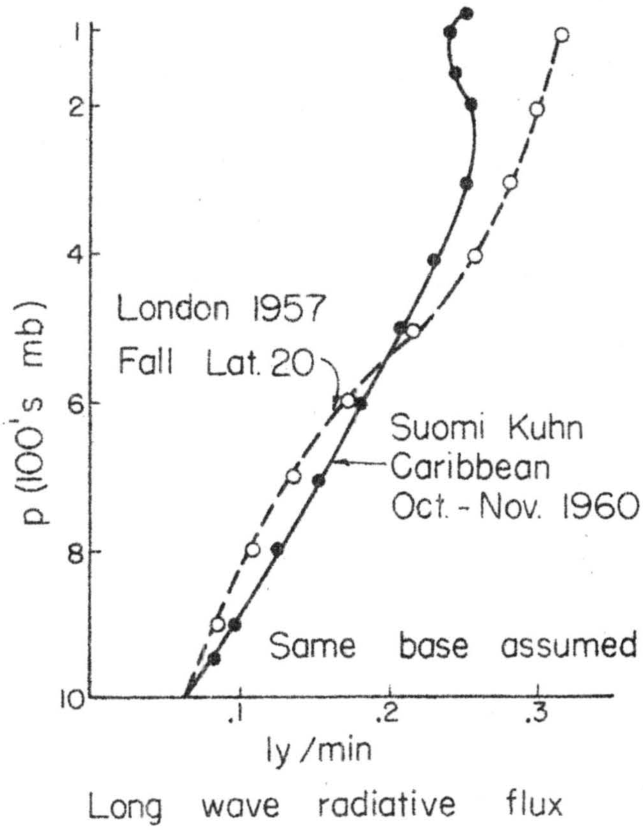

Fig. 5. Mean long wave radiative flux as in fig. 2, and corresponding curve from London (1957) for latitude 20N in autumn.

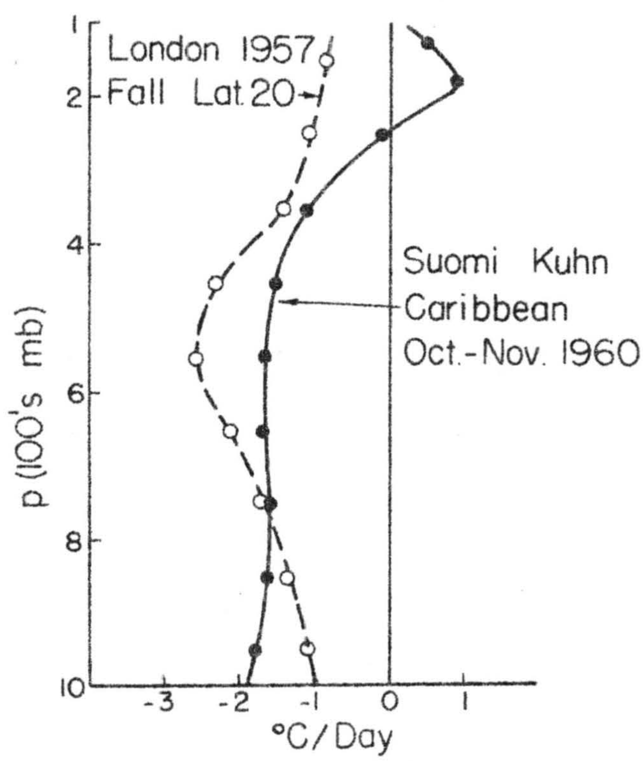

Fig. 6. Cooling (C/day) computed for 100-mb layers from fig. 5.

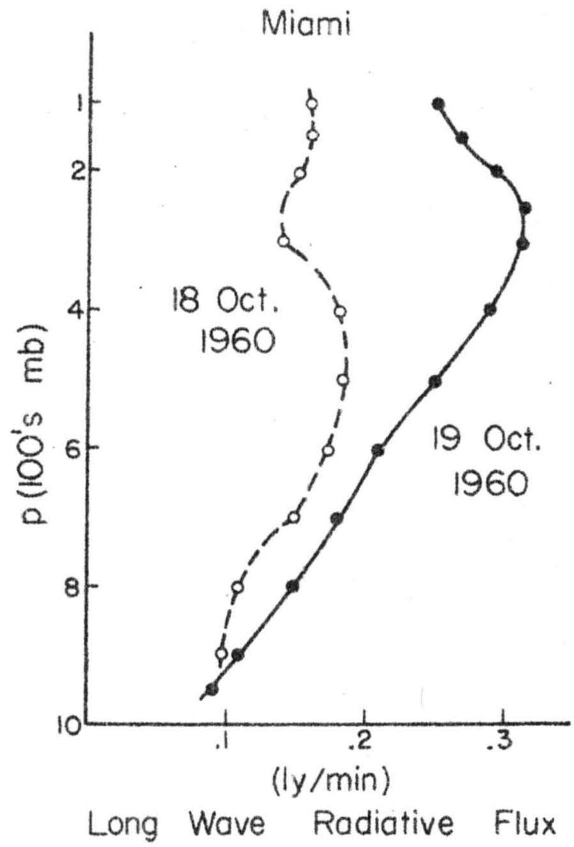

Fig. 7. Long wave net emission on two succeeding days at Miami, Fla.

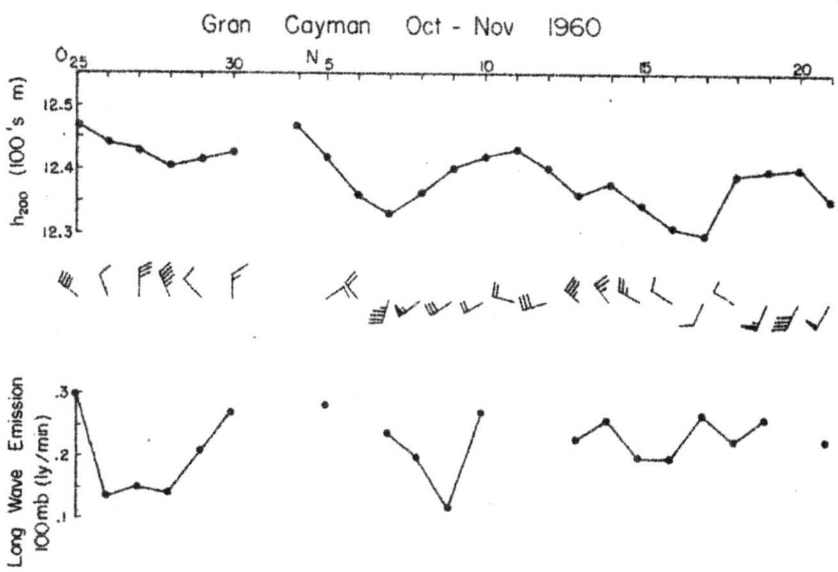

Fig. 8. Time section of 200-mb height and wind, and of net long wave emission at 100 mb, at Gran Cayman. Winds plotted according to international synoptic convention. Direction convention: clockwise from north, taken from top of diagram.

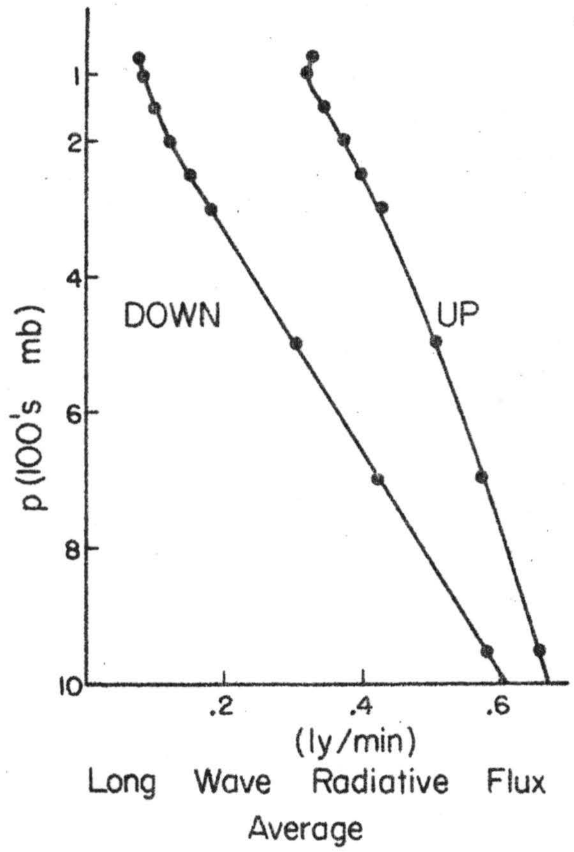

Fig. 9. Upward and downward long wave radiative fluxes, mean of all soundings.

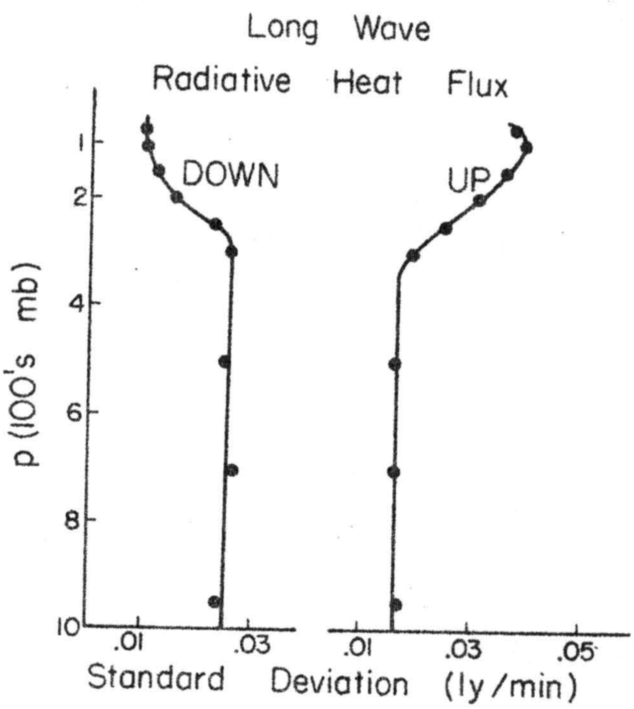

Fig. 10. Standard deviation of upward and downward radiative fluxes, determined at first for each station separately and then averaged over the five stations.

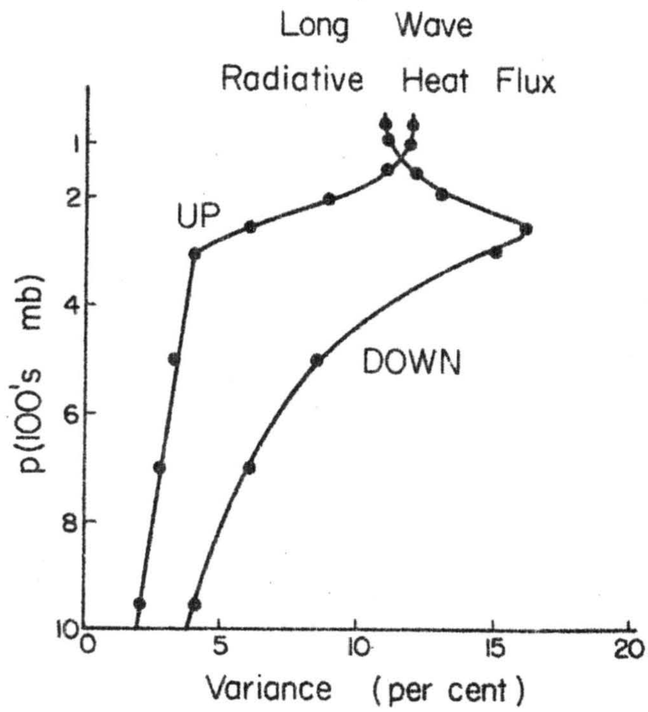

Fig. 11. Variance of the upward and downward radiative fluxes.

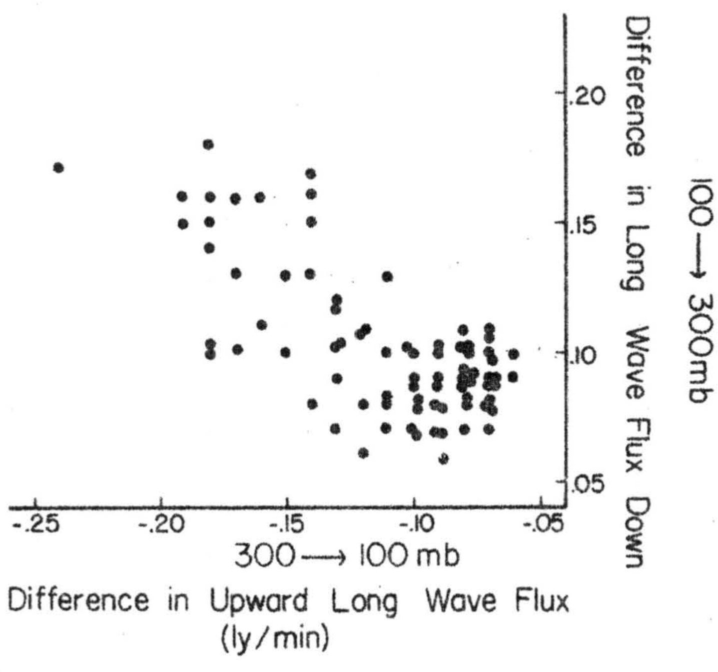

Fig. 12. Scatter diagram relating difference in downward radiative flux from 100 to 300 mb with difference in upward radiative flux from 300 to 100 mb.

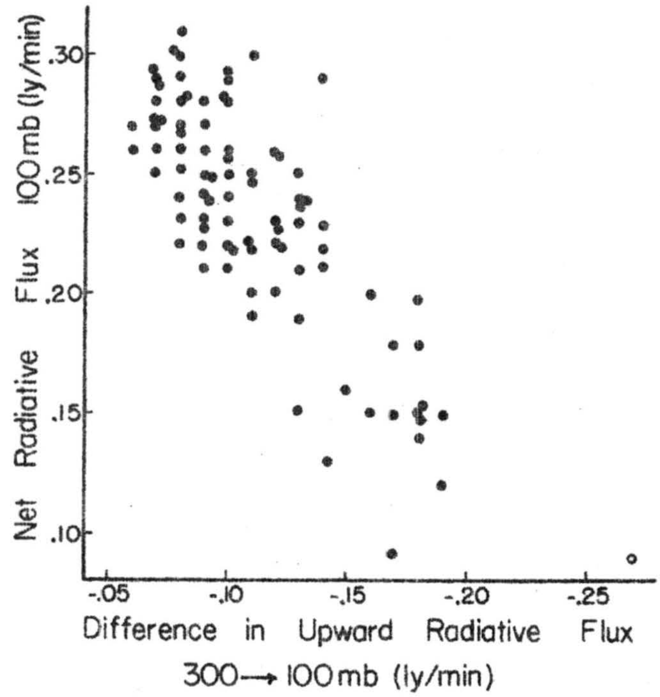

Fig. 13. Scatter diagram relating net emission at 100 mb with the difference in upward radiative flux from 300 to 100 mb.

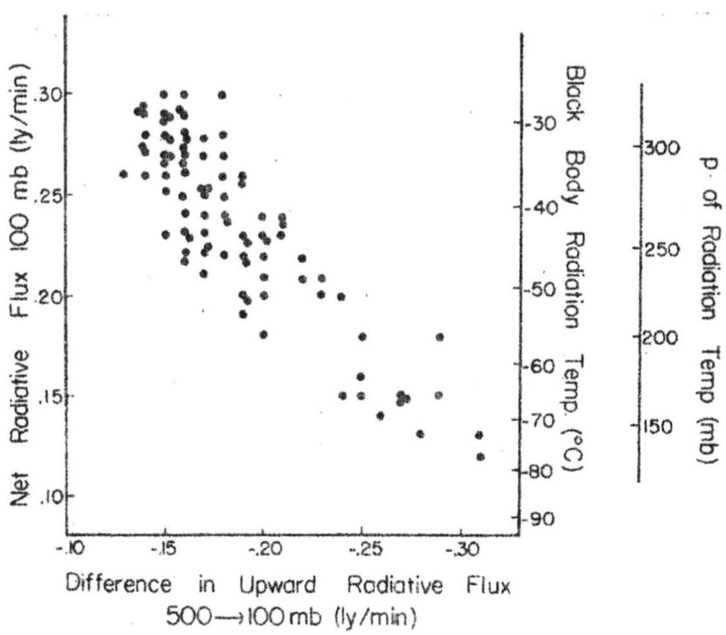

Fig. 14. Scatter diagram relating net emission at 100 mb with the difference in upward radiative flux from 500 to 100 mb. Scales on right: pressure and black body temperature of equivalent radiation surface from tropical standard atmosphere.