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CWB 9757

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University of Wisconsin
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# INFRARED RADIATION MEASUREMENTS IN THE ATMOSPHERE

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# INFRARED RADIOMETER SOUNDINGS ON A SYNOPTIC SCALE

## I. INTRODUCTION

Large synoptic scale radiative balances in the atmosphere have already been determined by calculation (Moller, 1956, London, 1957, Houghton, 1954). Recently, single station measurements of the infrared radiation flux in the troposphere and stratosphere have been obtained using balloon-borne radiometersondes (Pohl, 1956, Suomi, Staley and Kuhn, 1958, Kuhn, Suomi and Darkow, 1959).

Long wave radiation measurements from above the atmosphere have been underway since October 13, 1959, the date of the launching of the United States' satellite, Explorer VII. They are also planned for the meteorological satellite Tiros II.

The purpose of this paper is to present the results of a synoptic measurement of radiation flux obtained from a simultaneous ascent of 15 radiometersondes. The geographical area covered is Central and Western United States. To the writers' knowledge, this represents the first measurements of atmospheric infrared radiation flux divergence on a synoptic scale.

## II. OBSERVATION NETWORK

Radiometersonde measurements were made at fifteen cooperating U.S.W.B. upper air stations at 06Z, 29 July, 1959. The balloon-borne radiometersondes described by Suomi and Kuhn (1958) and Suomi, Staley and Kuhn (1958) were released on two lines of Weather Bureau upper air stations. One group was on the line: Point Arguello, California through International Falls, Minnesota. The other formed a line from San Antonio to International Falls. In addition to the upward and downward streams of infrared radiation, air temperatures, pressure, and humidity observations were obtained simultaneously. Since all soundings were made at night no solar energy was involved.

Net radiation, $R_n$, is defined as the difference between the upward, $R_L\uparrow$, and downward, $R_L\downarrow$, streams of infrared radiation, positive when directed away from the earth's surface, thus,

$$R_{net} = R_L\uparrow \; - \; R_L\downarrow > 0 \qquad (\text{cal cm}^{-2}\ \text{min}^{-1})$$

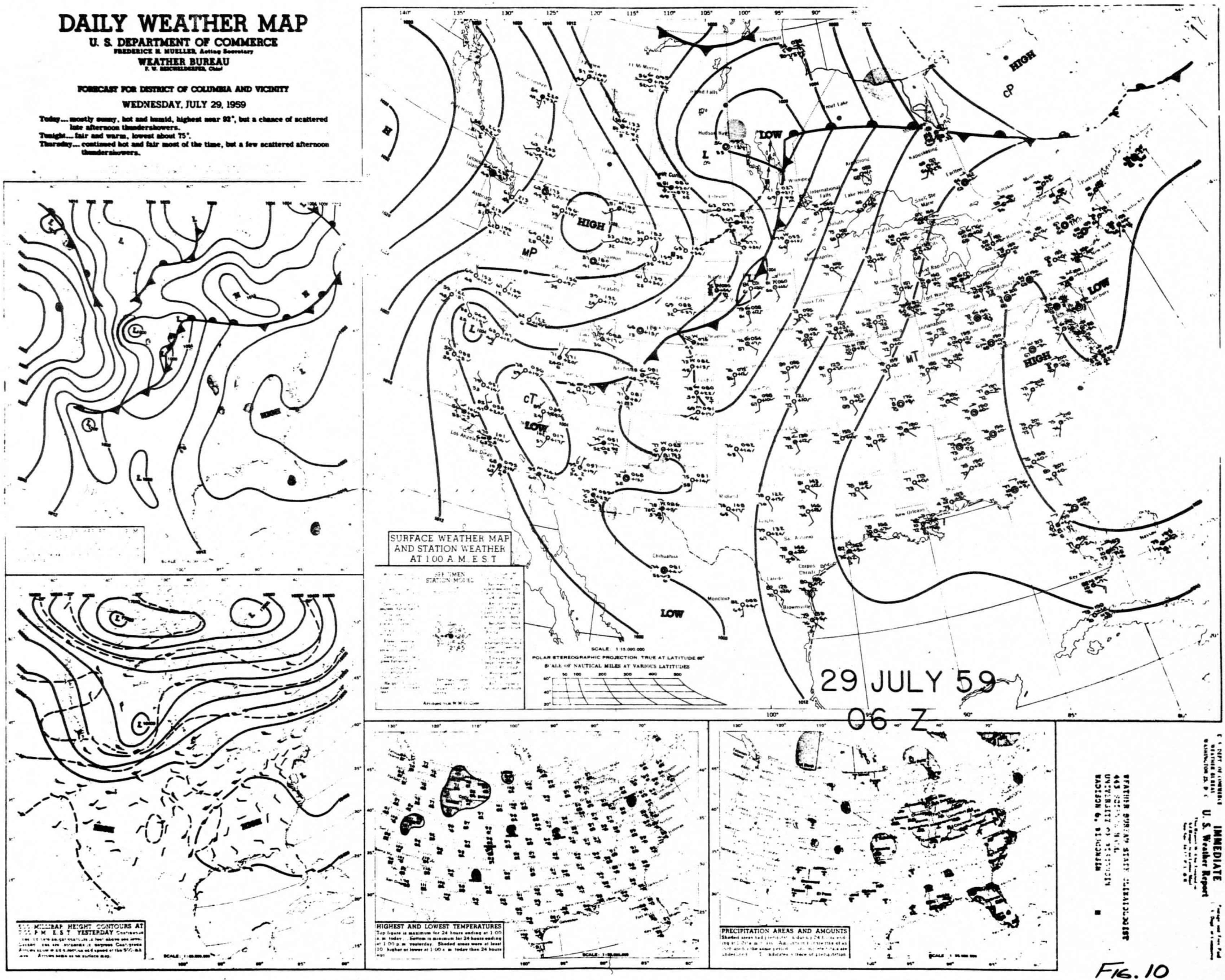
The radiometersonde directly measures $R_L\uparrow$ and $R_L\downarrow$ separately. Details of its theory and construction are given in reference by Suomi and Kuhn (1958).

## III. THE RADIATION DATA

Two sets of cross sections through the atmosphere have been evaluated, one is for the line from Point Arguello, California to International Falls, Minnesota and the other is for the line from San Antonio, Texas to International Falls. Figure 1 is the synoptic surface chart.

The cross sections have been evaluated to show the following data:

1. Temperature and humidity profiles (Figs. 2 and 3).
2. Net radiation profiles (Figs. 4 and 5).
3. Vertical divergence of net radiation expressed in cal $cm^{-2}$ $min^{-1}$ per 100 millibars (Figs. 6 and 7).



# DAILY WEATHER MAP

U. S. DEPARTMENT OF COMMERCE
FREDERICK H. MUELLER, Acting Secretary
WEATHER BUREAU
F. W. REICHELDERFER, Chief

FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY

WEDNESDAY, JULY 29, 1959

Today... mostly sunny, hot and humid, highest near 92°, but a chance of scattered late afternoon thundershowers.
Tonight... fair and warm, lowest about 75°.
Thursday... continued hot and fair most of the time, but a few scattered afternoon thundershowers.

WEDNESDAY, JULY 29, 1959

SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M. E.S.T

500 MILLIBAR HEIGHT CONTOURS AT 7:00 P.M. E.S.T. YESTERDAY

HIGHEST AND LOWEST TEMPERATURES

PRECIPITATION AREAS AND AMOUNTS

29 JULY 59
06 Z

U. S. DEPT. OF COMMERCE
WEATHER BUREAU
WASHINGTON 25, D. C.

IMMEDIATE
U. S. Weather Report

WEATHER BUREAU STATE CLIMATOLOGIST
443 SCIENCE HALL
UNIVERSITY OF WISCONSIN
MADISON 6, WISCONSIN

FIG. 10

Figure 1.

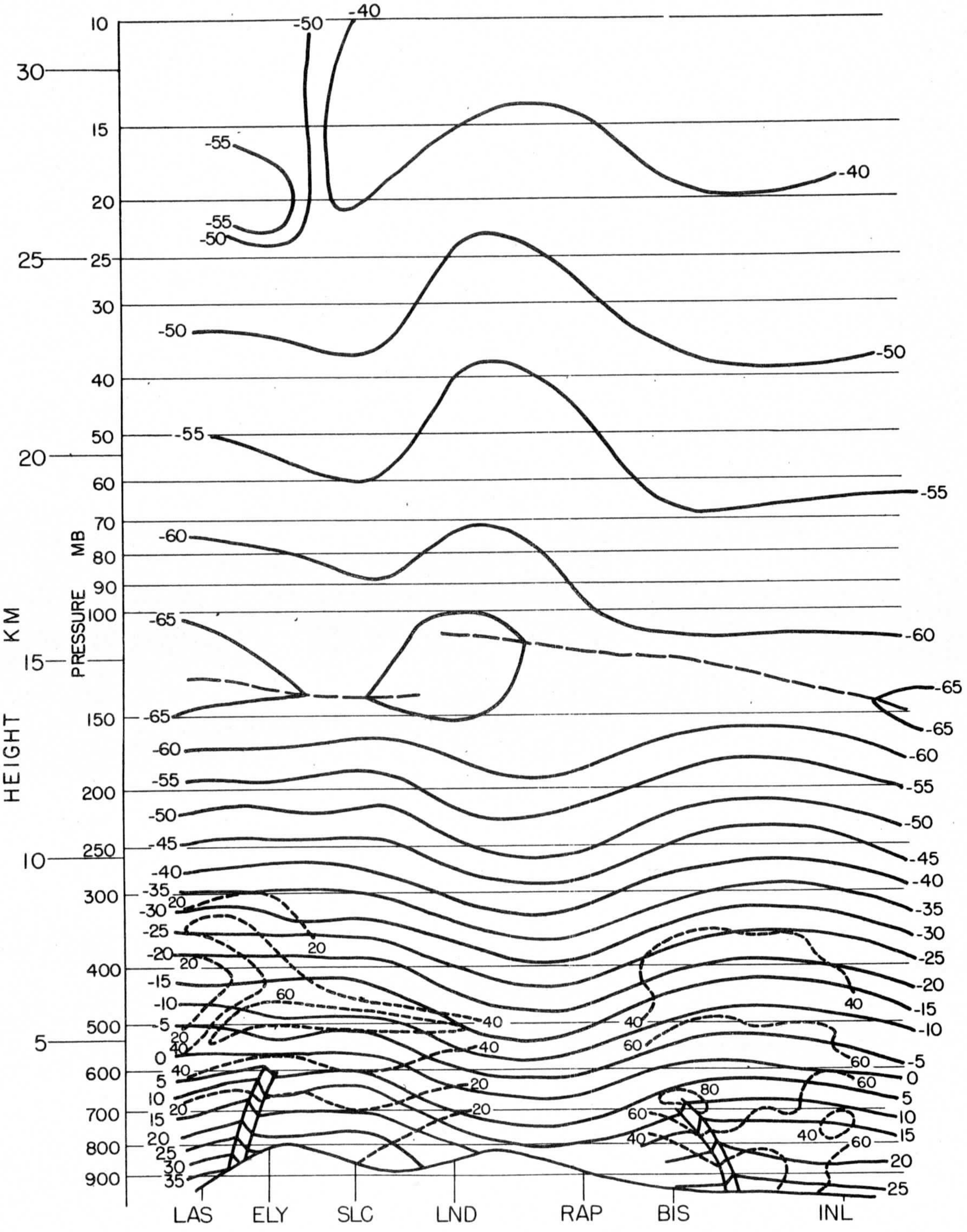

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Figure 2.

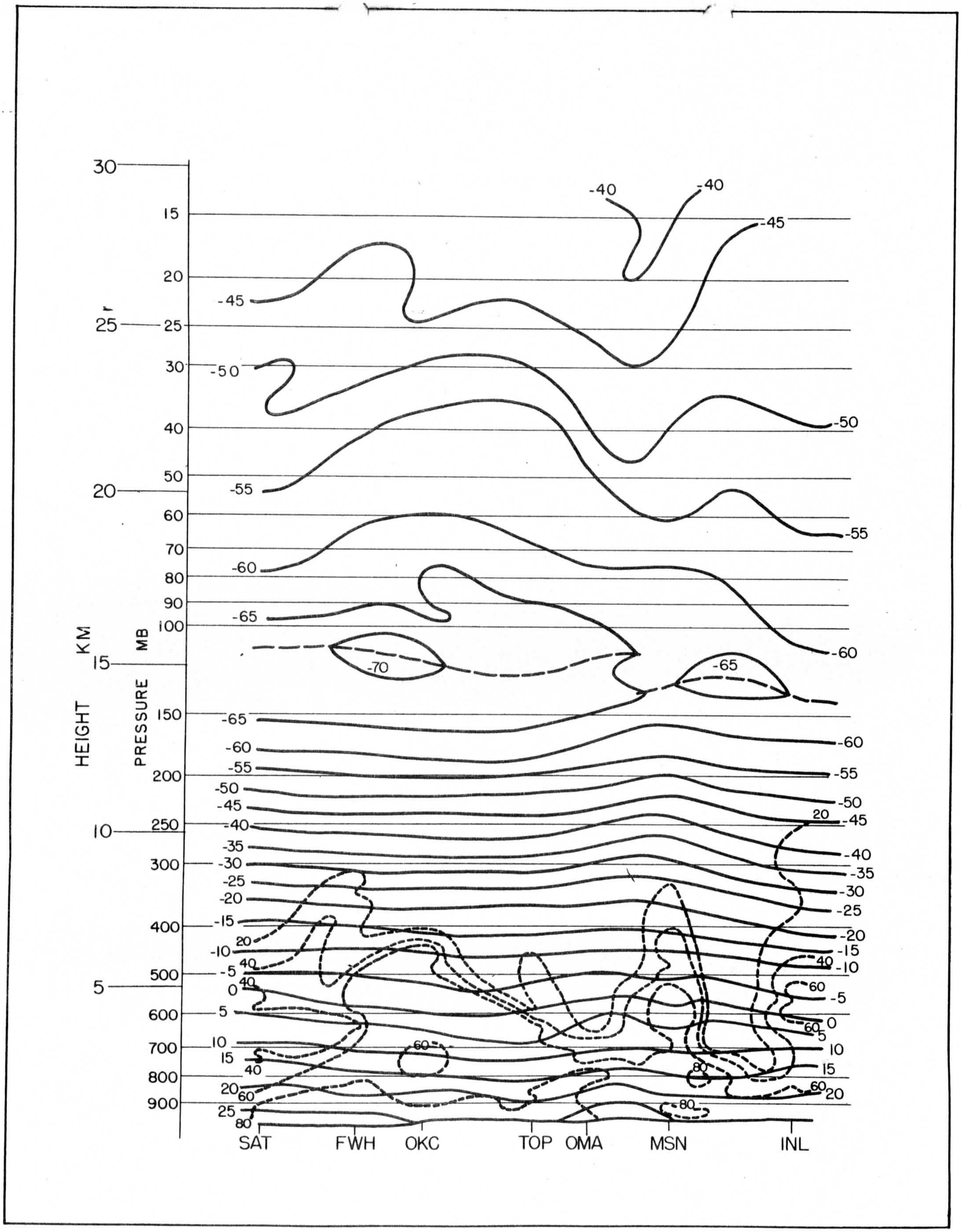

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Figure 3.

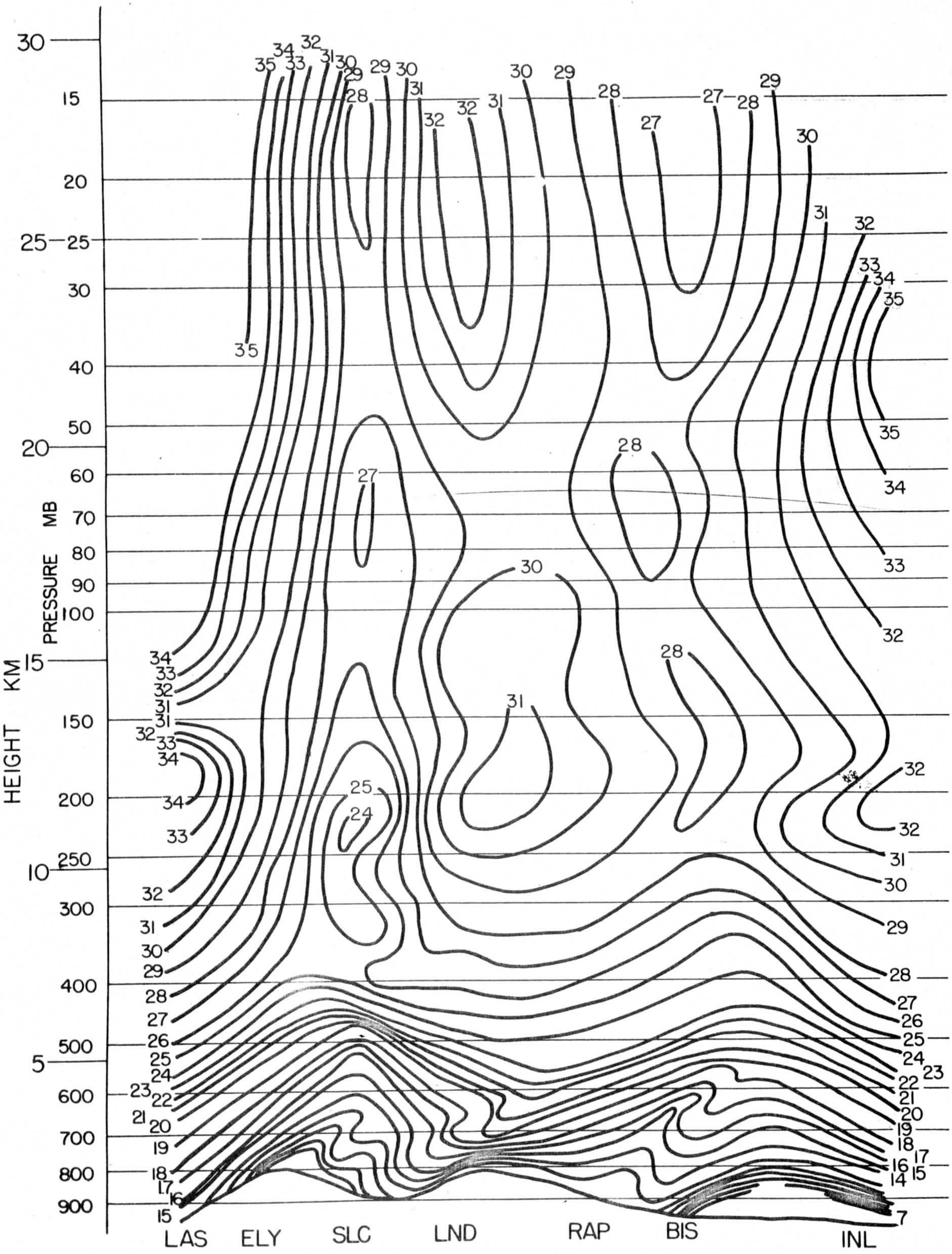

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Figure 4.

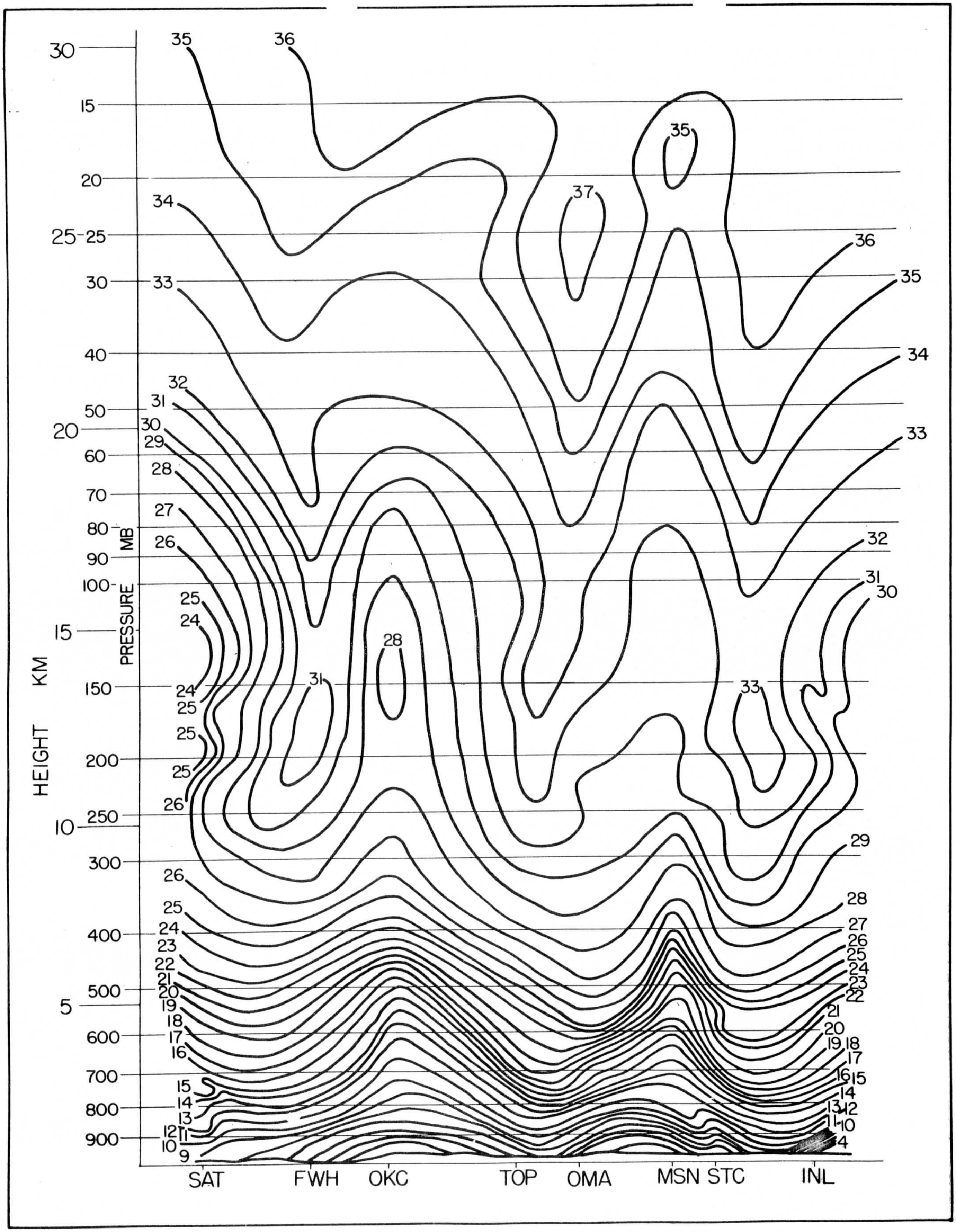
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Figure 5.

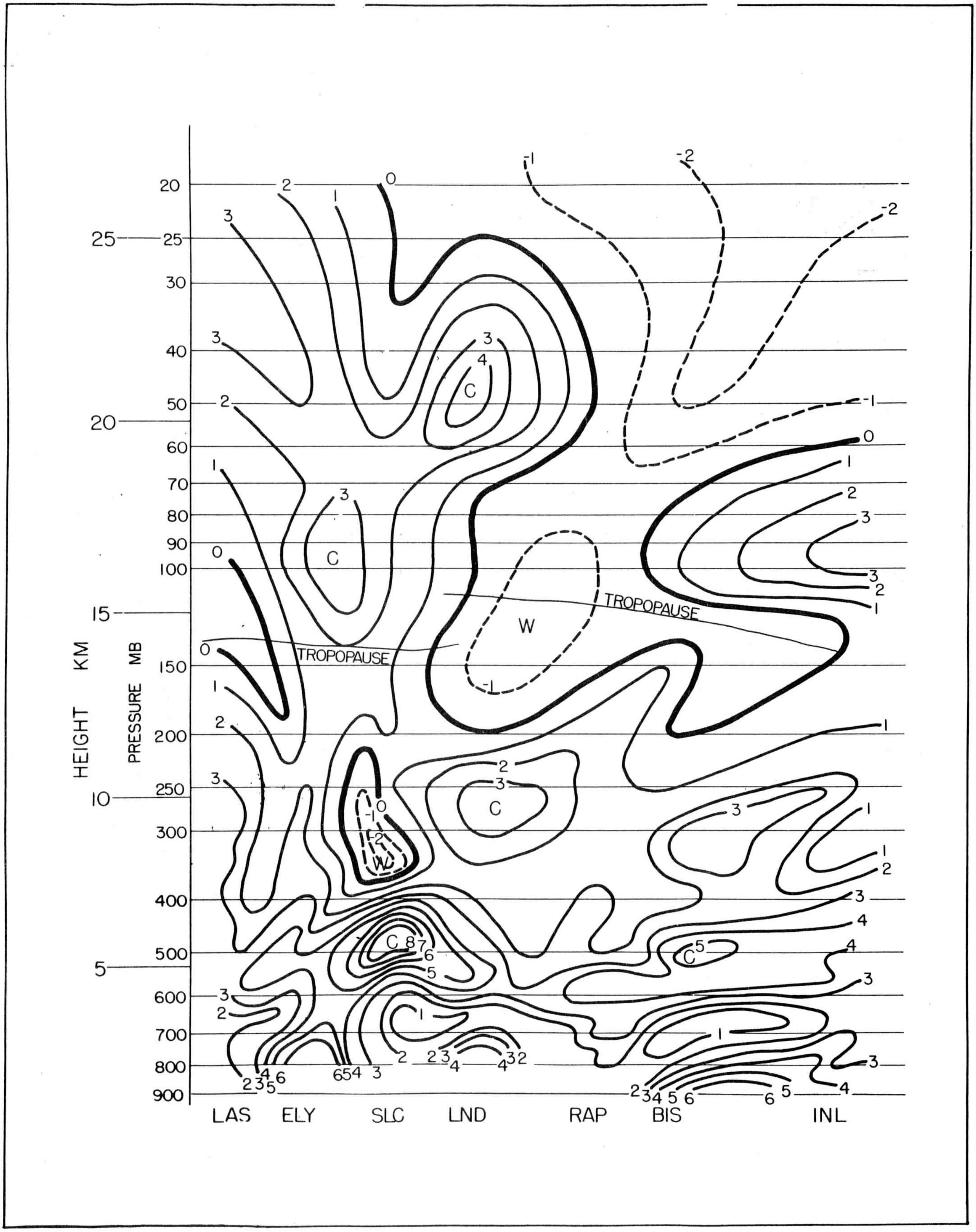
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Figure 6.

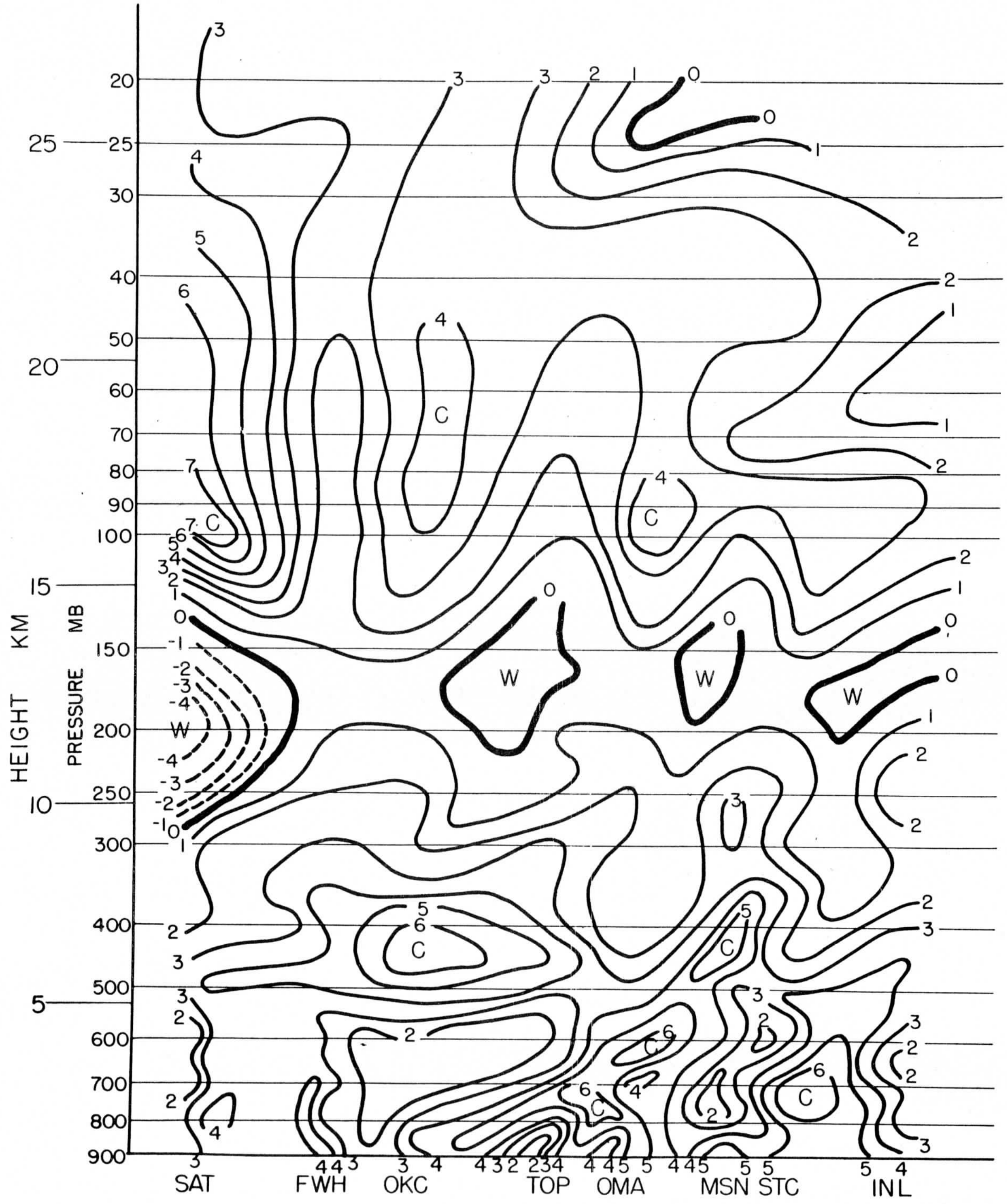
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Figure 7.

The data given in (1) and (2) above are from the radiometersonde soundings directly. The data in (3) is obtained by a differentiation with respect to pressure of the data given in (2). It can be expressed as a cooling rate from the relationship:

$$\frac{\partial T}{\partial t}\left({}^{\circ}C/day\right) = -\frac{g}{C_p}\frac{\Delta R_n}{\Delta p}$$

where values of $\Delta R_n / \Delta p$ correspond to 0.01 cal $cm^{-2}$ $min^{-1}$ per 100 millibars represent cooling rates of 0.6°C per day, g is acceleration of gravity in c.g.s. units, $C_p$ is the specific heat of air at .239 c.g.s. It is possible to perform the mechanics of differentiation with respect to pressure in several ways. One method is to perform the differentiation on each net radiation sounding and from this draw a cross section designating isolines of cooling rates. The other is to prepare cross sections of the atmosphere plotted on a linear pressure scale, then using graphical differentiation to obtain the cooling rates. The latter procedure was used because it is somewhat easier to interpolate cooling rates between stations. Results in turn were then plotted on a logarithmic pressure scale. This was done for (3) above. Perhaps as experience is gained with this type of analysis, the graphical differentiation step will be unnecessary.

## IV. DISCUSSION OF RESULTS

### 1. TROPOSPHERIC RADIATION

Figures 4 thru 7 indicate that the greatest divergence of net radiation in the vertical occurs in the lower half of the troposphere. The average divergence for the complete group of stations from the surface to the 400 mb level is 0.20 ly/min. In contrast, the average divergence froom 400 mb to the 15 mb level for the same stations is 0.07 ly/min. In this example 75% of the divergence of net radiation occurred in the lower 7 kilometers of the troposphere. In this case the troposphere was the principal heat sink for the atmosphere.

Radiation cooling, occurring in the lower half of the troposphere centered at cloud tops or above moist layers, may produce instability. Instability was present at INL, STC, MSN, OMA, TOP averaging -1 for the Showalter Stability Index. This radiational cooling may have played a part in the occurrence of nocturnal thunderstorms on the 29th and again, farther east, on the 30th, ahead of the front (Fig. 1) in that part of the cross section where strongest flux divergence was measured. Since representative radiational cooling can be measured several hours before the outbreak of such storms, a radiational profile may be important as one of the factors in picking out potentially unstable areas.

It is interesting to note that the tropospheric radiational pattern is the controlling feature of the radiational pattern at the top of the flights. This has important implications for infrared measurements made from satellites. Figures 4 and 5 illustrate this feature. In both instances the outgoing net radiation is less over the frontal regions than on either side. This is expected on the basis of cold, high level, moist radiating surfaces such as middle clouds. In this group ascent the flux divergence in the lower 400 mb appears to fix the flux pattern at 30 km.

## 2. STRATOSPHERIC RADIATION

### a. RADIATORS

The radiation balance in the stratosphere depends upon the absorption of solar radiation by ozone, water vapor, and upon the infrared emission by these same radiators and by $CO_2$ and particulate matter.

However, until recently, there have been very few direct measurements of stratospheric emission in the infrared. Estimates of infrared stratospheric emission were made by computations based on laboratory measurements of the transmissivities of carbon dioxide, ozone and water vapor for low pressure and absorber concentrations. The radiometer measurements, on the other hand, measure total radiation for any and all radiators present.

If we can independently obtain the radiative contribution to infrared cooling of $CO_2$ and $O_3$ in the lower stratosphere, then the difference between this calculation and the measured total infrared radiation gives the radiative cooling due to water vapor and other radiators. To have any meaning the calculated and observed values must have been made from the same temperature and $O_3$ profiles. Fortunately this set of observations is very close to that used by Plass for his calculated values. Table I shows the agreement between Plass' temperatures and ours to be good. Plass' (1956) radiative cooling computations were based on an average $O_3$ concentration at middle latitudes after the NRL rocket measurements of 14 June, 1949, and for the rocket panel temperature profile. Comparing his computations with the measured cooling rates between the tropopause and 21 km we obtain the excess or deficiency, if any, of the total measured cooling with respect to that due to $CO_2$ and $O_3$. This necessitated, however, verifying that our temperature profiles, specifically the temperature lapse in this same interval, are the same as those used by Plass.

In Figures 6 and 7, from 21 through 25 km, the measured radiational cooling rates over Las Vegas, San Antonio, Fort Worth and Oklahoma City, were equal to or exceeded $-1.8^{o}C$/day. Plass' computed values of the total $CO_2$ and $O_3$ cooling, using average $O_3$ and $CO_2$ concentrations, vary from $-0.3^{o}C$/day at 21 km to $-1.4^{o}C$/day at 25 km. At 21 km the average measured cooling above Fort Worth, Las Vegas, San Antonio and Oklahoma City is $-2.2^{o}C$/day. Since our measurements were in deep tropical air, for the most part, and since Plass used the average mid latitude $O_3$ concentration, the excess of measured over computed warming is, if anything, less than would be expected. Plass' figure for $CO_2$ and $O_3$ cooling is $-0.3^{o}C$/day at 21 km. Table I summarizes these comparisons.

Since the observed temperature lapses agree essentially with the Rocket Panel profile the excess total measured cooling, $\partial T/\partial t$, in this ascent could be caused by any or all of the following factors:

(1) a concentration of $O_3$ below 21 km and above tropopause;

(2) a concentration of ice crystals below 21 km and above tropopause;

(3) particulate matter below 21 km and above the tropopause.

While one cannot positively rule out the first factor, even for a summer situation, the latter two seem the most likely. Repeated haze and Cirrus reports above the tropopause from balloon observations support this observation (Farquharson, 1952, Grant, 1951, and Endlich and McLean, 1956).

TABLE I

| Stations at 25 km | SAT | FWH | OKC | LAS | MEAN | PLASS |
|---|---|---|---|---|---|---|
| df/dz (°C/km at 25 km) | 2.3 | 2.0 | 2.0* | 2.1* | 2.1 | 2.0** |
| $\partial T/\partial t$ (°C/day) | -1.8 | -1.8 | -1.8 | -1.8 | -1.8 | -1.4 |
| Excess of measured total radiative cooling over computed $CO_2$-$O_3$ cooling | -0.4 | -0.4 | -0.4 | -0.4 | -0.4 | —— |
| Stations at 21 km | | | | | | |
| dT/dz (°C/km at 21 km) | 2.0 | 1.0 | 1.7* | 1.7* | 1.6 | 2.0** |
| $\partial T/\partial t$ (°C/day) | -3.0 | -1.5 | -2.1 | -1.5 | -2.0 | -0.3 |
| Excess of measured total radiative cooling over computed $CO_2$-$O_3$ cooling | -2.7 | -1.2 | -1.8 | -1.2 | -1.7 | —— |

The area of large scale warming occuring from 15 km upward over the Lander-International Falls line (Fig. 6) suggests another feature. In spite of the steady decrease in the $O_3$ concentration above 22 km, from 0.01 cm/km to 0.0003 cm/km (Plass, 1956), an underneath approach to the high temperature level near 50 km could result in radiative convergence. However, there is also evidence of drastic departures from the accepted level of maximum $O_3$ concentration at 22 km. This also could produce such warming. In any case departures from a typical case in the stratosphere are too great to be ignored.

### b. RADIATION AT THE TOP OF THE ATMOSPHERE DETERMINED MAINLY BY FLUXES IN LOWER ATMOSPHERE

As would be expected the strongest flux divergence occurs immediately above moist or cloud layers. The strongest flux convergence and resulting warming, on the other hand, occur just beneath the base of clouds or inversions.

The synoptic chart for 06Z on the 29th of July (Fig. 1) and the individual temperature and humidity soundings for the stations along the North-South line (Fig. 3) show moist tropical air was present. The mT air had persisted along this line for several days prior to the ascent date.

The cross section of figure 3 showing high relative humidities and warm air distributed as nearly horizontal isotherms to the base of the tropopause identifies the air mass from SAT through INL as mT. A Rossby diagram for any of these stations further substantiates this fact.

On the other hand, the cross section of figure 2 from LAS through INL indicates drier, cooler, polar air between SLC and BIS. Between Lander and Rapid City the air is 10°C colder than at any of the stations in the mT air mass. Humidities are also much lower at Lander and Rapid City. Thus, synoptically, the two contrasting air masses are identified. Interestingly, direct radiation measurements at heights equal to or greater than 25 kilometers can also be used for such identification.

The contrast in the infrared radiation flux at 25 km over the group of stations in the mT air and those in the mP air is evident. Those stations in mT air (Fig. 5) average 0.35 ly/minute for the measured net radiation. The two stations in the mP air (Fig. 4) average 0.27 ly/min net radiation. With the weak frontal situation the radiometersondes detected a twenty-two percent difference in the net radiation from one air mass to the other. It is apparent that satellite radiation measurements could detect such differences over a much wider range. Ambiguity can occur, however, in the differentiation of air masses by this technique when comparing net radiation over clouds, and over cold clear air masses with surface temperatures at or near cloud top temperature. Table II gives 06Z reported weather at each station.

From these measurements over two summertime air masses, not having strong contrasts, it seems evident that either balloon-borne or satellite-borne radiometers can detect air mass types.

### c. MEASURED HEATING OR RELATIVE WARMING OCCURS BELOW TROPOPAUSE AND NOT AT TROPOPAUSE

Staley (1957) in using Braesfield and Barret's soundings has computed the radiative cooling in the vicinity of the tropopause by means of Brooks' (1950) Tabular method. He finds warming centered on the tropopause relative to the layers above and below. Figure 7 demonstrates a frequently observed feature of infrared radiation profiles in the vicinity of the tropopause. The maximum "relative" warming occurs from 25 to 50 millibars below the tropopause rather than centered at the tropopause. A more detailed analysis of measured radiative effects in the vicinity of the tropopause is being prepared by Mr. G.L. Darkow of the Department of Meteorology, University of Wisconsin. This result will be reported on later.

TABLE II - Reported WX for flights 00Z 29 July 1959

| Station | PPP | TTT | RH | WX |
|---|---|---|---|---|
| TOP | 981.4 | 25.8 | 0.81 | ○ |
| SLC | 869.6 | 23.9 | 0.28 | ⦶ 4Ac |
| INL | 965.1 | 25.4 | 0.72 | ○ |
| OMA | 963.8 | 24.0 | 0.86 | ⦶ 2Sc |
| OKC | 969.1 | 23.9 | 0.91 | ○ |
| FTW | 993.9 | 26.8 | 0.79 | ○/⦶ |
| STC | 972.2 | 25.2 | 0.76 | ○ |
| LAS | 929.7 | 30.8 | 0.10 | ○ |
| SAT | 986.8 | 26.0 | 0.80 | ⊕ 9St |
| LND | 829.0 | 18.8 | 0.34 | ○ |
| ELY | 808.0 | 21.8 | 0.17 | ⦶ ⊥ Cu |
| BIS | 949.9 | 25.6 | 0.16 | ⦶ 3As* |
| MSN | 975.7 | 25.7 | 0.77 | 120⦶/-⦶ |

*RW - occurred 30 sec. after release

Results of this synoptic ascent indicate that valuable and world-wide data on weather identification can be obtained at satellite heights such as from Explorer VII. Though balloon-borne measurements of the flux of infrared radiation cannot range as wide or as high as those obtained via the satellites, their advantages in providing vertical detail of <u>flux divergence</u> is very useful.

## FIGURE LEGEND

| | |
|---|---|
| Fig. 1: | U.S. Weather Bureau Surface Chart for 06 GMT 29 July 1959 |
| Fig. 2: | Atmospheric Cross Section for 06 GMT 29 July 1959,<br>Las Vegas through International Falls<br>Solid lines are isothermes<br>Dashed lines are isolines of relative humidity<br>Double line is frontal boundary |
| Fig. 3: | Atmospheric Cross Section for 06 GMT 29 July 1959,<br>San Antonio through International Falls<br>(All lines identified the same as for Figure 2) |
| Fig. 4: | Atmospheric Cross Section of Net Radiation for 06 GMT 29 July 1959,<br>Las Vegas through International Falls<br>Solid lines are isolines of net radiation in hundreths of calories per square centimeter per minute |
| Fig. 5: | Atmospheric Cross Section of Net Radiation for 06 GMT 29 July 1959,<br>San Antonio through International Falls<br>(All lines identified the same as for Figure 4) |
| Fig. 6: | Atmospheric Cross Section of Net Radiation Divergence in the vertical for 06 GMT 29 July 1959,<br>Las Vegas through International Falls<br>Solid and dashed lines are isolines of the vertical divergence of net radiation in hundredths of calories per square centimeter per minute. W indicates warming and C indicates cooling |
| Fig. 7: | Atmospheric Cross Section of Net Radiation Divergence in the vertical for 06 GMT 29 July 1959,<br>San Antonio through International Falls<br>(All lines identified the same as for Figure 6)<br>W indicates warming and C indicates cooling. |

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# MEASUREMENTS OF INFRARED RADIATION IN THE ATMOSPHERE WITH TWO TYPES OF RADIOMETERS

## ABSTRACT

In an experiment to confirm the effect of convection and conduction on the economical net radiometer we have designed, built and flown with a radiometersonde one flux plate type of net radiometer along with its required dc amplifier. The shape of the net radiation curve measured by the flux plate agreed well with that measured by the economical net radiometer.

## I. PRINCIPLE

While a few soundings of infrared radiation have been published (1) aside from those made with the economical net radiometer and calculations of infrared flux have been published, these cannot be used to confirm the measurements made by the economical net radiometer because of differences of place and time. A check can be obtained by flying a second type of radiometer on the same balloon with an economical net radiometer. We have accordingly done the experiment reported here using a flux plate radiometer in which convection does not occur and in which air conduction is small and at times zero.

This radiometer consists of a flux plate, such as is used in a ventilated radiometer (2) with thin polyethelene-covered air layers added for protection from convection. It is different from the economical net radiometer because 995‰ of the radiation flux passes through the radiometer by glass conduction, 2‰ by air conduction and 3‰ is carried by radiation. In contrast to this, radiation and conduction are about equal in the economical net radiometer. In principle the two radiometers should agree in measured values of radiation. This agreement is the confirming evidence sought in the experiment.

Both types of radiometers are protected from convection by thin air layers. Such layers suppress convection by their thinness and by a small temperature gradient in the presence of the finite viscosity of air. The experiment checks the effectiveness of these layers and the effect of the remaining air conduction. Now the flux plate develops a maximum temperature difference across itself of about .3°C. This small value makes it possible that at some heights the temperature of both sides of the flux plate may be so near the outside air temperature that air conduction as well as convection essentially vanishes. This condition is not possible in the economical net radiometer because of the large temperature difference between the top and bottom blackened layers. However because for the flux plate air conduction accounts for only 2%. of the net radiation we cannot expect to detect any differences at this equal temperature condition.

Along with the comparison of results the flux plate radiometer can give additional information. It has a 2 or 3 second time constant enabling it to detect atmospheric layers of high or low net radiation which cannot be detected by the economical net radiometer with its one minute time constant.

## II. STRUCTURE OF THE FLUX PLATE RADIOMETER

The flux plate, made of 68 turns of constantan wire wound on a glass microscope slide and copper plated to make thermocouples (2), is mounted horizontally in the middle cell of three equal air cells, each ¼ inch thick. If the symmetry of the mounting is perfect the temperature difference across the plate will be proportional to the net radiation and will not depend on the actual temperature of the plate. The symmetry is tested by passing current through a heater wire interlaced with the thermocouple wire around the glass plate. When tested this way the radiometer showed no observable asymmetry.

The flux plate radiometer weighs only 35 grams but the amplifier that goes with it weighs 2½ kg.

## III. TELEMETER

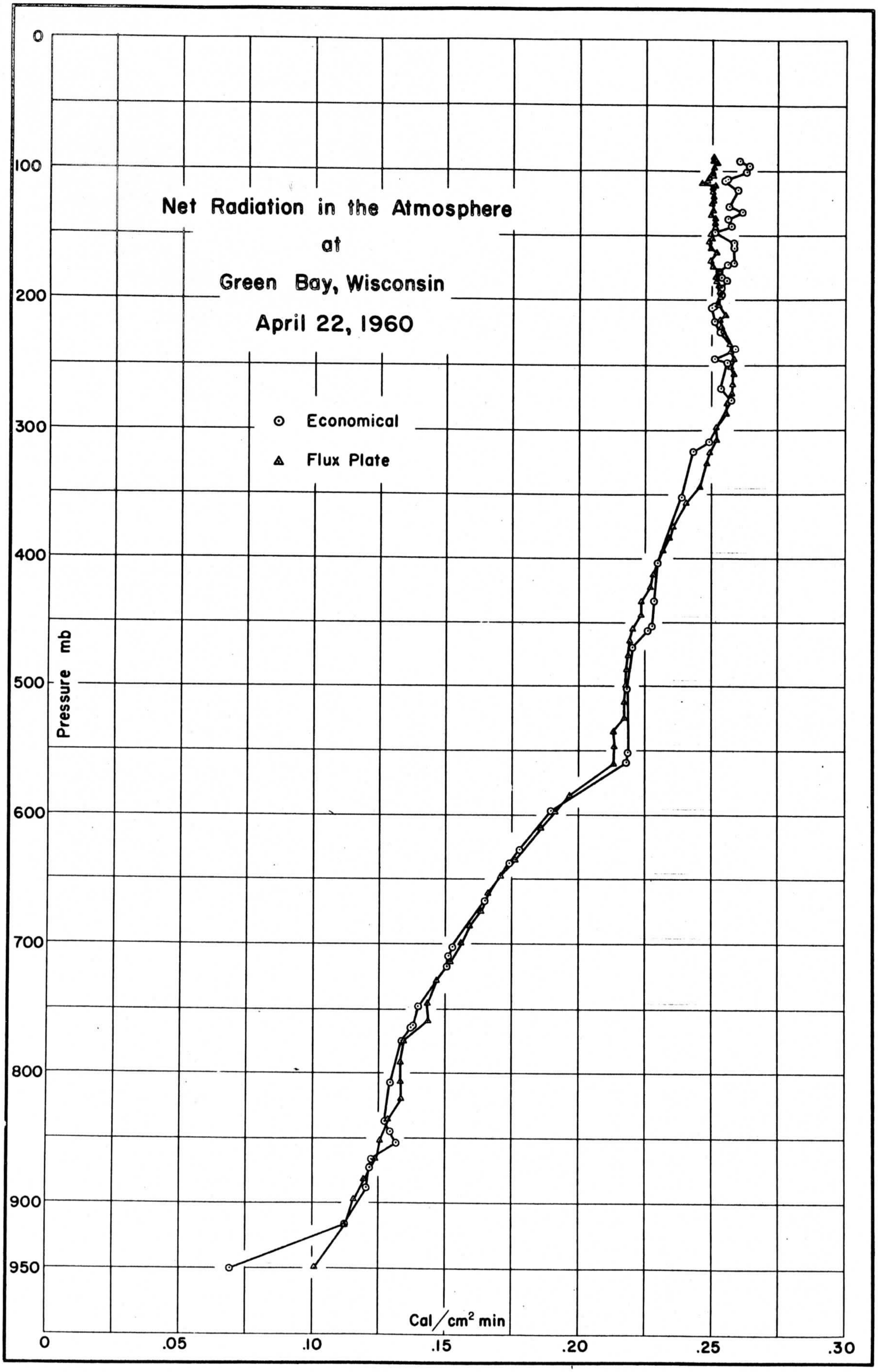
The signal from the flux plate, perhaps 500 micro-volts, is sent to the ground to be recorded by a standard radiosonde receiver. For this telemeter we have designed a chopper type dc amplifier to be flown with the radiometer. The flux plate voltage is amplified 30,000 times and applied to the grid circuit of the blocking oscillator (3) producing charges of blocking frequency. This signal, along with a reference voltage, air temperature, temperatures from the economical net radiometer and monitoring signals, is selected in sequence by a Brailsford 6 volt motor once every 30 seconds during the flight. The dc amplifier consists of a chopper and synchronous rectifier and an associated two tube ac amplifier. A transistor oscillator drives the chopper at 400 cps. The amplifier is placed in a styrofoam box at the side of the radiosonde with one radiometer at each end. The complete radiometer-sonde consisting of a radiosonde, an amplifier, two radiometers and all batteries weighs 4200 grams and has a value of about $200.

## IV. FLIGHT AND RESULTS

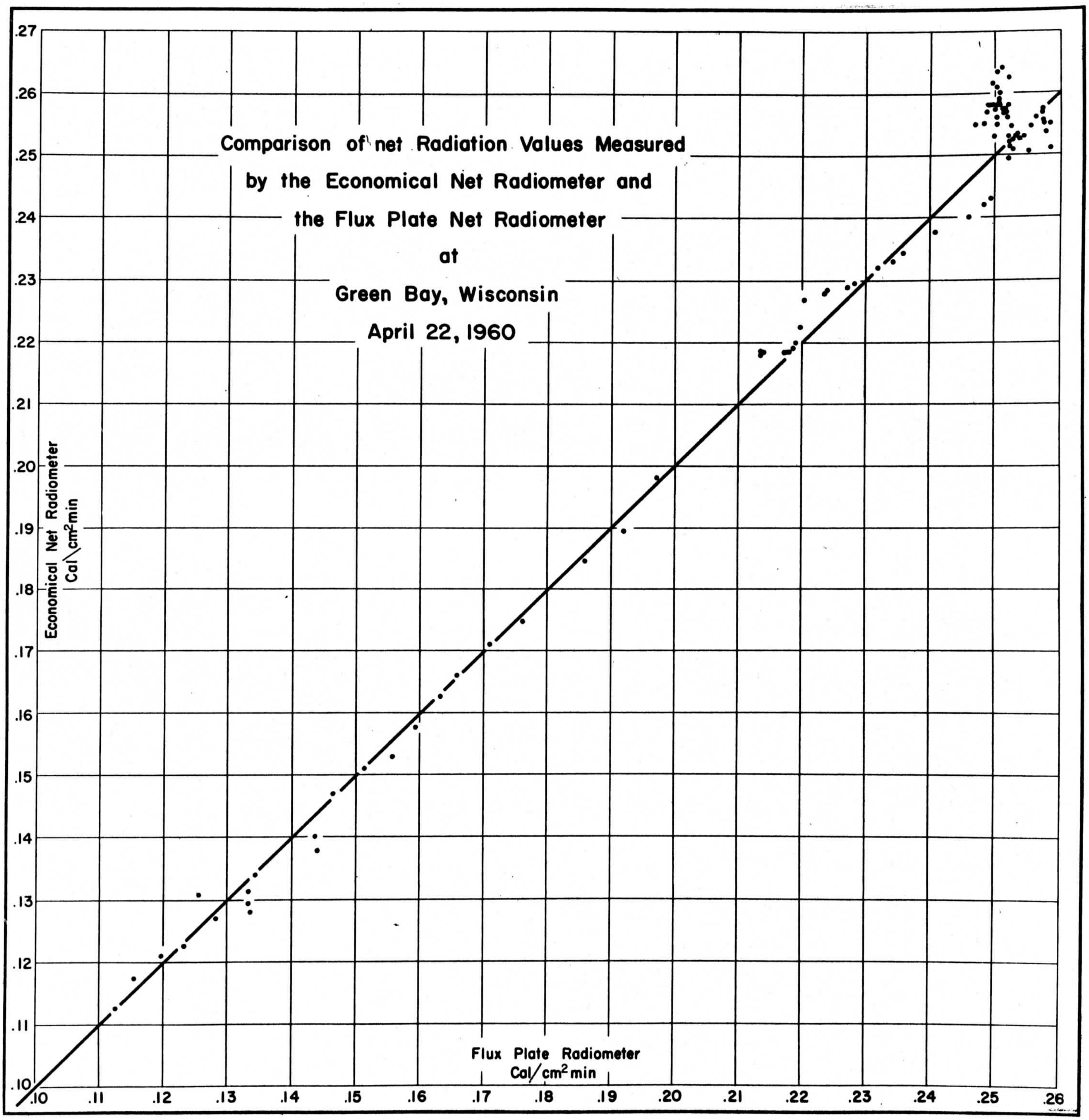
On April 22, 1960 a night flight was made using a Darex J11-22P-2000 balloon. It was launched by the staff of the United States Weather Bureau radiosonde station at Green Bay, Wisconsin. The unit functioned well up to 90 mb where a failure developed.

The two graphs following this section show the net radiation measured by the two radiometers and a comparison of them. The changes with height of the two curves were gratifyingly alike. They increased together up to 560 mb where they both sharply broke to a constant value for the next 100 mb after which they gradually increased up to a maximum at 250 mb with a slight decrease again to the top of the flight. Individual differences in the shapes were less than 5%.

Concerning the possibility of there being layers of high or low net radiation (4) not being revealed by the economical net radiometer, the flux plate measurements of this flight do not show such layers.



Net Radiation in the Atmosphere
at
Green Bay, Wisconsin
April 22, 1960



Comparison of net Radiation Values Measured by the Economical Net Radiometer and the Flux Plate Net Radiometer at Green Bay, Wisconsin April 22, 1960

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# INFRARED RADIATION MEASUREMENTS NEAR THE TROPOPAUSE

## INTRODUCTION

Numerous direct measurements of infrared radiative flux by airborne radiometers (1), (2), at a variety of locations and under a variety of synoptic conditions show large and frequent variations in the radiative cooling pattern of the upper troposphere and lower stratosphere. These variations in measured radiative flux values substantiate the existence of strong and variable absorber concentrations at these levels. The observations suggest that previous conclusions concerning the role of infrared cooling in the vicinity of the tropopause have, in general, been oversimplifications and require reassessment.

Computed radiation flux values in the upper troposphere and lower stratosphere have been based on either assumed absorber concentrations or on a relatively few measurements of water vapor concentrations at these heights. These same computational techniques make no provision for the contribution of non-black body clouds and particulate matter to radiative flux values. Observed radiation flux values indicate that computations dependent on assumed absorber concentrations underestimate the variability of the role of infrared radiational cooling at high levels.

## MID LATITUDE "ANNUAL" AVERAGE

Radiometersonde measurements under a variety of synoptic conditions in the United States and the Antarctic indicate that the atmosphere of

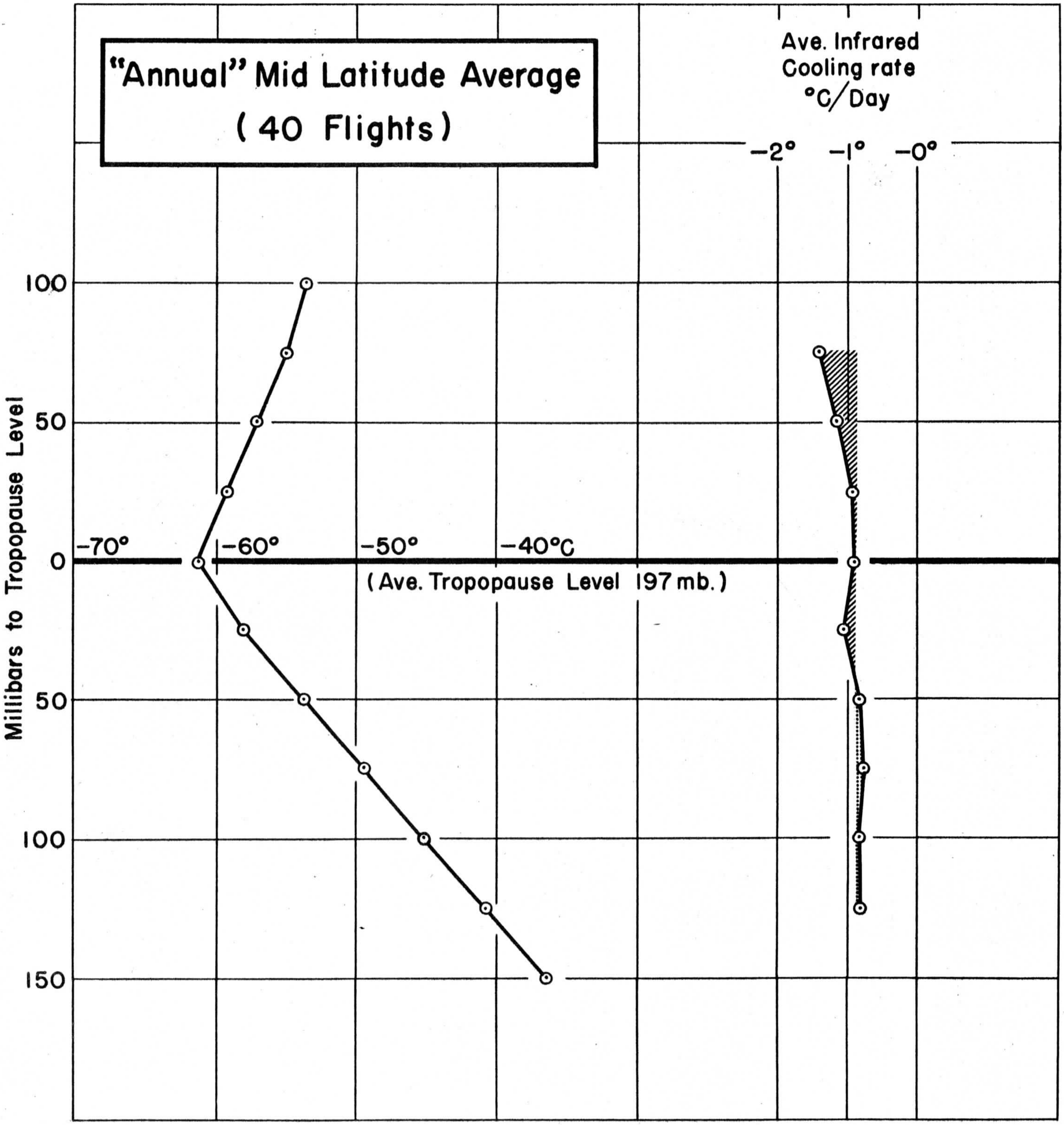
"Annual" Mid Latitude Average
(40 Flights)
Ave. Infrared Cooling rate °C/Day
−2°
−1°
−0°
100
50
0
50
100
150
−70°
−60°
−50°
−40°C
(Ave. Tropopause Level 197 mb.)
Millibars to Tropopause Level

Figure 1.

the upper troposphere and lower stratosphere is seldom in instantaneous infrared equilibrium. The average measured air temperatures and infrared cooling rates for forty radiometersonde soundings made during all seasons and at a number of stations in the Central and Western United States are given in figure 1. In this averaging the tropopause was used as a reference level. Measured temperature and radiation values were averaged at twenty-five millibar increments above and below the tropopause.

Pronounced variations in radiative cooling profiles consistently observed in flights made under similar synoptic conditions are lost in this "annual" average. If infrared absorber concentrations are continuous through a level of temperature minimum such as the tropopause, a relative radiational warming maximum centered at the temperature minimum should occur. This is not apparent in figure 1. If, on the other hand, a discontinuous decrease in absorber concentrations occurs in layer of uniform temperature lapse rate, a radiational cooling maximum should occur at the level of absorber discontinuity. This also is not apparent in figure 1. These features, however, are observed in individual soundings and in the average of soundings made under more uniform conditions of air temperature and absorber concentrations.

## MID LATITUDE TROPICAL TROPOPAUSE

Figure 2 shows the average air temperature and infrared cooling rates for seven soundings made through a high level tropopause with cirrus clouds. The soundings were made simultaneously along a north-south

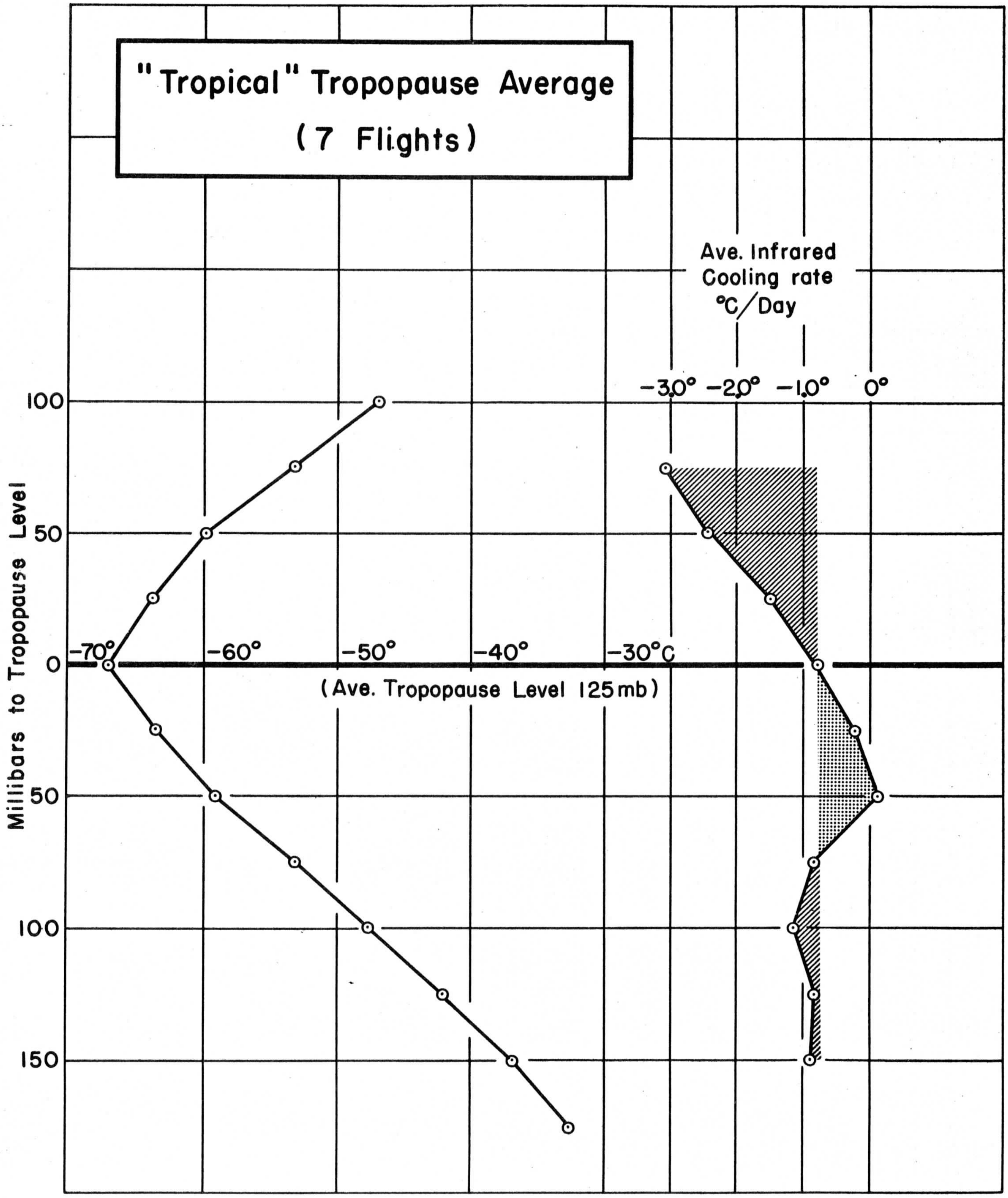
"Tropical" Tropopause Average
(7 Flights)
Ave. Infrared
Cooling rate
°C/Day
−3.0°
−2.0°
−1.0°
0°
100
50
0
50
100
150
Millibars to Tropopause Level
−70°
−60°
−50°
−40°
−30°C
(Ave. Tropopause Level 125 mb)

Figure 2.

line of upper air stations from Fort Worth to International Falls at 0600Z, 29 July 1959. A pronounced relative warming maximum is centered at a level 50 millibars below the tropopause. Since this relative warming maximum occurred in a layer of uniform temperature lapse rates it must be due to net radiation convergence at the base of a pronounced absorber concentration. Moisture and cloud measurements at these heights are not available. It may be that the absorber concentration increase is the cirrus cloud layer reported in the surface observations. There is no indication of a layer of maximum cooling associated with the top of the layer of increased absorber concentration nor is there a tendency for a relative warming maximum at the tropopause expected with a continuity of absorber concentration through the level. It is possible that sufficient decrease in absorber concentration occurred to counteract the radiative warming tendency due to the temperature distribution. The cooling rates in the lower stratosphere are two to three times as large as the average values for other synoptic conditions.

The effect of infrared radiation in this case is to increase the temperature lapse rate in the fifty millibar layer below the tropopause — presumably in the cirrus layer. Above the tropopause, infrared cooling tends to decrease strongly the intensity of the inversion layer.

## ANTARCTIC POLAR NIGHT SOUNDINGS

As a contrast to the average conditions associated with the high level "tropical" tropopause the average of polar night soundings at the South Pole Station and Hallet Station, Antarctica were compiled. These

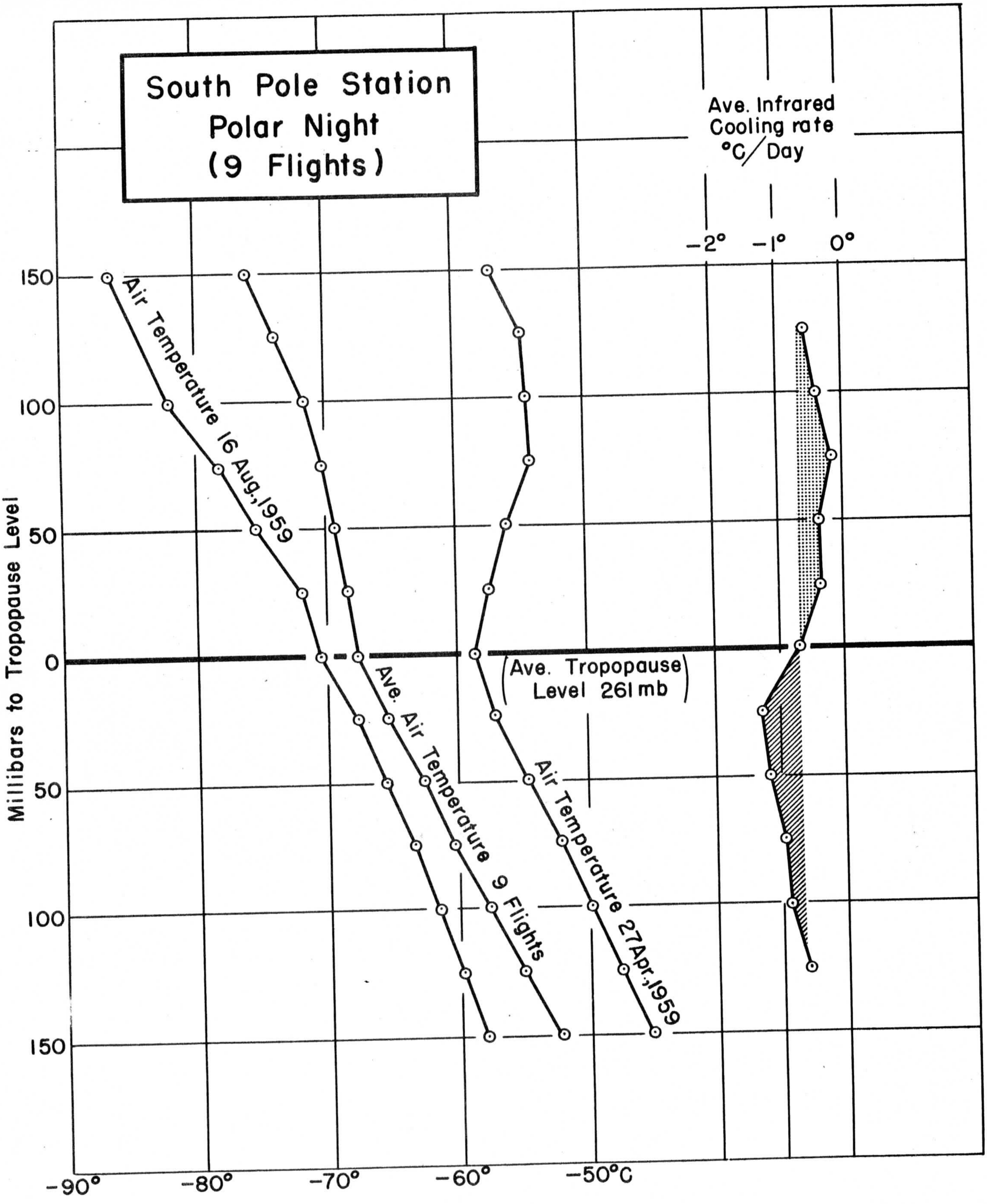
South Pole Station
Polar Night
(9 Flights)
Ave. Infrared Cooling rate °C/Day
−2°
−1°
0°
Air Temperature 16 Aug., 1959
Ave. Air Temperature 9 Flights
Air Temperature 27 Apr., 1959
(Ave. Tropopause Level 261 mb)
Millibars to Tropopause Level
150
100
50
0
50
100
150
−90°
−80°
−70°
−60°
−50°C

Figure 3.

average soundings are of added interest because the contribution of infrared cooling to the observed temperature decrease during the polar night can be studied without the complicating factor of diurnal solar radiational heating.

The average of nine soundings made during the polar night at the South Pole Station is given in figure 3. The soundings covered a period from 27 April 1959 through 16 August 1959. The observed air temperatures at the beginning and end of the observational period are also given in figure 3.

The lower stratospheric infrared cooling rate average is approximately 0.4°C/day. Assuming the air remains under the influence of this average cooling rate during the entire 112 day period the total temperature decrease due to infrared cooling would be 45°. The observed temperature decrease at a level 100 millibars above the tropopause is only 28°C. This implies that some mechanism such as subsidence or warm air advection is operating to compensate for the strong radiational cooling.

The average infrared cooling rate in the upper troposphere is approximately 1.0°C/day. The total temperature decrease due to this average temperature decrease is only 10 to 13°C. Thus in the upper troposphere compensating warming due to advection and subsidence must be much larger than in the lower stratosphere.

The vertical distribution of radiational cooling is such that the layer from 25 millibars below to 75 millibars above the tropopause would tend to stabilize. Above and below the layer destabilization would occur. Thus the eventual disappearance of the antarctic tropopause during the

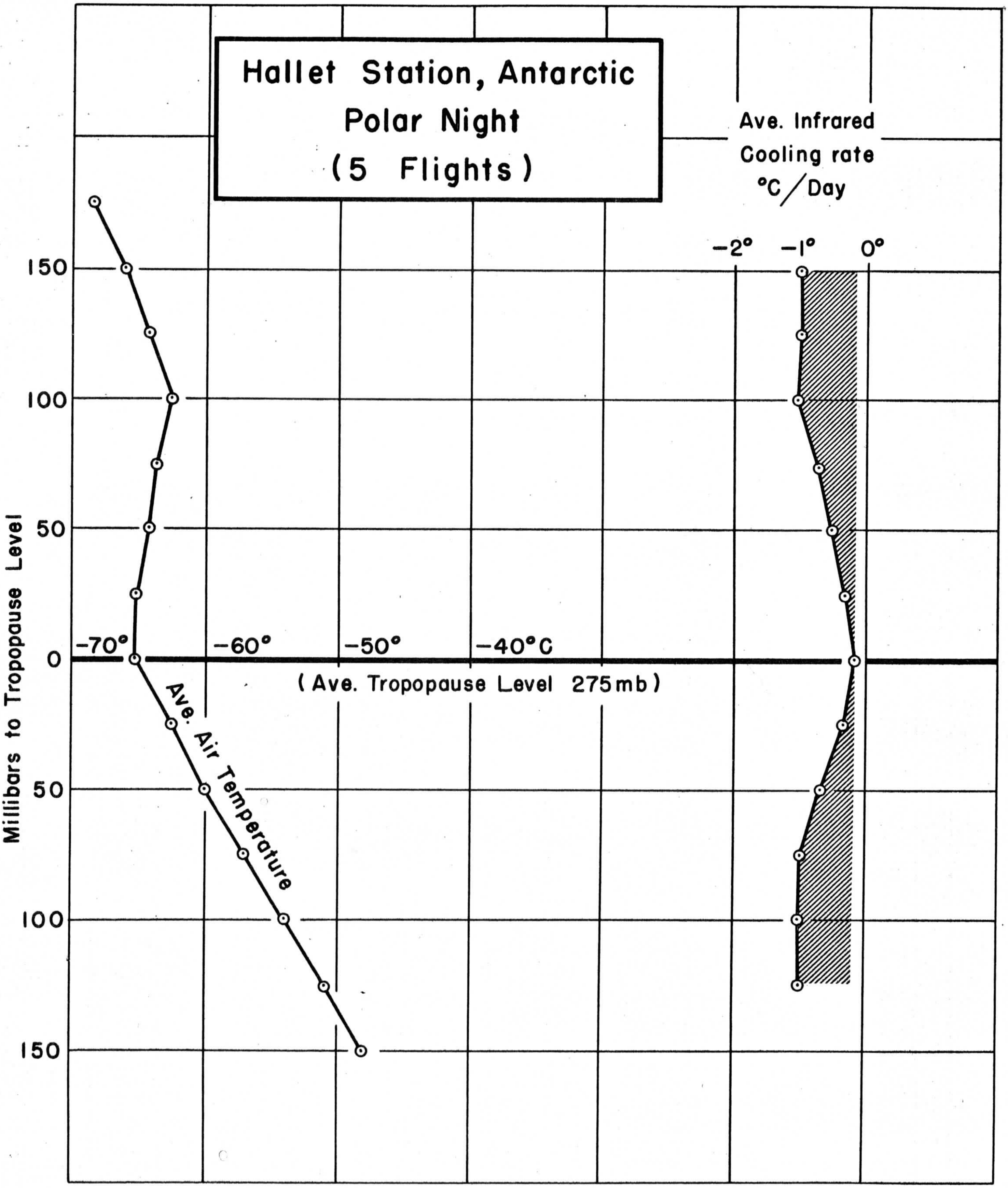
Hallet Station, Antarctic
Polar Night
(5 Flights)
Ave. Infrared
Cooling rate
°C/Day
−2°
−1°
0°
150
100
50
0
50
100
150
Millibars to Tropopause Level
−70°
−60°
−50°
−40°C
(Ave. Tropopause Level 275mb)
Ave. Air Temperature

Figure 4.

polar night may not be simply ascribed to vertical gradients of infrared cooling alone.

The average observed air temperature and infrared cooling rates of five soundings at Hallet Station, Antarctica during the polar night are shown in figure 4. In contrast to the average South Pole sounding a pronounced warming maximum is centered at the tropopause level. This indicates a continuity of radiative absorbers through the tropopause. Both the upper troposphere and lower stratospheric cooling rates beyond the warming layer are the same. The vertical differences in cooling rates are such that the tropopause would be destroyed by stabilization of the 75 millibar layer below and destabilization of the 100 millibar layer above.

## UPPER AIR COLD LOW DEVELOPMENT

The air temperature and radiative cooling profiles observed at Albuquerque, New Mexico at 0254 GCT 5 March 1959 are shown in figure 5. Plotted cooling rates are the average rates for overlapping 50 millibar layers. This sounding passed through an extremely low tropopause that had formed with the rapid development of a "cut off" low in this area during the previous 24 to 36 hour period.

Strong radiational cooling is observed in a layer centered at the tropopause level. In view of the observed temperature distribution this cooling must have resulted from a rapid vertical decrease in absorber concentration presumably a cloud layer with tops near tropopause. Surface observations at the time of release indicate a strato-cumulus overcast.

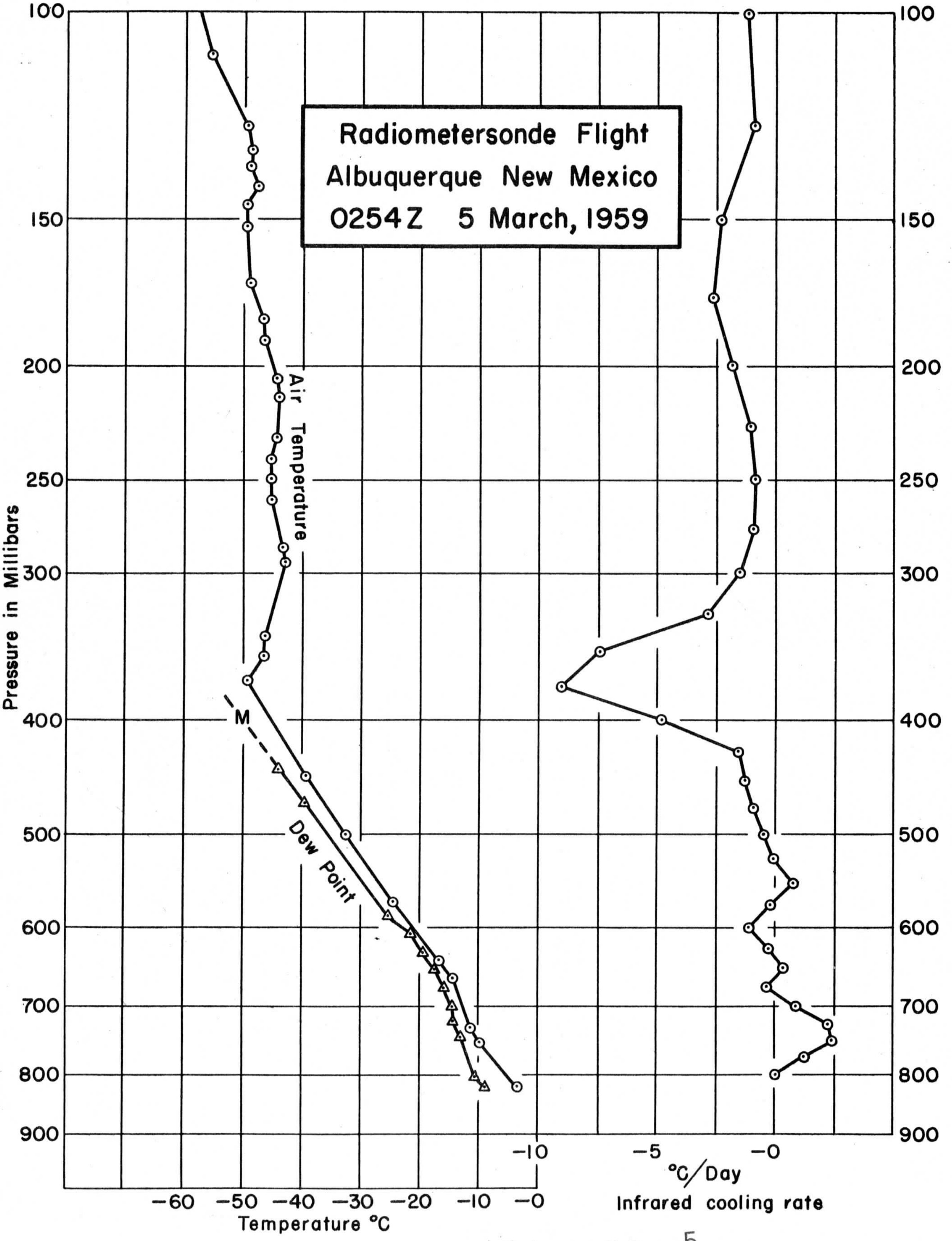
Radiometersonde Flight
Albuquerque New Mexico
0254Z 5 March, 1959
Pressure in Millibars
100
150
200
250
300
400
500
600
700
800
900
Air Temperature
Dew Point
M
−60
−50
−40
−30
−20
−10
−0
Temperature °C
−10
−5
−0
°C/Day
Infrared cooling rate

Figure 5.

The strong vertical gradients of infrared radiation in the upper troposphere and lower stratosphere are consistent with the observations of regions of non conservative potential vorticity by Staley (3), Kleinschmidt (4), and others in similar cases of rapidly developing upper air cold lows. Unfortunately this particular sounding was made after the circulation development and associated tropopause lowering or reformation was all but completed. It is not possible, therefore, to state whether the observed vertical gradients of infrared cooling contributed to the development or are its by-product.

## RADIATION OBSERVATIONS AND PREVIOUS CONCLUSIONS

The radiative properties of the atmosphere have been assigned an important role in many theories of tropopause formation. Gold (5), Emden (6), and Goody (7) consider the tropopause as the boundary between a lower stratosphere in quasi-radiative equilibrium and a troposphere in some form of convective equilibrium. More recently, King (8) has computed radiative equilibrium temperature profiles based on assumed absorber concentrations and concluded that the upper troposphere region is the only region in the atmosphere in infrared radiative equilibrium. Ohring's (9) computed values indicate that radiative equilibrium is not obtained at any point in the stratosphere.

Staley (10) concludes that sufficient evidence exists to suggest a continuity of all radiative components through the tropopause in which case the gross effect of radiation is to destroy the temperature profile curvature at the tropopause. Möller (11), on the other hand, suggests the existence of cloud or haze layer tops at the tropopause might contribute sufficient radiational cooling at the tropopause to account for the observed temperature profile curvature.

Measured radiation flux values indicate that the exact role of infrared radiational cooling in tropopause formation and deformation is not known. Both strong radiational cooling and relative warming are observed at the tropopause in many individual soundings. The relative importance of each to large scale tropopause changes can be decided with additional infrared measurements at a variety of locations and under a variety of conditions of temperature and absorber concentration distribution. Such measurements are being made.

## CONCLUSIONS

This preliminary look into the observed infrared radiation effects near the tropopause suggests the following:

1. The observed variability in time and space of infrared radiation flux gradients in the upper troposphere and lower stratosphere precludes any simple generalizations as to the gross effect of infrared radiative cooling at these heights.
2. Infrared radiation may indirectly contribute to the intensification of a tropopause level, by increasing the instability of the upper troposphere and/or increasing the stability of the lower stratosphere. The role of cirrus clouds and haze layers in this respect may not be dismissed until more observations are made of their contribution as a wide spread vertical discontinuity in radiative components.
3. Infrared radiation contributes to the destruction of the tropopause in many situations, presumably those with a continuity of absorber

concentrations through the tropopause.

4. Synoptic observation of vertical gradients of infrared radiation in the upper troposphere and lower stratosphere may not only contribute to our understanding of the rapid development of upper air lows but might possibly serve as a simple means of forecasting their development.

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