Atmospheric and Surface Properties from Spectral Radiance Observations in the 4.3-Micron Region[1]

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ABSTRACT

Atmospheric temperature profiles, obtained from spectral radiances of the earth between 2160 and 2360 cm^{-1} measured by a balloonborne, multi-detector, grating spectrometer at 3.5 mb during a 6-hr flight, are described. Representative profiles obtained both before and after sunrise and for clear and cloudy skies show that atmospheric temperatures accurate to ~2K can be inferred. The variations of surface temperature during the flight are discussed.

1. Introduction

In a previous paper (Shaw *et al.*, 1967) observations were described of the spectral radiance of the earth between 2100 and 2700 cm^{-1} made with a scanning grating spectrometer from an altitude of 30 km. The surface temperature and the temperature profile of the atmosphere were derived from these measurements but, because of the low absolute accuracy of the radiances near 2300 cm^{-1}, there was poor agreement between the derived profiles and local radiosonde observations.

A multi-detector grating spectrometer has since been constructed (Schaper and Shaw, 1970) which samples the radiance of its field of view (FOV) in 35 spectral intervals between 2000 and 2700 cm^{-1} in 10 sec. The methods of controlling the temperatures of the in-flight calibration plate, the chopper blades, and the detectors in this instrument, and the preflight calibration techniques were all improved considerably compared with those used previously. Thus, the spectral radiances of bodies near earth temperatures can be measured with absolute accuracies estimated to be ~3%. During a balloon flight of this instrument on 11 July 1968, over 400 sets of data were obtained over a period of 6 hr. Variations in surface temperatures and atmospheric temperature profiles from the surface to the balloon derived from the spectral radiances between 2160 and 2360 cm^{-1} by the analytical method described by Chahine (1968, 1970) are discussed in this paper. Examples are given of both nighttime and daytime profiles and profiles obtained when the FOV of the instrument contained either no clouds, partial clouds, or complete cloud cover.

a. Balloon flight

The balloon was launched from Palestine, Tex., at 0152 CDT 11 July 1968. Float altitude (3.5 mb) was reached at 0430 and this altitude was maintained to within ±0.2 mb until 1020 when the gondola was returned to the earth. As shown in Fig. 1 the balloon travelled westward at ~100 km hr^{-1}. Sunrise at the surface beneath the balloon occurred at 0645 and, at the balloon altitude, at 0618.

Observers in an airplane tracking the balloon made visual estimates of the cloud cover and of the heights of the cloud bases during part of the flight and, after sunrise, photographs of the FOV obtained from cameras on the gondola were also available. As indicated in Fig. 2a the balloon passed over two extensive areas of cloud near 0500 and 0900 CDT. In both cases the aircraft observers estimated that the bases were near

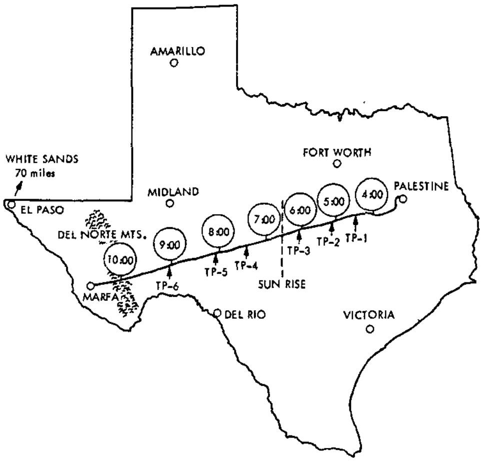

FIG. 1. Path of balloon launched from Palestine, Tex., 11 July 1968. Several launch sites of radiosondes from which temperature information was obtained are indicated. The locations of the balloon at which the temperature profiles (TP) discussed in this paper were obtained are identified.

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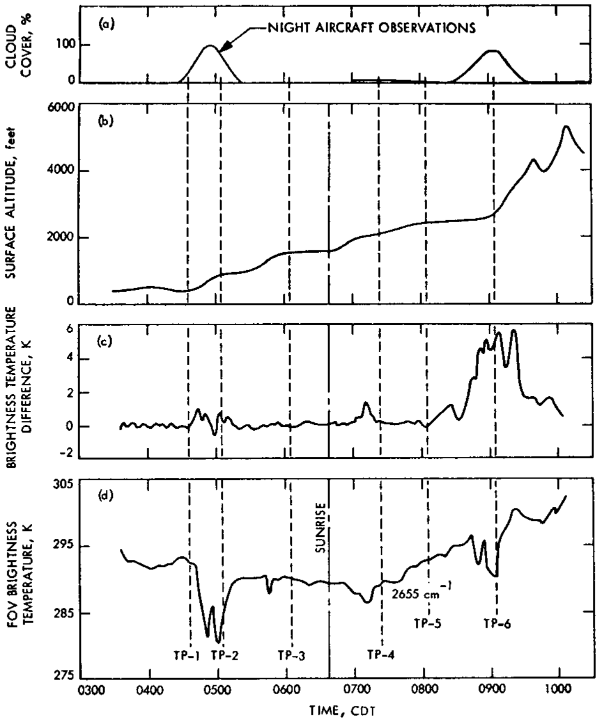

FIG. 2. Time variations of observed parameters: estimate of cloud coverage in the FOV, a.; surface elevation in the FOV, b.; difference in brightness temperature at 2655 and 2510 cm^{-1} of the FOV, c.; and spectral brightness temperature at 2655 cm^{-1} of the FOV, d. The vertical dashed lines labeled TP indicate the times at which the radiance data obtained were reduced to obtain temperature profiles.

3500 m and that the cloud layer was shallow. For most of the remainder of the flight the FOV was free from clouds although there was evidence of haze in the lower atmosphere near dawn. The elevation of the surface beneath the balloon increased with time as shown in Fig. 2b.

b. Measurements

The earth's radiance was measured at 35 frequencies between 1975 and 2655 cm^{-1} with a spectral resolving power ($\nu/\Delta\nu$) of approximately 100. During successive 3-min intervals of the flight the instrument made four observations of the spectral radiances of the earth, two of a calibration plate, and three observations with an opaque shutter behind the entrance slit to provide an instrument zero. The signal-to-noise ratios (SNR), measured during the flight, were close to those determined during the preflight calibration, and readings from other sensors monitoring the instrument performance confirmed its stability during the flight.

The lowest spectral radiances, about 0.1 erg sec^{-1} ster^{-1} cm^{-1}, were observed near 2300 cm^{-1}. This corresponds to a brightness temperature of the FOV of ~230K, the brightness temperature $T_b(\nu_i)$ being obtained from

$$B(\nu_i,T_b)=N(\nu_i)\,.$$

In this expression $N(\nu_i)$ is the measured spectral radiance and $B(\nu,T)$ the Planck blackbody function. The SNR was over 100 at 2300 cm^{-1} and higher at other frequencies. This was sufficient to allow variations of brightness temperatures as small as 0.1K to be observed.

c. Temporal variations in radiance

The principle purpose of this balloon flight was to estimate the accuracy with which temperature profiles could be determined by comparison with other measurements which were available. Since clouds can influence the results significantly, an attempt was made to determine the presence of clouds directly from the radiance data obtained in spectral regions when the atmosphere is nearly transparent. These include the region near 2160 cm^{-1} and 2510–2655 cm^{-1}. Throughout most of this latter region the transmittance of one air-mass is in excess of 0.85 (Shaw, 1970) so that most of the radiant flux detected originates either from the surface or from clouds in the FOV.

The variation of the spectral brightness temperature of the FOV at 2655 cm^{-1} with time is given in Fig. 2d. This temperature generally decreased from the time observations were begun until sunrise at the ground. Shortly after sunrise the temperature began to increase. Superimposed on these general trends were temperature decreases when clouds were known to be in the FOV. Although both the nighttime (0500) and daytime (0900) clouds were observed to have bases at the same height and although the photographs showed essentially complete cloud cover at 0900, the minimum daytime brightness temperature is ~10K higher than the minimum nighttime temperature. This difference is attributed to the presence of scattered solar flux and is discussed in more detail below.

The spectral transmittance of a vertical path through one air mass is approximately the same at both 2510 and 2655 cm^{-1} (Shaw, 1970). Thus, at night, the brightness temperature at these two frequencies should be the same and, for the prevailing atmospheric conditions at the time of the balloon flight, be within 1K of the surface spectral brightness temperature when no clouds are present. The difference ΔT in these brightness temperatures, i.e.,

$$\Delta T = T_b(2655) - T_b(2510),$$

is shown in Fig. 2c. From 0330 to 0700 this difference does not exceed ±0.2K except near 0500 when clouds were in the FOV. These small differences demonstrate the instrument stability, low noise level, and relative calibration accuracy.

The magnitude of ΔT increases when clouds are in the FOV and the slope of the ΔT curve changes sign more frequently than the slope of $T_b(2655)$. These variations are caused by small differences in the transmittance of the instrument with direction of the incoming flux, and by variations in sensitivity across the active areas of the detector surfaces (Wolfe, 1965). Provided the radiance of the FOV is uniform, these instrumental variations do not affect the accuracy with which this radiance is determined. However, if a partial cloud cover which causes radiance variations across the FOV is present, the observed brightness temperature depends on the cloud distribution and may vary from detector to detector.

Between 0430 and 0500 the brightness temperature at 2655 cm^{-1} decreased from 294 to 277K. Since the temperature at the cloud base was ~280K this indicates the fractional cloud cover increased from zero to almost 100%. During this time the maximum value of ΔT did not exceed 1K; thus, the effects of the instrumental sensitivity variations with direction, although noticeable, are not important for most measurements.

After sunrise, solar flux scattered by clouds and the surface can contribute to the measured radiance. This flux increases to higher frequencies in contrast to the thermal flux which decreases rapidly with frequency and causes the ΔT values to be positive.

Fig. 2c shows that ΔT was strongly positive when clouds were present after sunrise and remained positive near 1000 even though no clouds were present. These results indicate that clouds are more effective scatterers than the surface, at least during the conditions existing at the time of this flight. By assuming that both the clouds and the surface are diffuse reflectors and that the reflectivity is independent of wavelength, Shaw (1970) has shown that the clouds at 0900 reflected ~10% of the incident solar flux compared with ~4% reflected from the earth at 1000. This is sufficient to cause the 2655 cm^{-1} brightness temperature of the clouds at 0900 to be ~10K higher than would have been observed at night. At 2160 cm^{-1}, when the atmosphere is also highly transparent, the corresponding difference between daytime and nighttime cloud temperatures is estimated to be less than 1K because of the much higher thermal radiances at this frequency. The measured minimum radiances at 2162 cm^{-1} at 0500 and 0900 corresponded to a difference of less than 2K in brightness temperatures (277 and 279K, respectively).

In addition to the extensive clouds at 0500 and 0900, a small patch of clouds was photographed at 0715 CDT. This is also indicated by an increase in ΔT and an associated decrease in $T_b(2655)$ in Fig. 2. Between 0945 and 1008 the spectral brightness temperatures at 2510 and 2655 cm^{-1} varied considerably although there were no clouds in the FOV. These variations, together with those of ΔT are shown in Fig. 3. From 0945 to 0955 the altitude of the terrain beneath the balloon decreased slowly as the balloon drifted along a valley. From 0955 to 1002 there was a sharp increase in altitude as the balloon crossed the Del Norte Mountains, and after 1002 the altitude decreased. The observed temperature variations are thus consistent with the expectation that the valley floor is warmer than the mountain. The nearly constant value of ΔT also indicates that there is little change in the reflectivity and hence emissivity of the terrain. The spatial resolution of these temperature changes is also consistent with the width of the FOV which is shown in Fig. 3.

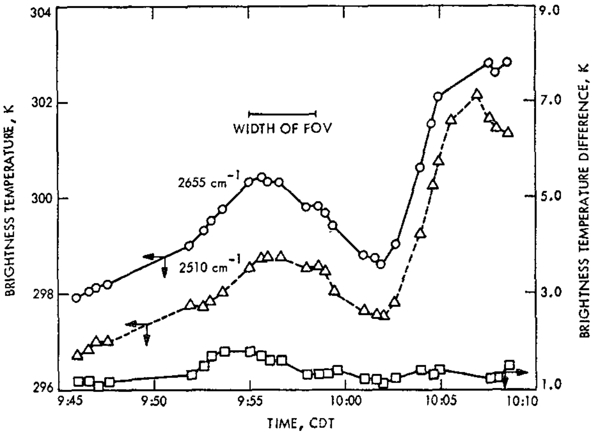

Fig. 3. Time variations of observed brightness temperature of the FOV at two wavenumbers, and the difference of the two brightness temperatures.

This analysis of the radiance observations in regions where the atmosphere is transparent has shown that the interpretation of the measurements is consistent with other observations. The presence of clouds can be inferred, the presence of scattered solar flux can be detected at high frequencies, and as expected, this flux is insignificant compared with the thermal flux at lower frequencies and in regions of strong atmospheric absorption.

d. Atmospheric temperature profiles

Atmospheric temperature profiles were derived from sets of radiance data between 2160 and 2360 cm^{-1} with the analytical technique described by Chahine (1968). Chahine (1970) has estimated that the average accuracy of a temperature profile derived from observations in this spectral region which have a 2% rms random error is 1K, irrespective of the size of the set of sounding frequencies, provided the vertical transmittance of the atmosphere is known. Spectral transmittances of the atmosphere in this spectral region have been calculated by McClatchey (1967) who included the effects of CO_2, N_2O, CO, H_2O and N_2. These calculations compared well with experimental observations over the spectral region of interest and were used in the initial data analysis. The method of minimization of the residuals

(Chahine, 1970) was applied to the radiance data obtained at 0439 CDT to improve our knowledge of these transmittances. These transmittances were then used for the reduction of the data discussed in this paper. Since the observed radiance data have an rms noise level of ~1% and since the absolute radiance calibration of the instrument was made to 3%, the agreement between calculated and actual profiles is expected to be within 2K for clear sky cases.

Information concerning the actual temperature profile from the surface to about 10 mb was obtained from radiosondes launched from ESSA Weather Bureau stations near the flight path at 0500 CDT 11 July 1968. Some of these stations are named in Fig. 1. Temperatures at several pressure levels were interpolated from each sounding and the maximum and minimum temperatures at each pressure level, as determined from these radiosonde data, are shown in Fig. 4. Rocket measurements of temperatures at pressures <10 mb above White Sands, N.M., on the days before and after the flight, are also shown in this figure. These data indicate that the temperatures of the upper levels of the atmosphere were not changing rapidly with time.

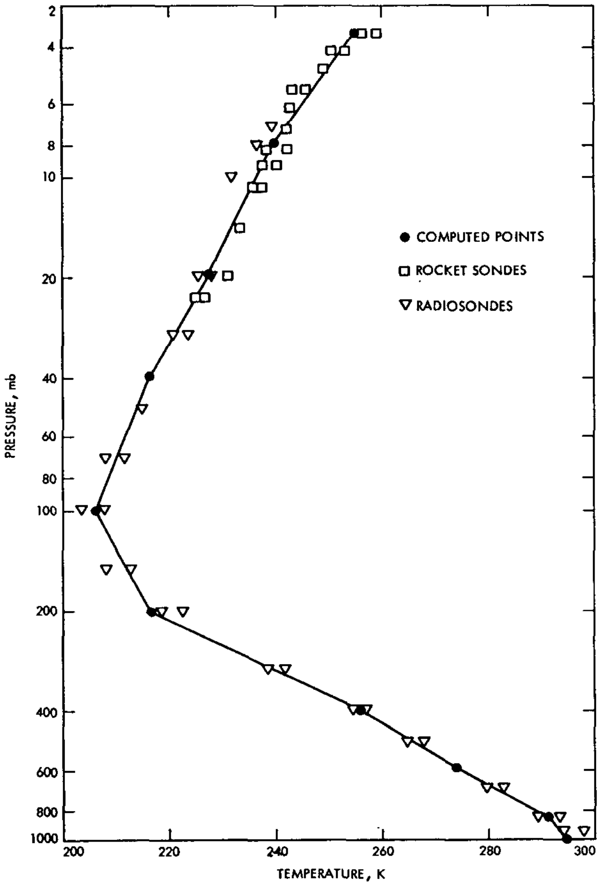

FIG. 4. Temperature profile derived from 0436 CDT radiance data (solid circles). Radiosonde and rocketsonde temperature extremes as obtained from instruments launched close to the balloon flight path are also shown.

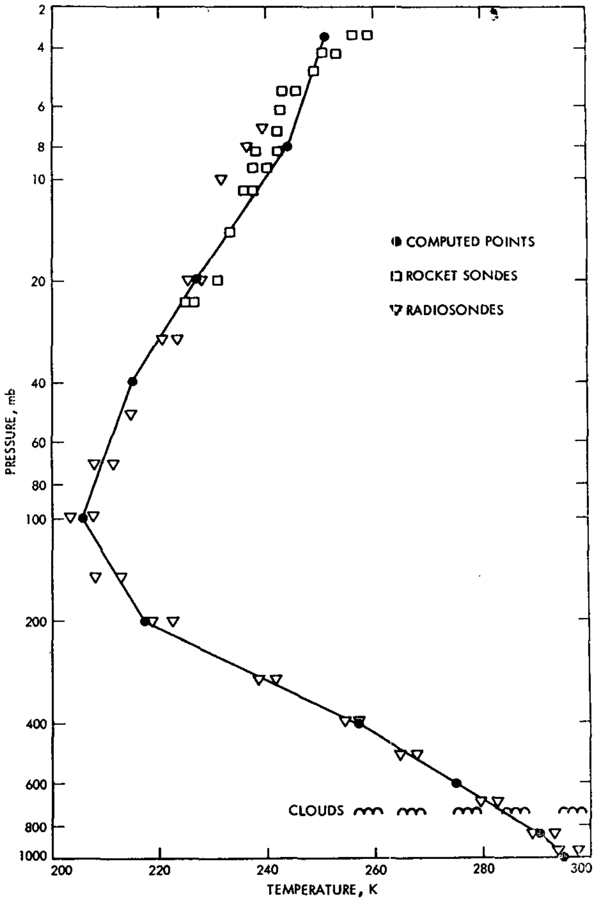

FIG. 5. Temperature profile derived from 0505 CDT radiance data. The cloud height was estimated to be 700 mb and the cloud cover 89%.

Although the actual temperature profile of the atmosphere below the balloon at the times radiance observations were made is not available, the data described above are sufficiently consistent that any calculated profile which does not fall more than 1–2K outside the ranges shown can be considered verified and probably accurate to 2–3K.

The temperature profile obtained from the radiance measurements at 0436 is shown in Fig. 4. Both visual observations and inspection of the radiance measurements at 2510 and 2655 cm^{-1} shown in Fig. 2 indicated there were no clouds in the FOV at this time. With the possible exception of the 200-mb temperature, the calculated profile shows excellent agreement with the radiosonde and rocketsonde data. In addition, the surface temperature inferred from the radiances between 2160 and 2360 cm^{-1} is within 1K of that shown in Fig. 2.

The profile from the 0505 data shown in Fig. 5 was obtained even though there were clouds in the FOV. Provided the clouds constitute a partial opaque layer at some pressure level, this level and the extent of the clouds can be estimated if the surface temperature is known. In this method (Chahine, 1970) a value for the cloud level is assumed and a temperature profile and cloud fraction are obtained which give computed spectral radiances in best agreement with the observed radiances. As the assumed pressure level is varied, the normalized sum of the residuals between the observed and calculated radiances reaches a minimum value when the assumed cloud height is equal to the actual height. If more than one layer of clouds are present or if the optical depth of the clouds is not small, the pressure level at which the minimum of the residuals occurs gives an effective cloud height. If no clouds are present, a plot of the residuals as a function of assumed cloud pressure level will show no minimum. The curve at the right-hand side of Fig. 6 shows that there is no positive indication of a minimum in the residuals plotted in this way for the data at 0436. Hence it is confirmed that there were no clouds in the FOV at this time. However, the corresponding plot of the residuals at 0505 shown on the left-hand side of Fig. 6 shows a pronounced minimum at 700 mb indicating the cloud top level. This curve was obtained by assuming the same surface temperature as the previous clear FOV inversion and the amount of cloud cover was estimated to be 89%. When the corresponding cloud top temperature, cloud fraction, and surface temperature are used to calculate the expected radiances at 2510 and 2655 cm^{-1}, these values give brightness temperatures within 1K of those actually measured at these frequencies. Similar agreement has been obtained for the other profiles considered, strongly suggesting that there was a minimal dependence of cloud or surface emissivity on frequency in the spectral region from 2160–2655 cm^{-1}.

A number of other profiles and the corresponding plots of the residuals are shown in Figs. 7–12. Clouds were present in the FOV at some of these times and their presence is indicated in the plots of the residuals. The clouds were confirmed by visual observation, photographs, and analyses of the radiances at 2510 and 2655 cm^{-1}. A nighttime profile obtained from the 0605 radiance data is given in Fig. 7. The corresponding residuals in Fig. 8 show evidence of a shallow minimum

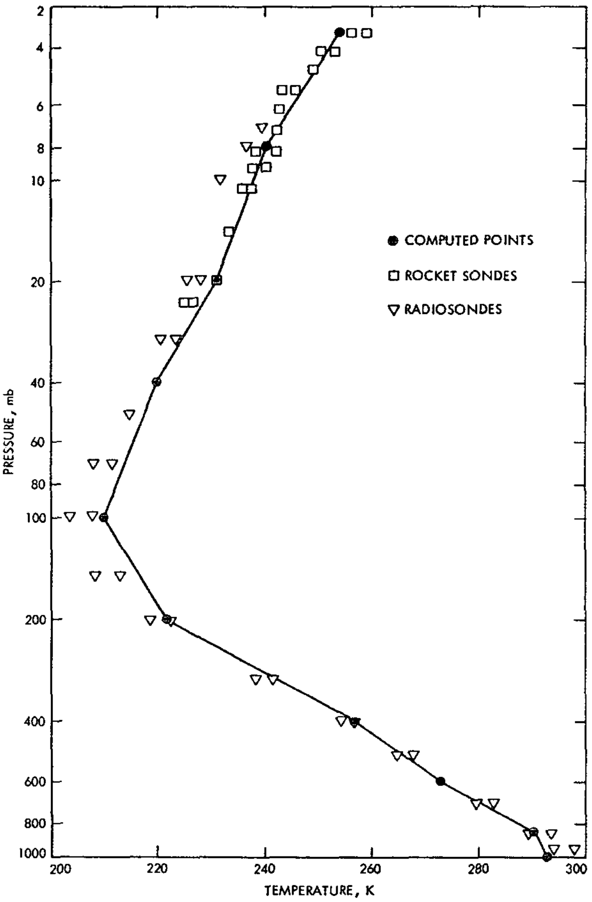

FIG. 7. Temperature profile derived from 0605 radiance data. The estimated cloud cover was less than 4% and the profile was obtained by assuming no clouds.

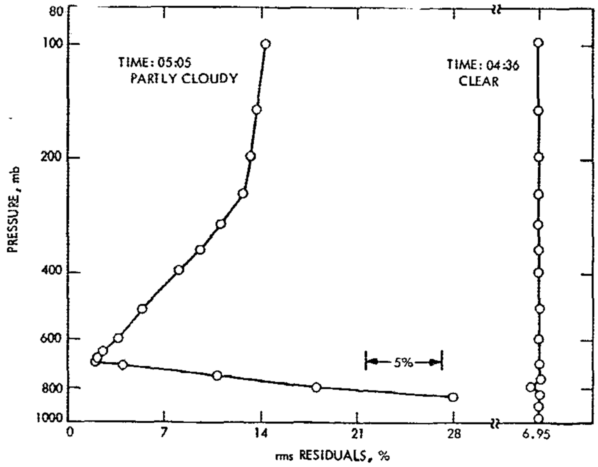

FIG. 6. Variation of residuals with assumed cloud pressure levels for 0436 and 0505 radiance data.

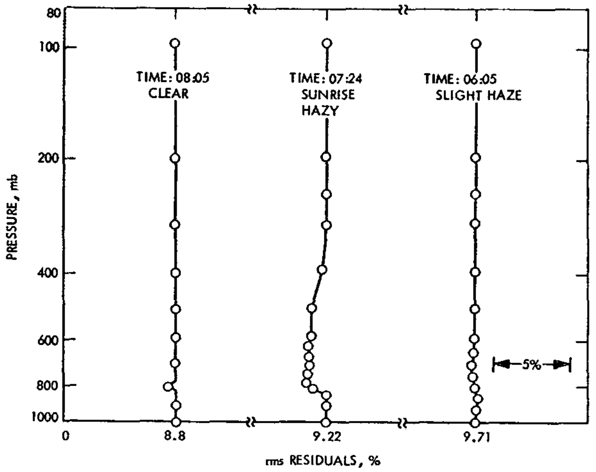

FIG. 8. Variation of residuals with assumed cloud pressure levels for 0605, 0724 and 0805 CDT radiance data.

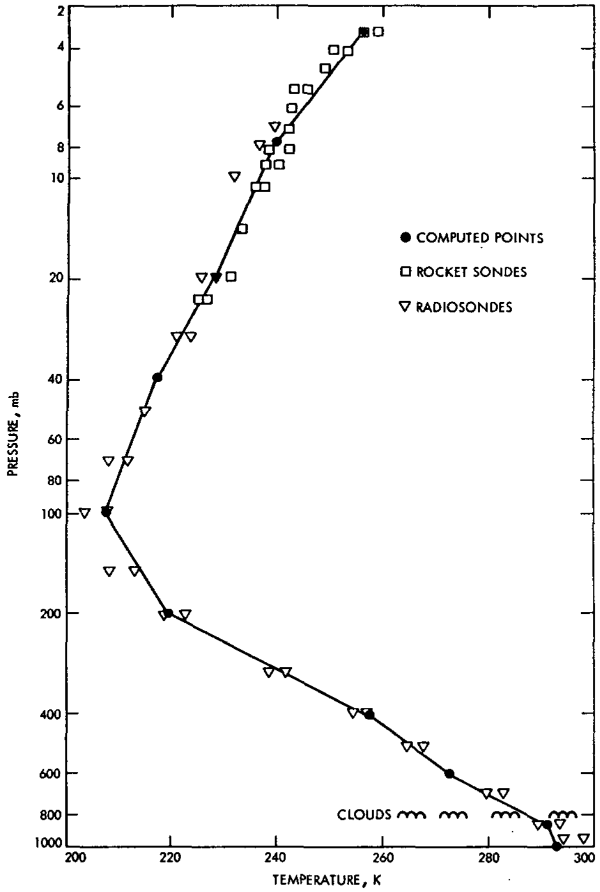

FIG. 9. Temperature profile derived from 0724 CDT radiance data. The cloud height was estimated to be 800 mb and the cloud cover 29%.

near 800 mb, but, since the estimated cloud cover was less than 4%, the profile in Fig. 7 was obtained by assuming the FOV was cloud free. This small amount of cloud or haze was not observed from the tracking plane and its presence cannot be detected from analysis of the 2510 and 2655 cm^{-1} radiance data.

The earliest daytime profile, that for 0724, is shown in Fig. 9, and the corresponding residuals are shown in Fig. 8. There is a broad minimum in the residuals curve which makes it difficult to infer the correct cloud height. If we assume the cloud top to be at 800 mb, then the corresponding fractional cloud cover will be 29%. Assumption of a higher cloud top would have led to a smaller fractional cloud cover.

The plot of the residuals for the 0805 data, presented in Fig. 8, shows no minimum. Thus, the FOV was probably cloud free. This was confirmed by photographs and the low value of ΔT in Fig. 3 at this time. The 0805 temperature profile is shown in Fig. 10.

The final profile, presented in Fig. 11, was obtained from the measurements at 0905. At this time, the sun was 25° above the horizon and photographs showed the FOV was completely filled by clouds. The large value of ΔT in Fig. 2 indicates that a considerable fraction of the total radiance at short wavelengths was due to scattered solar flux. The profile in Fig. 11 is nevertheless in excellent agreement with the radiosonde and rocketsonde data. The pressure level of the cloud tops was estimated to be between 675 and 700 mb from the plot of the residuals shown in Fig. 12, and a cloud top temperature of 278K was obtained. The fraction of the FOV covered by clouds was estimated to be between 97 and 99%, assuming the surface temperature to be the same as that for the previous clear FOV inversion.

The cloud top temperature was also determined from the spectral radiance at 2510 and 2655 cm^{-1}, by assuming that the FOV was completely filled by the clouds (Shaw, 1970). It was found that the brightness temperature of the clouds due to emitted thermal flux was 276.4K and that the partial spectral reflectance by solar flux scattered in the zenith direction was 0.036. Since no other data on the scattering properties of the clouds were available, the spectral directional emissivity of the clouds in the zenith direction was computed by assuming the clouds were Lambertian scatterers, and an actual cloud temperature of 278.8K was obtained. If

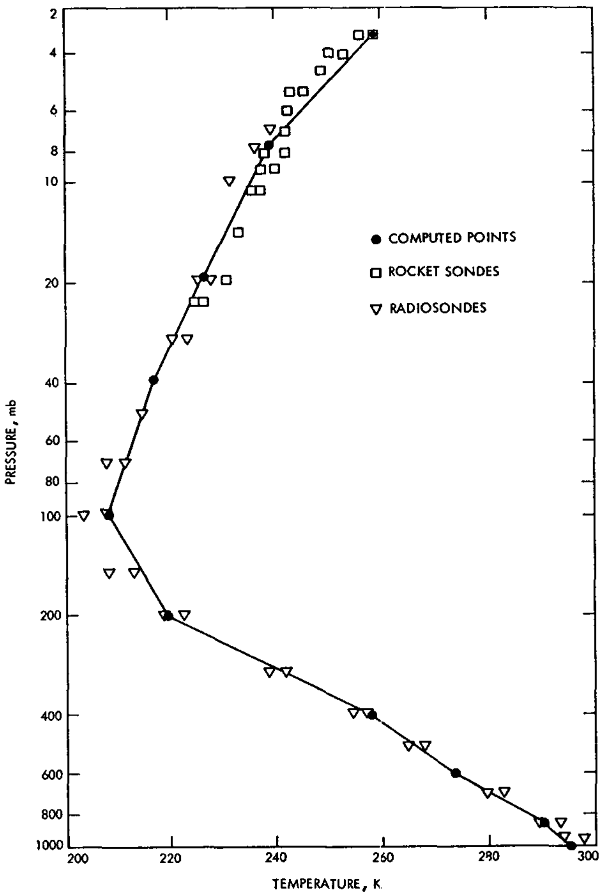

FIG. 10. Temperature profile derived from 0805 CDT radiance data. The sky was estimated to be cloud free.

instead of 100% cloud cover only 95% of the FOV was covered by the cloud and 5% was filled by the surface at a temperature of 296K, the calculated temperature of 278.8K is ~1K higher than the true cloud top temperature. Thus, there is excellent agreement between the cloud top temperature determined from the radiance observations at 2510 and 2655 cm^{-1} and that obtained from the measurements near 2185 cm^{-1}. No correction was applied to these latter data for the contribution by reflected solar flux, since this would alter the calculated cloud top temperatures by less than 1K.

2. Conclusions

It has been demonstrated that atmospheric temperature profiles from the surface to pressure levels below 4 mb can be inferred from measurements of the earth's radiance between 2160 and 2360 cm^{-1}. These profiles have been obtained from both daytime and nighttime observations and under conditions of partial and complete cloud cover with no *a priori* knowledge of the atmosphere except its composition and (for the case of partly cloudy conditions only) the surface temperature.

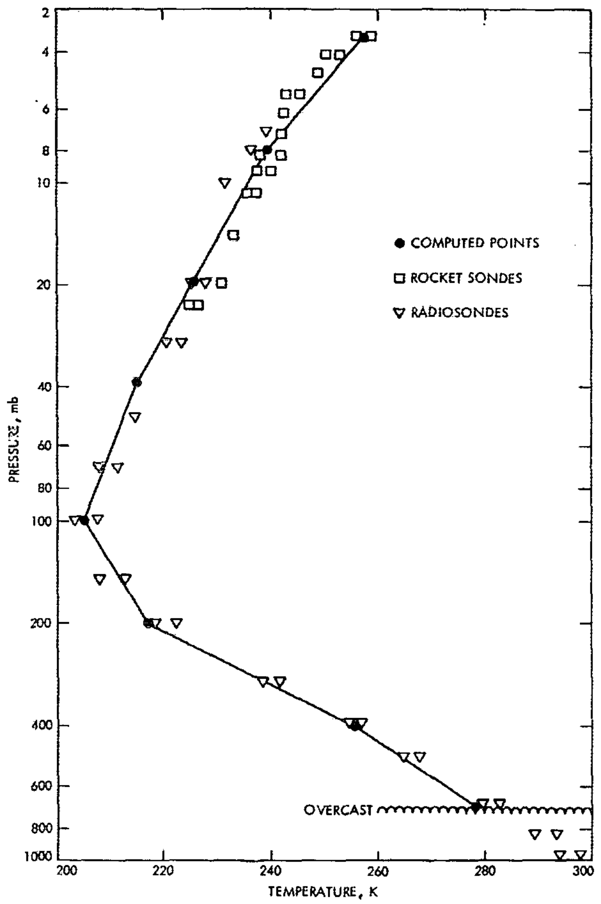

Fig. 11. Temperature profile derived from 0905 radiance data. The cloud height was estimated to be between 675 and 700 mb and the cloud cover to be between 97 and 99%.

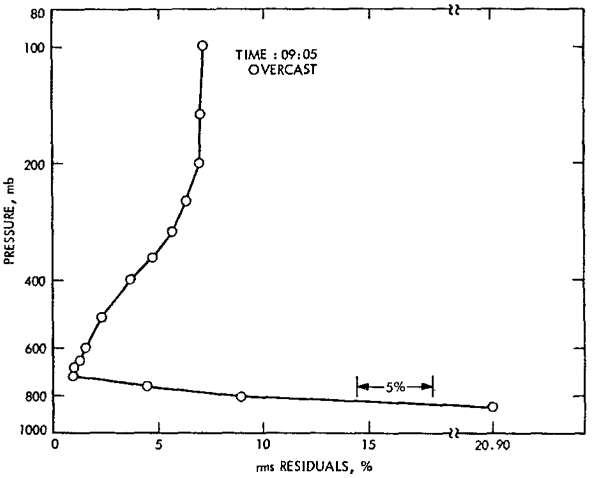

Fig. 12. Variation of residuals with assumed cloud pressure levels for 0905 CDT radiance data.

The ranges of temperature at a given pressure level obtained from several sets of radiance measurements during a 5-hr interval are close to the temperature ranges measured by radiosondes and rocketsondes near the balloon flight path. From these comparisons between observed and calculated temperatures it is estimated that the error in the determination of the mean temperature of atmospheric layers of thickness equal to the difference between the sounding levels shown in Figs. 4–12 does not exceed 2–3K at any altitude. This is close to that estimated from the error analysis. Despite the small contribution to the observed radiance from the low temperature region near the tropopause, the profiles demonstrate that the temperatures in this region can be determined accurately.

Measurements of the earth's radiance near 15 μ have recently been made by Wark and Hilleary (1969) and by Hanel and Conrath (1969) with satellite-borne instruments. Excellent temperature profiles have been inferred from the data obtained. However, because of the stronger dependence of the spectral radiance of bodies at room temperature at 4 μ compared with that at 15 μ, it is expected that higher vertical resolution can be obtained in the temperature profiles derived from measurements made at the shorter wavelengths. It is hoped that an experimental verification of this prediction can be made with satellite instrumentation in the future.

Acknowledgments. The data discussed in this paper could not have been obtained without the continuing interest and enthusiasm of the Infrared Instruments Group at Jet Propulsion Laboratory (JPL) which constructed, calibrated and prepared the instrument for the balloon flight. The success of the balloon flight itself and the later reduction of the data were due to the many hours spent in preparation by the JPL flight team headed by J. Riccio and also to the close cooperation of the personnel at the National Center for Atmospheric Research, Balloon Launch Facility, at Palestine, Tex.

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