Observational Evidence of Anomalous Infrared Cooling in a Clear Tropical Atmosphere

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While conventional methods of calculating radiation divergence may be sufficient in a true gaseous atmosphere, they often fail to reproduce measured values in the real atmosphere. This is most probably due to the presence of aerosols in insufficient quantities to be classified as a conventional cloud; however, these aerosols still play an important role in determining the divergence of infrared (IR) radiation.

Goody (1964) presents a diagram comparing the results of IR heating computations by several different techniques complied from data given by Kondratiev and Niilisk (1960) and Yamamoto and Onishi (1953). Rodgers and Walshaw (1966) reproduce this figure and superimpose their own data on it. Temperature and moisture data for all the computations were taken from London (1952) and represent 0–10° latitude for the month of March. Fig. 1 is a reproduction of Rodgers and Walshaw's figure with the addition of an average IR heating profile *observed* for clear conditions during the Line Island Experiment (Zipser and Taylor, 1968) in March and April 1967. Fourteen "clear" radiometersonde soundings from Christmas Island (1°55′N, 157°20′W) and Palmyra Island (5°53′N, 162°05′W) stations were averaged to produce the observed profile.

An improved model of the Suomi-Kuhn economical net radiometer (Suomi and Kuhn, 1958) was used to make the observations of IR cooling. Kuhn and Johnson (1966) report that the rms error of the filtered estimate for cooling from this version of the instrument is less than 0.25 C day^{-1}.

The agreement between calculated and observed cooling rates in Fig. 1 is reasonably good between 850 and 350 mb. Below 850 mb all computations underestimate the IR cooling, some by as much as 1.5C day^{-1}. Above 350 mb all computations generally overestimate the IR cooling. Above 800 mb Rodgers and Walshaw show the best agreement with the observed profile while Yamamoto and Onishi show good agreement with shape of the observed profile.

The differences among the calculations themselves are of the same order as the difference between the observed and calculated values. As pointed out by Rodgers and Walshaw these differences among the calculations are due to variations in computational procedure and spectroscopic absorption data of water vapor, carbon dioxide and ozone.

It is very useful at this point to discuss the sets of temperature and moisture profiles in the context of their effects on the IR heating distribution. The profiles in Fig. 2 show a comparison of London's temperature and moisture data used in the computations with the mean temperature and moisture profiles for the 14 clear radiometersonde soundings. The observed moisture profile in units of optical mass of water vapor has been pressure-corrected using a factor of 0.5 to make a direct comparison with London's data possible. The data are given here so authors of various computational methods may make their own comparisons with the observations of IR cooling.

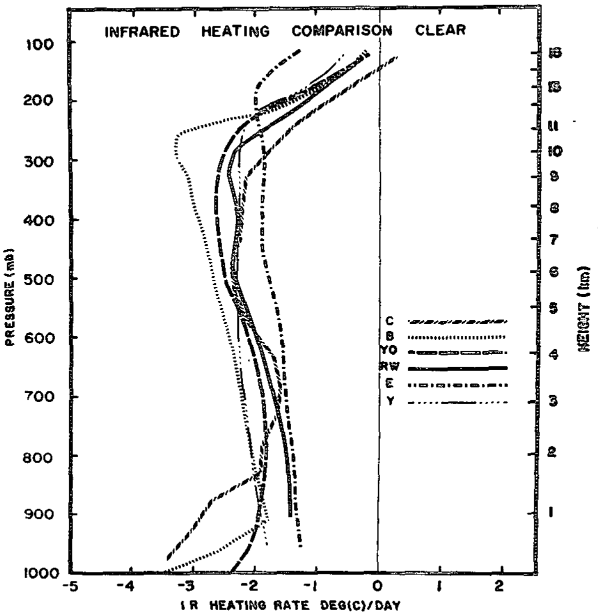

FIG. 1. Comparison of calculated and observed infrared heating rates in a clear atmosphere. Data for computations are from London (1952) for March, 0–10N. Observations are from the Line Island Experiment, March–April 1967. [This diagram has been taken from Rodgers and Walshaw (1966) with the observed profile superimposed.]

Symbol	Work		Method
RW	Rodgers and Walshaw	(1966)	Divergence numerical
YO	Yamamoto and Onishi	(1953)	Divergence chart
Y	Yamamoto	(1952)	Difference chart
B	Brooks	(1950)	Divergence numerical
E	Elsasser	(1942)	Difference chart
C	Cox	(Present Study)	Measurement

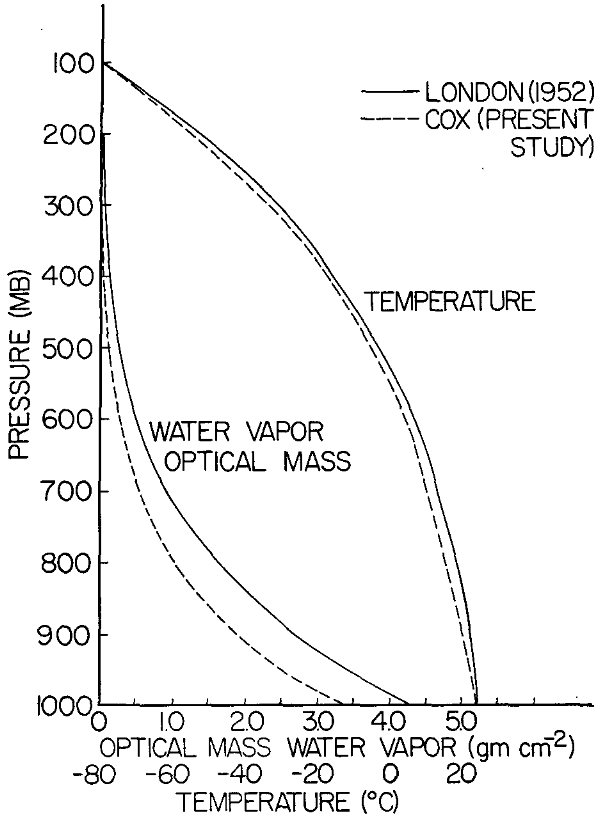

FIG. 2. Mean temperature and moisture profiles for March, 0–10° latitude, from London (1952) used for computations in Fig. 1, and mean temperature and moisture profiles for the clear soundings used to compile the observed cooling model.

London's temperature profile tends to be ~2C larger than the mean observed temperature in the clear soundings. By being systematically larger, London's temperature profile would tend to increase the radiative cooling. This comes about because the absorption of the atmosphere is not as temperature-dependent as the emission which obeys directly the Planck radiance law, thus resulting in a higher temperature and a greater loss of energy. As may be seen in Fig. 1, for pressures <800 mb, the majority of calculations do show cooling greater than or equal to the observed values.

The optical mass of water vapor tends to have an effect opposite to the temperature effect. The smaller the optical mass, the smaller becomes the mean divergence of net radiation which is proportional to the IR cooling rate.

From a comparison of the profiles in Fig. 1 one may see that the mean cooling for the surface to 100 mb layer does not vary appreciably among the three most recent works (Yamamoto and Onishi, Rodgers and Walshaw, and the present study). While the lower observed moisture profile would tend to show greater cooling at low levels than London's, it would not explain a difference of greater than 0.5C day^{-1}.

The observed cooling maximum in the surface to 800 mb layer in Fig. 1 may be due to the horizontal divergence of radiation (Staley, 1965) as the radiometersonde passes from an underlying surface of island to ocean. Fig. 3, based on calculations, shows the effect on radiative cooling rates of the radiometer viewing a changing effective surface temperature as a function of time and pressure. Let us assume that the island surface temperature is 22C, the ocean surface temperature 26C, and let the effective surface temperature as seen by the radiometer vary linearly with respect to pressure in the interval 1000–800 mb, as shown by the fine dashed curve. These conditions are similar to what one would expect near Christmas Island, which accounts for the majority of the clear radiometersonde observations.

If we interpret all of the divergence occurring as a vertical flux divergence, the solid cooling curve in Fig. 3 results. The coarse dashed curve represents the true radiative cooling over the island while the diagonally slashed curve represents the true cooling over the ocean. The differences are readily apparent. For the surface to 900 mb layer, the difference between the radiative cooling observed by an island-launched radiometersonde and that actually occurring over open ocean would be approximately 1.0C. Interestingly, this would explain some of the low-level differences in radiative heating rates shown in Fig. 1.

Another explanation for the disagreement between

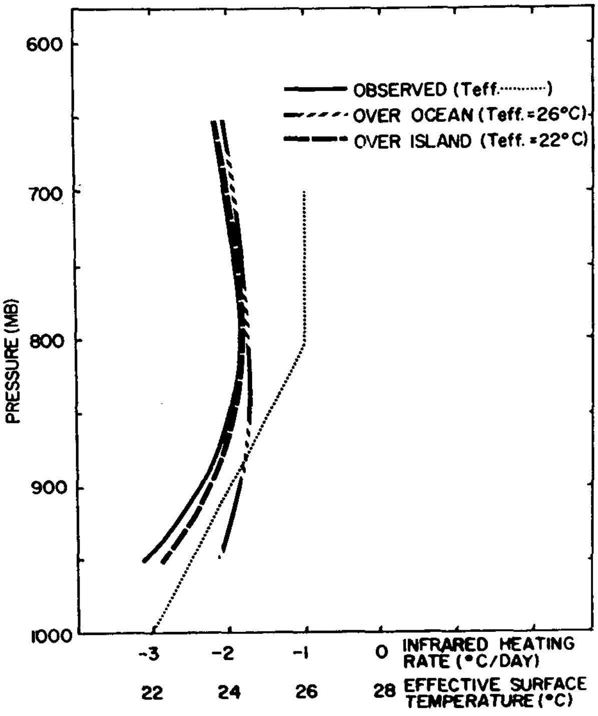

FIG. 3. Effect on radiative heating rates of balloonborne radiometersonde viewing a changing effective surface temperature (island to ocean).

calculations in a model atmosphere and observations in a real atmosphere is the presence of aerosols.The lower region of disagreement in Fig. 1, surface to 850 mb, quite probably contains haze and water droplets in insufficient amounts to be conventionally classified as a cloud; however, they still affect the IR divergence. While no measurements were made of the haze distribution, one intuitively expects the haze to be concentrated in the lower layers and to decrease with height. The effect of the haze in the presence of a positive lapse rate is to moderately decrease the upward IR irradiance while dramatically increasing the downward irradiance. The reason for the greater effect on the downward irradiance is that above the aerosol layers the spectral distribution of the downward irradiance stream is strongly biased toward CO_2 and water vapor emission. The atmospheric window, 8–12μ, contains very little energy. Only the very narrow, although intense, ozone band at 9.6μ emits in this wavelength interval. The emission from aerosols "fills in" this void in the spectral distribution of energy. Thus, the downward irradiance decreases faster with height as one proceeds through the top of an aerosol layer than it would in clear air; the upward irradiance decreases faster with height in the presence of aerosols also, however not as dramatically as the downward irradiance. The result is that the divergence of net radiation becomes larger and the radiative cooling increases.

Cirrus clouds could account for the observed disdiscrepancy above 350 mb. Cirrus just below the tropical tropopause would tend to cause IR heating in this layer. Cirrus at high levels causes little or no change in the upward irradiance beneath the cirrus cloud. However, with cirrus above the layer in question, the downward irradiance does not decrease nearly as fast as it ordinarily would in a clear atmosphere. As a result the presence of cirrus acts to decrease the divergence of net radiation and thus decrease the radiative cooling. Unreported cirrus may actually have been present when the "clear" radiometersonde observations were made or one may reason that some aerosol was indeed present but in insufficient quantity to be classified as cirrus cloud. It is quite possible that these clear soundings represent conditions as close to a true gaseous atmosphere as we ever attain in the tropics.

Let us see what the differences in cooling rates correspond to in terms of energy. For the 1000–850 mb layer, a 1.5C day^{-1} difference in cooling rate corresponds to 55.0 ly day^{-1}. This cooling of the lower layers would tend to stabilize the atmosphere and helps explain why the lower layers in the tropics are not "boiling" with convection. For the 350–100 mb layer, a smaller observed cooling of 0.7C day^{-1} corresponds to 42.8 ly day^{-1}. The upper layers, by not cooling as much to space as the computations predict, would tend to enhance a direct poleward (Hadley cell) energy transport.

A larger number of tropical radiometer soundings are being classified for cloud conditions from the radiometersonde data itself. We hope to use this same data set to show characteristic infrared cooling profiles for different cloud configurations. Fig. 1 is presented at this time because cloud conditions were derivable from several independent sources including aircraft observations, moisture profiles, time lapse photographs, satellite photographs, radar, radiation profiles and surface observations. This rather extensive compilation of data from the Line Island Experiment increases our confidence in choosing the clear cases. There will not be as much corroborating information available in the analysis of the remainder of our tropical data.

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