Horizontal Variation of Infrared Cooling and the Generation of Eddy Available Potential Energy[1]

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ABSTRACT

According to radiometersonde observations, the net vertical flux divergence of infrared radiation is positively correlated with the outward flux at the top of the atmosphere. Measurements of the latter quantity from the Explorer VII satellite are shown to be correlated with tropospheric temperature, such that warm air on the average is cooled less than cold air at the same latitude by infrared radiation. Calculations of the generation of eddy available potential energy by this process are presented and shown to be significant.

1. Introduction

In recent years considerable attention has been given to the problem of the atmospheric heat sources which provide the necessary energy to drive the circulation systems. Several investigators have evaluated the large-scale spatial distribution of heat sources but none of them has evaluated the heat sources based on infrared radiation. Margules (1906) has studied the energy in storms under adiabatic flow. In two adjoining air masses of different temperatures, a redistribution of mass can occur such that potential energy is converted into kinetic energy. Lorenz (1955) further pointed out that as a horizontally stratified atmosphere is heated or cooled non-uniformly the stratification will be disturbed, thus converting the potential energy into available form for the production of kinetic energy. The removal of heat appears to be as effective as the addition of heat in making more potential energy available.

Long wave radiation tends to cool the atmosphere almost everywhere; however, some areas will cool more rapidly than others. Differential cooling gives rise to horizontal temperature gradients, so that those areas which cool at a low rate will experience a relative warming compared to those areas which cool at a high rate. We will use the terms relative warming and heating interchangeably even though in reality everything is cooling. The first direct measurement of the terrestrial infrared radiation on a global scale was made from the 1959 Iota satellite (Explorer VII). This radiation data can be used to evaluate the conversion from the radiative thermal energy into available potential energy. The purpose of this paper is to estimate the generation of eddy available potential energy based on the horizontal variation of infrared cooling.

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2. The infrared radiation

Terrestrial infrared radiation produces a strong cooling rate in the lower troposphere and a weak warming near the tropopause (Suomi, Staley and Kuhn, 1958; Kuhn and Suomi, 1960). In addition, the pattern of radiative cooling is largely influenced by the cloud coverage associated with the cyclones and anticyclones found on all weather maps. Fig. 1 presents the net radiation flux observed by radiometersondes at Washington, D. C., on 14 January 1961 and 11 January 1961 in a storm (with clouds) and in an anticyclone (clear sky), respectively. The experimental result shows that at 100 mb the net flux in the storm is only half the amount observed in the high pressure area. The slope of the curve is a measure of the cooling rate, and the clear high pressure area has a much stronger cooling rate than the cloudy storm area.

The basic parameter measured by the Explorer VII satellite was the upward flux of long-wave radiation (Weinstein and Suomi, 1961). Since the downward flux of the long-wave radiation at the satellite height of 560–1090 km is practically zero, the net flux is equal to the upward flux. This has been observed to vary from 0.23 to 0.42 ly min^{-1} in the latitude belt from 20N to 50N.

The upward flux at the top of the atmosphere is an estimate of the flux divergence of the entire column of the atmosphere because of the small variation of the net flux at the bottom of the column. This is further demonstrated in Fig. 2 where the upward fluxes at the 25-mb level, taken from the radiometersonde observations at Washington, D. C., International Falls, Las

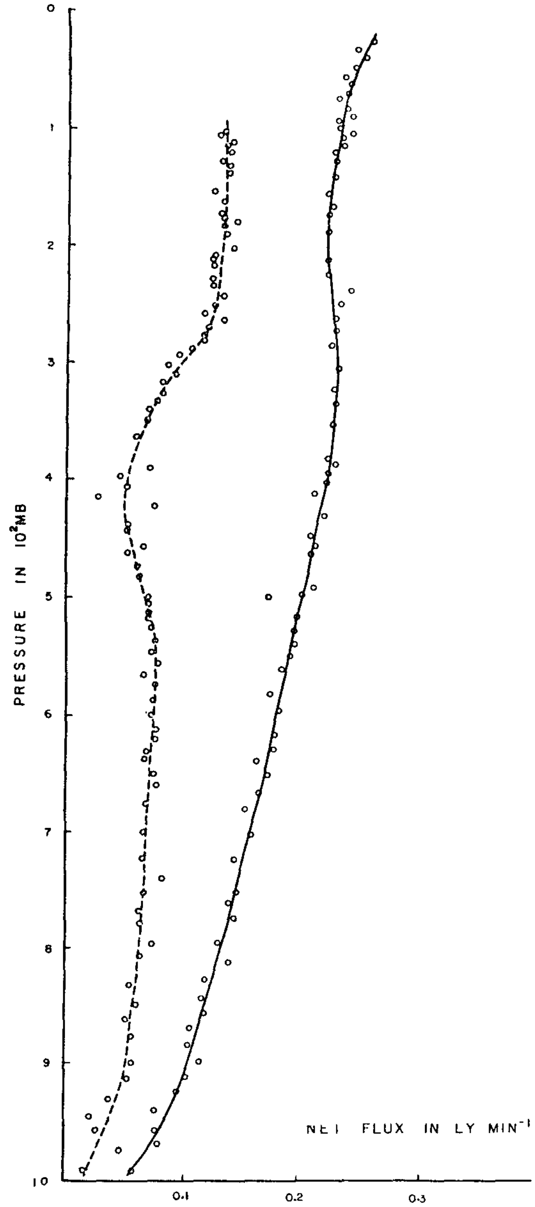

FIG. 1. Vertical variation of the net flux observed by radiometersonde at Washington, D. C. Solid curve is the net flux on 11 January 1961 in an anticyclone (clear sky condition). Dashed curve is the net flux observed on 14 January 1961 in a storm (with clouds).

Vegas, Miami, Curacao and St. Martins in the winter seasons of 1959, 1960 and 1961, are plotted against the corresponding flux divergence. Sabatini (1962) found a linear correlation coefficient of 0.88 between the upward flux to space and the infrared flux divergence from 193 radiometersonde soundings taken in the United States and the Caribbean. *Thus the upward flux of the infrared radiation observed by the satellite can be considered an estimate of the net infrared flux divergence.*

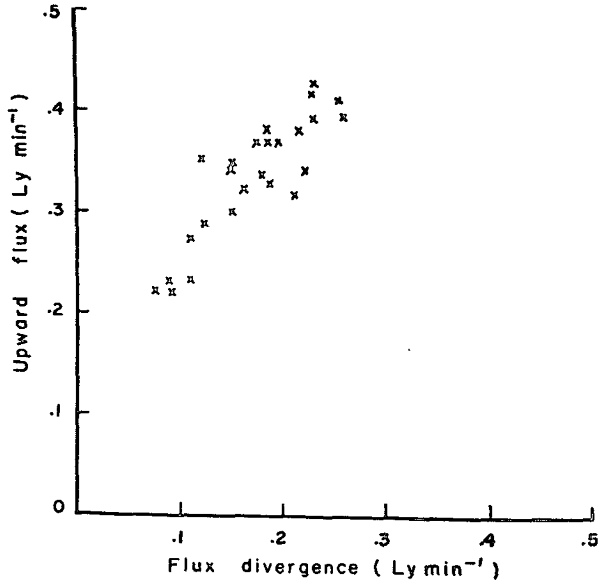

FIG. 2. Scatter diagram of the upward flux at the 25-mb level and the atmospheric flux divergence of a layer from surface to 100 mb, based on radiometersonde data.

3. Generation of eddy available potential energy

According to Lorenz (1955) the total generation of available potential energy can be broken down into the generation of zonal and eddy available potential energy. The eddy generation is an integral of the product of the departure of the heating rate from its latitudinal mean and the departure of the temperature from its latitudinal mean. Since the temperature is (hydrostatically) proportional to $\partial z/\partial p$, the eddy generation, G_e, may be expressed as

$$G_e = -\frac{1}{A}\int\int\int \frac{p}{R\bar{T}\left(1-\dfrac{\bar{\Gamma}}{\Gamma_d}\right)}\left(\frac{\partial z}{\partial p}\right)^*\left(\frac{dq}{dt}\right)^* dxdydp.$$

In this formula, $\partial z/\partial p$ will be replaced in effect by its vertical mean value, the 1000–100 mb thickness. The same will be done for dq/dt, the cooling rate per unit mass. We thereby ignore the small correlations between $\partial z/\partial p$ and dq/dt due to deviations from their vertical average. A is the total area, $p=600$ mb is the mean pressure, R is the gas constant of dry air, T is the mean temperature of the layer, Γ_d is the dry lapse rate (g/c_p), and $\bar{\Gamma}$ is the 700–300 mb mean lapse rate. The asterisk indicates the departure of a quantity from its latitudinal average.

The warm humid tropics lose more energy to space than do regions at higher latitudes. The covariance between zonally averaged thickness and zonally averaged relative warming is negative almost everywhere. However, in middle latitudes the longitudinal covariances represented in the formula above are predominantly positive. Some positive areas exist in the tropics but in general the longitudinal covariance in the tropics is negative or zero. The reliability of the estimates of covariance in tropical areas is much lower than the estimates at higher latitudes because there are far fewer radiosonde observations in the oceanic tropics. Moreover the distance between successive orbit passes is maximum in the tropics. One is, therefore, forced to do a considerable amount of interpolation in low latitudes.

Because of these limitations, we chose a region covering 30–50N and 40–180W (50–170W for cases in February). The longitudinal limits were determined by the telemetry coverage from the satellite. Thickness maps (1200 GCT) were analyzed for the period 1 through 3 December 1959, 1 through 8 February and 1 and 4 April 1960 as were the corresponding infrared radiation maps. The integrand was computed at 145 points (125 points for cases in February) on a grid system spaced five degrees apart. The covariances between 1000–100 mb thickness and the infrared radiation cooling rate were then evaluated in this region.

A positive generation of eddy available potential energy by the radiative process requires a positive correlation between relative heating and the temperature field. In other words, there is considerable generation of eddy available potential energy when the atmosphere is cooled at a low rate where the temperature is high or when the atmosphere is cooled at a high rate where the temperature is low. As an example, the linear correlation coefficient of the 1000–100 mb thickness and the cooling rate along 50N on 1 April 1960 has a positive value of 0.60.

In order to show the time variation of the production of eddy available potential energy in middle latitudes by this process, daily values of generation of eddy available potential energy are plotted in Fig. 3. The production of eddy available potential energy by the infrared radiative process are positive on 2, 3 December 1959, 3 to 8 February 1960, 1 and 4 April 1960, but negative on 1 December 1959, and 1, 2 February 1960. An appreciation of their magnitude can be obtained by comparing them with an estimate of the frictional dissipation of kinetic energy in the surface layer. According to Lettau (1959) the frictional dissipation is a function of surface roughness (Z_0), geostrophic wind speed (Vg) and latitude (ϕ). The region under consideration is approximately 1/3 land and 2/3 ocean. Taking the surface roughness over the continent as 49.0 cm and over the ocean as 0.2 cm and the average geostrophic wind speed is 12 m sec^{-1}, one finds the mean

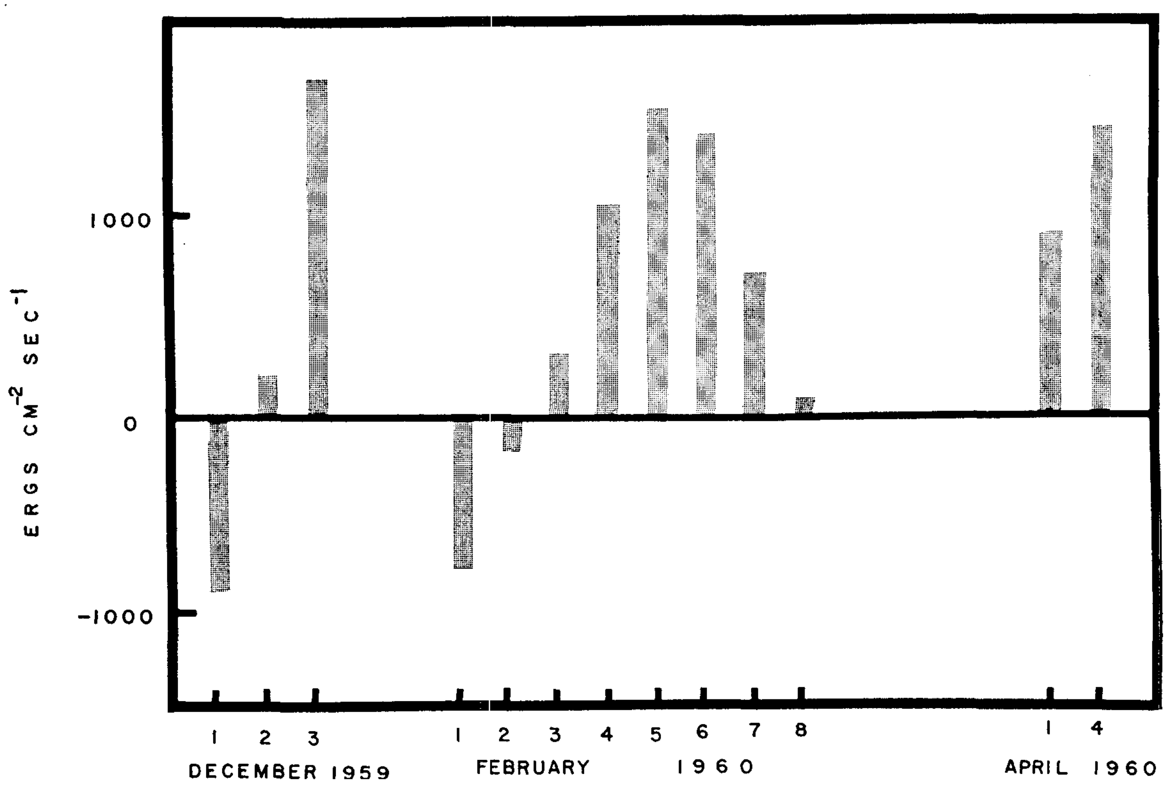

FIG. 3. Time variation of the generation of eddy available potential energy averaged over a region of 30 to 50N, 40 to 180W (50 to 170W for the cases in February).

TABLE 1. Generation of eddy available potential energy.

Authors	Energy production (ergs cm^{-2} sec^{-1})	Latitudinal band	Remark
Wiin-Nielsen and Brown (1962)	−3500	20–90N	Total heating based on 2 parameter model (January)
Clapp (1961)	+382 +174	30–60N 0–60N	Total heating based on heat-balance method (Dec.–Feb.)
Winston and Kruger (1961)	+500 to −6000	20–90N	Total heating (27 Dec. 58–13 Jan. 59)
Suomi and Shen	+580	30–50N	Infrared cooling 1–3 Dec. 1959, 1–8 Feb. 1960, 1, 4 April 1960

frictional dissipation in the region estimated by Lettau's nomogram is 1930 ergs cm^{-2} sec^{-1}. The available potential energy produced on 3 December 1959, 5 and 6 February 1960, and 4 April 1960 is close to that removed by friction. However, it should be emphasized that this value of friction is only an order of magnitude estimate.

Independent estimates of the generation of eddy available potential energy are listed in Table 1. Clapp (1961) obtained a positive value for the generation of eddy available potential energy due to the total heating, while Wiin Nielsen and Brown (1962) obtained a large negative value. The values of Winston and Kruger's computation (1961) vary from a small positive value to a large negative value. The average value of generation by infrared cooling for the cases studied in this paper is less than the estimated value of dissipation by friction but equal to or greater than the estimates of eddy generation from other sources. More cases must be studied to determine whether this mode of generation of eddy available potential energy is an important meteorological phenomenon or merely a straw added to a bonfire.

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