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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Humidity up to the Mesopause

N. SISSENWINE
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Part I of this research was supported by the Air Force
In-House Laboratory Independent Research Fund

OFFICE OF AEROSPACE RESEARCH
United States Air Force

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Abstract

In Part I the results of seventeen northern California soundings of humidity up to 25 to 30 km, generally a month apart, utilizing a highly sophisticated alpha-radiation hygrometer and associated balloon sounding equipment are described. The stratosphere was never found to be near saturation as has been suggested by some investigators, nor was it as dry and completely devoid of variability as is indicated by the most accepted circulation theory. A very dry layer was found above the tropopause, followed by a slight increase in humidity up to an average altitude of about 25 km. Above this level, a general decrease in water vapor with altitude was deduced. Variability in this region of the lower stratosphere approached a factor of 10. Spasmodic transfer of water vapor upward through the tropopause is suggested, and speculation related thereto provided.

In Part II a model moisture profile is presented as an engineering reference standard. Typical dew point (or frost point) and mixing ratio profiles from the surface to 80 km for mid-latitudes are provided. The model is based on latest compilations of tropospheric and stratospheric humidity data up to 32 km and experimental rocket samplings of noctilucent clouds.

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HUMIDITY UP TO THE MESOPAUSE

Part I. Mid-Latitude Stratospheric Humidity Regime to 30Km

1. INTRODUCTION

More than 20 years ago British scientists (Dobson et al, 1945; Brewer, 1949; Brewer, 1955; Helliwell et al, 1956, 1957, and 1960), reporting upon initial aircraft investigations of humidity in the lower stratosphere, presented evidence that the tropopause acts as a cap to water vapor, which enters the atmosphere from the earth's surface, preventing it from penetrating into the stratosphere. This finding was presented in conjunction with a circulation theory which indicated that tropospheric air passes into the stratosphere only over equatorial regions from where it moves northward. It sinks back into the troposphere at higher latitudes, closing the cycle.

Tropical tropospheric air, which is wetter than all other surface level air, following this route into the stratosphere would have to pass through the very cold tropopause of the tropics, less than -80°C, where the water vapor density would be forced down to a level lower than elsewhere due to condensation. As this air departs upward from this level, the mixing ratio (the weight of water in a given weight of dry air) must remain constant if there is no source or condensation of water vapor. The mixing ratio that most closely depicted these British findings is 0.002 g per kg which may be interpreted as 2 parts per million (ppm). It follows that water-vapor density, the absolute humidity, must become monotonically

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lower as atmospheric density falls off with altitude. Frost point (and dew point) has a 1-to-1 relationship with absolute humidity, and thus would have a parallel decrease with altitude. Chemical production of water in the stratosphere could reverse this trend, but there has been no substantial evidence of this although some speculation exists (Hesstvedt, 1964, and 1965; Rangarajan, 1963; Dobrovolskiy, 1964; Suvorov, 1964; and Khvostikov, 1966). In some very early United States experimental work in which relatively crude frost-point devices were carried to 30 km by balloon (Barrett et al, 1950), thin saturated layers were observed but are suspect since some frost-point temperatures exceeded free air temperatures in these layers.

Measurement of the very small quantity of water vapor that can be contained in the atmosphere in layers at very cold temperature, is extremely difficult. Doing this without contaminating the air sampled with outgassing of water, which has collected on the surfaces of the sensor and platform before launching and when ascending through moist tropospheric levels, complicates this problem even further. Thus the British findings were considered quite authoritative for many years and have not been completely contradicted to date, although evidence to be presented herein and by others (Murcray, et al, 1966; Pybus, 1966; and Brown and Pybus, 1964) indicates some modification may be in order. Many slightly earlier investigations in England, Japan, and the United States (Mastenbrook and Dinger, 1961) summarized by Gutnick (1962), indicated much higher humidities at 15 to 30 km. Some current parallel investigations (Mastenbrook, 1963, 1965a, and 1965b; and Williamson and Houghton, 1965) are providing evidence more in keeping with the British theory. Some of the wetter findings appear to be definitely unrealistic; for example, Fedynskii's (1967) rocket observations of nearly 1 part per hundred at 75 km. Also, some of their earlier wet soundings were later disclaimed by the investigators, after changing their sounding technique (Mastenbrook, 1964; and Brown and Pybus, 1964). Therefore, those accepting the dry, nonvarying stratospheric humidity theory view with mistrust all data showing mixing ratios other than that near the average value speculated by the British, 2 ppm. However most recent British findings, from an aircraft-carrying-man monitored frost-point instrumentation equivalent to that flown during early experiments but to higher altitudes, provided moist layers in the lower stratosphere not in agreement with the dry theory (Murgatroyd, 1967). Unfortunately, the aircraft crashed during these experiments, and the findings have not been published.

There are basic scientific reasons for substantiating or contradicting the British theory of a dry, nonvarying stratosphere. For meteorology, presence of nonuniformly mixed water vapor at these altitudes could lead to local modifications of the circulation pattern, since it could account for absorption of solar energy in the infrared spectrum. The resulting differential heating would lead to pressure gradient changes, and these to changes in the wind field. From an astronomical viewpoint, the water vapor in the stratosphere must be known when observations of the atmospheric constituents of other planets are made from balloons in the earth's stratosphere. There are also engineering reasons for looking into this matter. In the development of aerospace systems, an unexpected amount of water vapor could affect the performance of infrared devices when used in the stratosphere, and on horizon sensing instrumentation used for spacecraft (Gutnick, 1960).

In 1965, a program supported by AFCRL's Laboratory Director through special funding (Grantham et al, 1965) was initiated to help shed light on this quandary which had been aptly described by Gutnick (1961) in a widely acclaimed paper "How Dry the Sky? ".

The planned program involved flights of two frost-point soundings per month for one year from the surface to about 27 km from Chico, California. This schedule was modified due to the usual difficulties encountered in field work. Balloons of 500,000 cu ft with controlled valving and ballasting for obtaining desired vertical velocities, were employed. A total payload of 450 lbs included the alpha-radiation hygrometer which, when sealed with a recorder and dry ice in a desiccated stainless steel container, weighed 75 lbs. The sensor package was lowered 2000 ft from the load bar on a hydraulic reel shortly after launch, to separate it from water vapor which may be outgassed from the surface of the balloon and associated command and control equipment on the load bar.

Response time to anticipated humidity changes in the atmosphere dictated that the vertical velocity of the instrumentation be less than about 800 feet per minute at the most critical altitudes, with the optimum rate about 200 to 300 feet per minute. The total flight time for a sounding was limited by FAA flight regulations, which require that balloon flights commence and terminate during daylight hours. Since the greater emphasis was to be placed on the descent portion of the flights, balloon ascents were increased to 600 to 700 feet per minute so that descent rates could be maintained at the optimum vertical velocity, about 200 to 300 feet per minute. On most flights, descent was begun as soon as the float altitude was attained. The normal flight configuration lasted between six and eight hours, well within designed battery and heat-sink coolant life.

An analog strip recorder, housed within the hygrometer package, was keyed by a commutator to register, each minute, six frost-point temperatures, two instrumentation calibrations, and one each of the following measurements: ambient air temperature, atmospheric pressure, heat-sink temperature, and internal hygrometer package temperature. In reducing the frost-point data, 5-minute running averages were used to average the servo-cycle of the hygrometer.

As a further precaution against contamination, balloons were packaged dry, instead of being dusted with cornstarch, the usual lubricant. However, after two successful flights, a series of balloon bursts during ascent indicated the desirability of dusting the folds of the balloon with lubricant. Teflon powder was chosen because of its extremely low moisture absorption qualities.

The alpha-radiation hygrometer invented by John G. Ballinger, is an automatic frost-point instrument (Ballinger et al, 1964 and 1965a) in which the temperature of a polonium surface is controlled by a servomechanism that strives to maintain a stable deposit of frost on it. Brousaides and Morrisey (1967) have recently summarized this equipment, as developed by Honeywell Incorporated for the Air Force Cambridge Research Laboratories. The polonium emits alpha-radiation which is monitored by a Geiger-Mueller detector. The frost point is recorded by a miniature thermistor embedded in the polonium. The accuracy of the sensor in this instrumentation varies with true frost point, atmospheric pressure, and time allowed for the sampled air to reach equilibrium with the sensor. Poorest performance, 2°C to 3°C errors in frost point, are found near 100 mb when the frost point is between -80°C and -90°C because of the low-mass transfer rates of the very few water-vapor molecules in the relatively high density of air molecules. At the top of the soundings the sensor error is only a fraction of a degree, but the recorder limits readings to about 1°C. Figure 1 depicts the frost-point error band for this sensor determined from a laboratory test cell. It may be noted that a frost point of -90°C is the practical lower limit of this equipment. Fortunately this did not prove to be a detriment in these experiments.

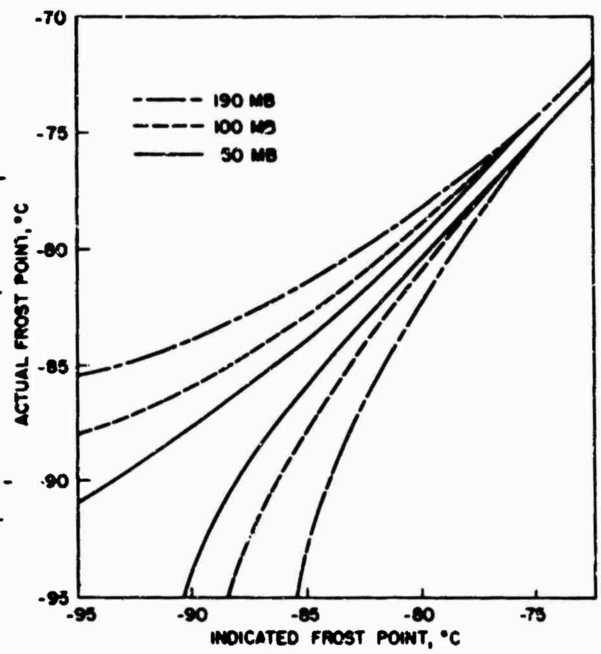

Figure 1. Frost-Point Error Curves for the Alpha-Radiation Hygrometer

2. FINDINGS

As already indicated, balloon problems detracted from the two-flights per-month goal. Some malfunctioning of equipment, due to damage incurred in recovery, also reduced this average and caused the program to extend into 1966.

Of the planned 24 flights, 17 soundings were obtained which provided useful data into the stratosphere but one of these was for only a very short distance above the tropopause. Dates of the 17 successful soundings are listed in Table 1. Soundings not discussed in the text of this report appear in the Appendix.

Table 1. Dates of Humidity Soundings, Chico, California

8 Jan 1965	22 Jun 1965	27 Oct 1965
10 Jan 1965	25 Jun 1965	7 Dec 1965
24 Feb 1965	22 Jul 1965	27 Feb 1966
23 Mar 1965	21 Sep 1965	25 Apr 1966
22 Apr 1965	23 Sep 1965	27 Apr 1966
22 May 1965	25 Oct 1965	

Figure 2 depicts the first sounding. Despite the extensive precautions to prevent contamination, its presence on ascent is quite apparent. In the stratosphere, ascent frost points averaged around -75°C. Frost points were colder by 10°C or more during descent. This amounts to a factor of 5 in the water-vapor density at these temperatures. This early finding led to careful study of the configuration of the sounding system as shown in Figure 3. The geometry of the sensor in the stainless steel container A, which was lowered 2000 ft from the hydraulic reel B, still had one shortcoming. Air passing over the instrument container could sweep molecules of water vapor off its surface, and then be sucked into the sensor intake which protrudes directly beneath it. Though the bottom and walls of the cylindrical container were stainless steel, a relatively nonhygroscopic material, the top had to be constructed of heavy-gage aluminum which is more prone to surface absorption. It was quite apparent that our ascent data could not be considered as truly representative of the stratosphere with this defect. The remedy was to bend the stainless steel intake tube 90 degrees, and lengthen it slightly to get it out of the boundary layer. The tube was in itself a possible source of contamination (Ballinger et al, 1965), and had to be kept as short as possible. The electronic command and control equipment is contained in C. It was permitted to breathe through a vapor trap. The container for dessicated ballast is D. The radiosonde instrument, E, was used to provide flight support data, and as a tracking beacon. Radiosonde pressures, corrected for 2000 ft separation, were used to specify altitude.

The effectiveness of this configuration was proven several flights later as shown in Figure 4. In this case the air encountered in ascent was actually drier

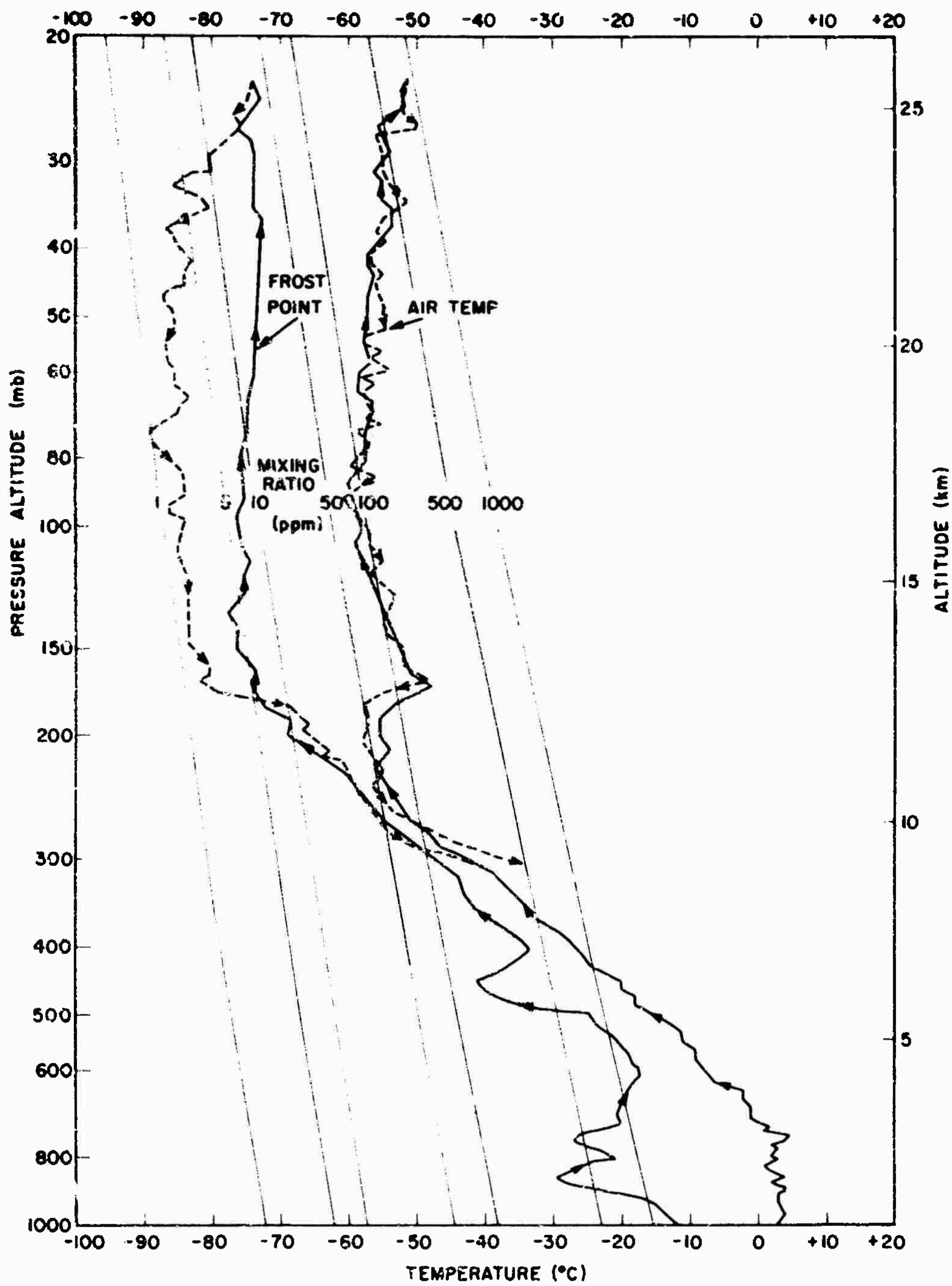

Figure 2. First Sounding, 8 January 1965, Chico, California

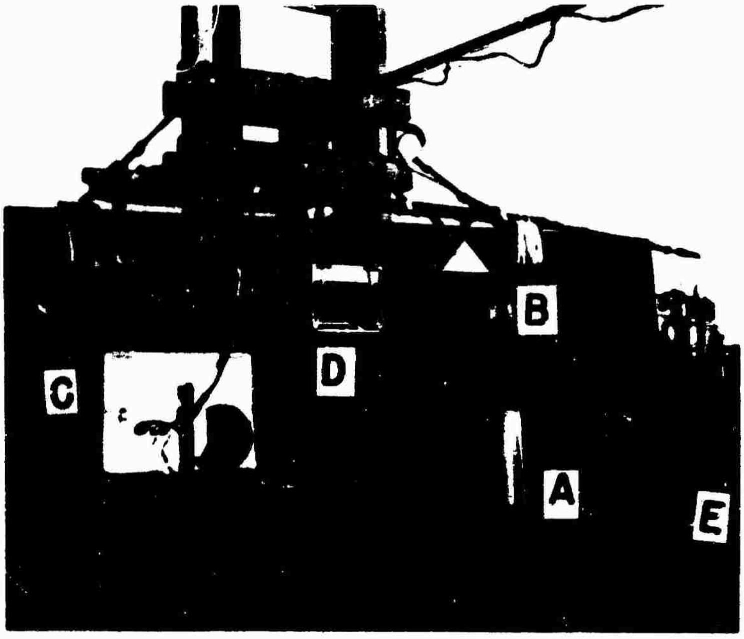

Figure 3. Stratospheric Humidity Sounding System. A-hygrometer and recorder container. B-hydraulic reel. C-electronic command and control equipment. D-ballast container. E-radiosonde

than that encountered in descent in the stratosphere and upper troposphere. During the several hours of flight the balloon had moved a considerable distance across a mountain range, and was sampling a different air mass. This flight effectively provided two independent soundings. Also apparent in Figure 4 is the horizontal stratification (layering effect) in the frost point profile. Several lamina are observed on both ascent and descent portions of the sounding. Examples are the layers at 140 and 50 mb. These stratified layers range in depth from a few hundred meters up to over a kilometer. Similar layering effects in other atmospheric constituents have been observed by other investigators (Hering and Borden, 1967; and Pittock, 1966). Pittock, for instance, reported a remarkably stable thin (0.5 km) layer of ozone and volcanic debris in tropical air which had been quasi-horizontally advected from about 8°S (originating from the Mt. Agung volcanic eruption) to 40°N. It was present over Boulder, Colorado at 50 mb for at least a month.

Figure 5 shows the monthly summary of all data found acceptable. Frost points are averages through the pressure levels indicated. There appears to be an annual cycle for layers higher in altitude than 100 mb (about 16 km). A maximum is reached in the late winter and a minimum in the summer. However,

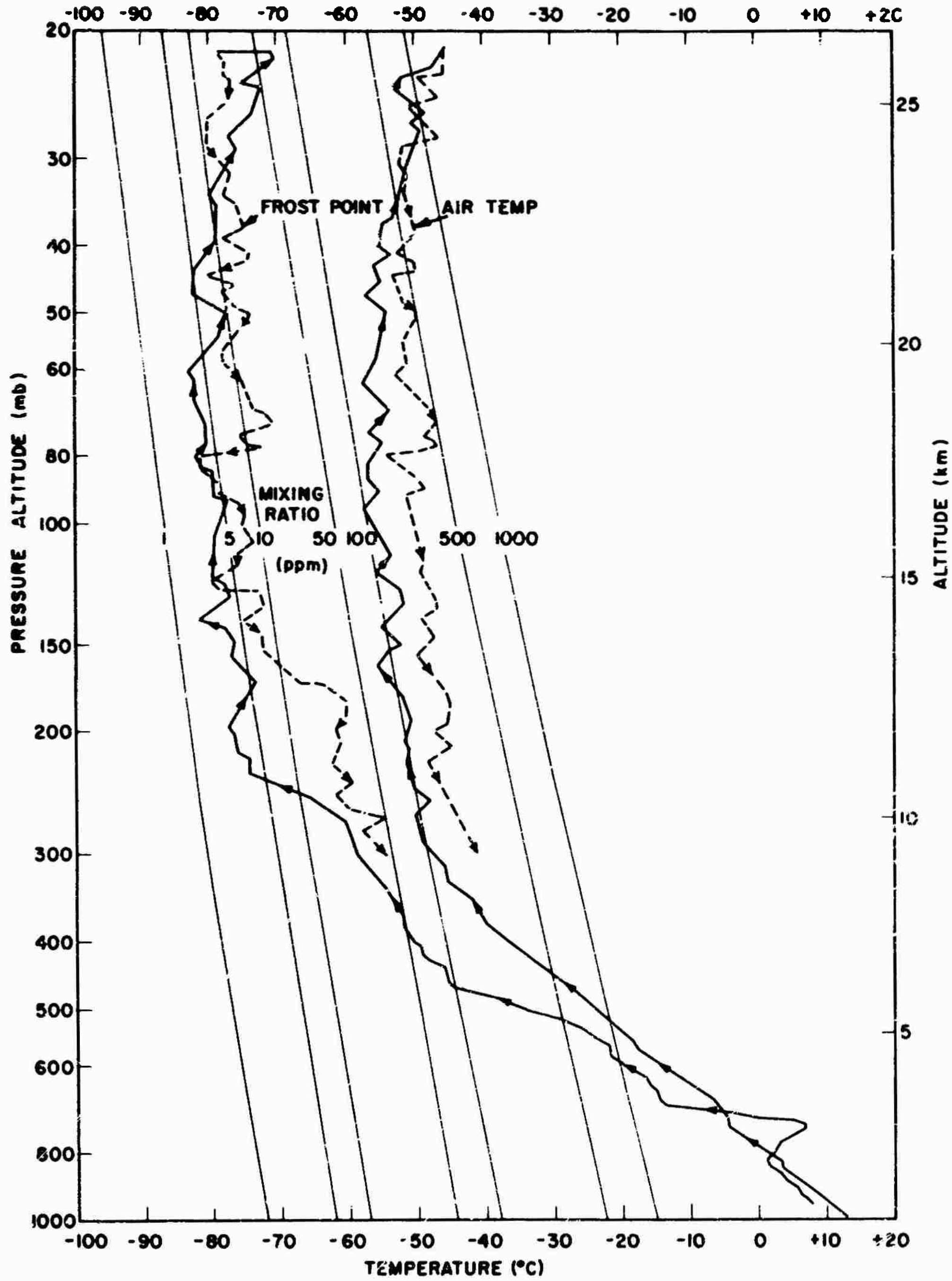

Figure 4. Sounding, 22 April 1965, Chico, California

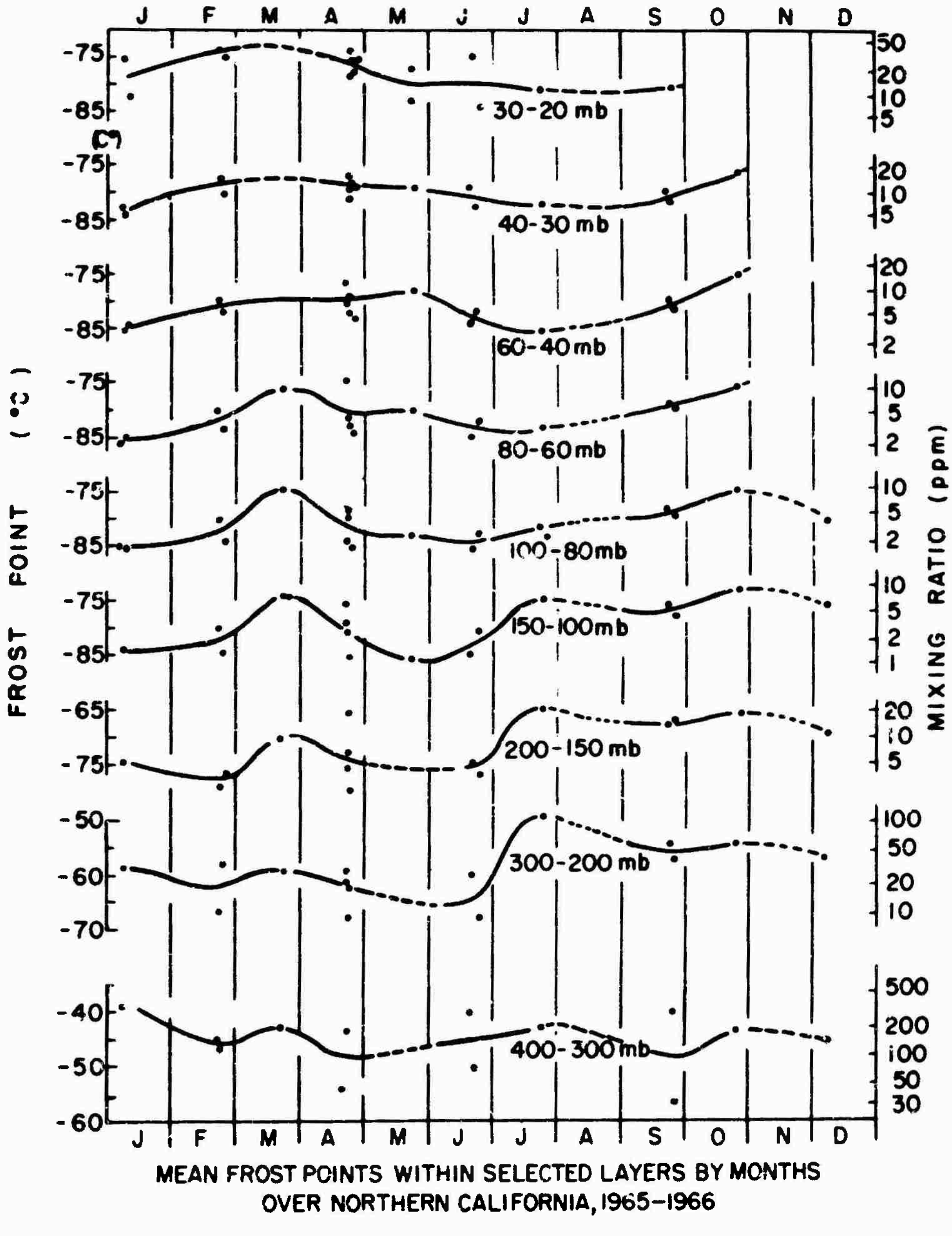

Figure 5. Mean Frost Points with Selected Layers by Months

there is probably little significance in deducing such systematic variation from this limited data sample. The range of the 5 data points obtained during April above 60 mb (2 in 1965, 3 in 1966) is nearly as great as that of the range of the annual cycle. Though such an annual cycle has been suggested in a theoretical study on ozone and water vapor in the stratosphere by Roney (1965), a harmonic analysis revealed that cycles depicted by the Chico data are not statistically significant.

As indicated earlier in this report, the humidity that can best be attached to the nonvarying dry British stratosphere is 2 ppm by weight; that is, a mixing ratio of 0.002 g per kg. The values obtained in this study near the 100 to 150 mb layer, which is the maximum altitude of the original British aircraft data, are in good agreement with this nominal value. Our data ranged from 1 to 10 ppm at this level. However, as can be noted from the scale on the far right of Figure 5, though the annual cycle appears to be damping out with altitude, the proportion of water vapor appears to be increasing, attaining some 10 to 40 ppm near the top of the soundings. This increase is sufficient so that the frost point increases from about -81°C at 18 km to about -79°C at 25 km. This trend can make the reliability of these data suspect. If continued upward, the partial pressure of the water vapor at some altitude would exceed total atmospheric pressure. This is not physically possible.

For this reason, a special experiment was arranged to carry the equipment to higher altitudes. This sounding (Figure 6) reached a pressure of 8 to 9 mb, about 32 km as compared to the usual 25 km. The lower 25 km of this sounding differs little from the earlier soundings. Once above the tropopause, frost point decreases to a -84°C minimum, and increases to a maximum of -75°C at 23 mb, about 25.5 km. However, above this point a trend is established toward lower frost-point values. At 9 mb it dips to -82°C, lowering the mixing ratio to 27 ppm, still 10 times that at the base of the stratosphere.

A convincing factor in this high-altitude sounding that provides confidence in the presence of a slightly more moist layer at 25 km than immediately above or below this level, is that it is seen in both ascent and descent. There are some differences due to time and space, since about 3 hours elapsed between ascent and descent through the 25 mb level. If contamination were thought to be the reason for the maximum in humidity on ascent, it would be difficult to argue that this is the cause of the maximum on descent, since the system had dried out at higher altitudes as evidenced by the lower humidities with higher temperatures. Also, the air sampled in descent is less likely to have had any contact with the boundary layer air of the balloon system than on ascent. The fact that the sensor had the range to attain much colder frost points, which were observed both above and below this layer, also establishes confidence in the instrumentation and the slightly increased humidity at 25 km.

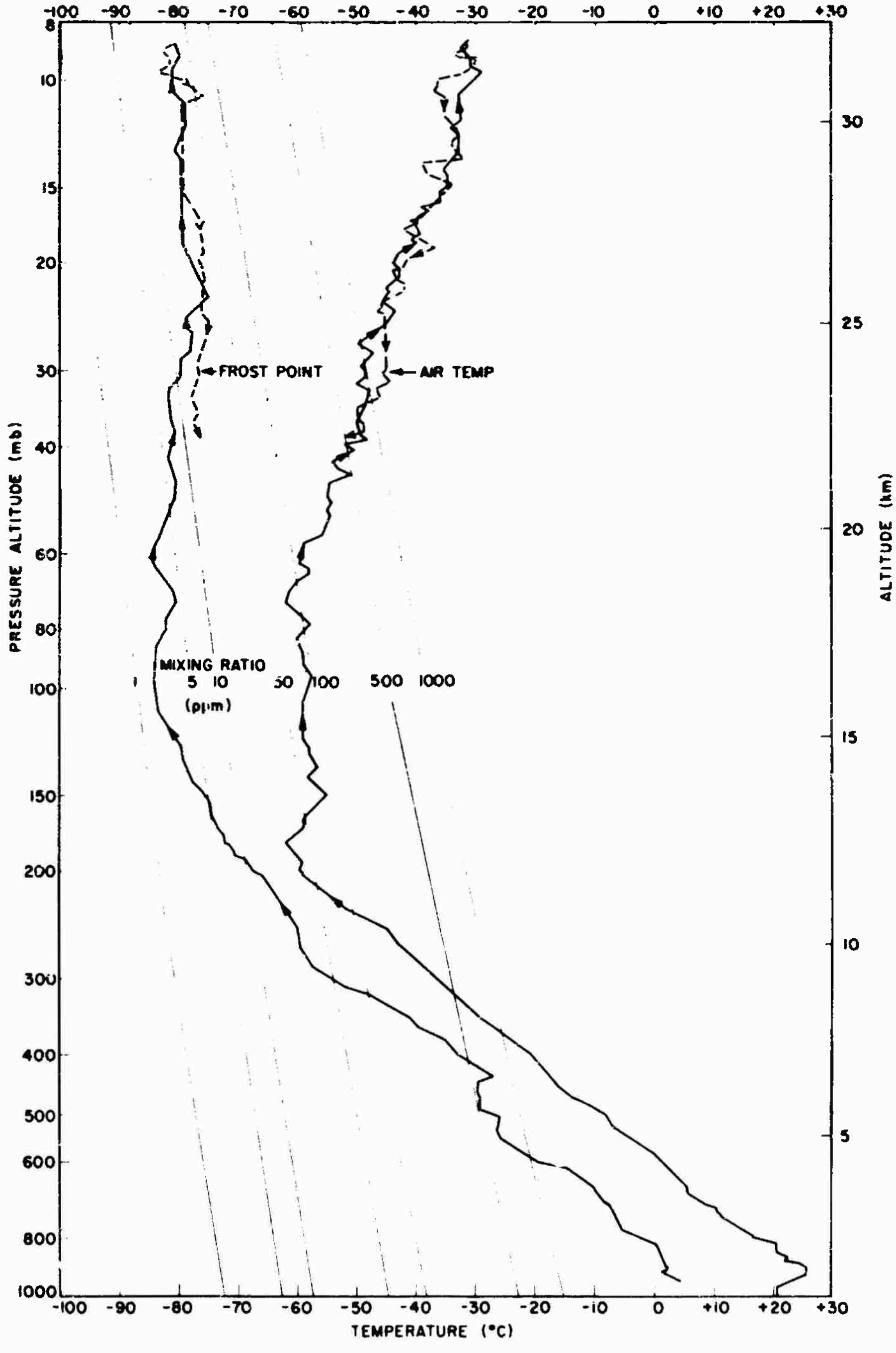

Figure 6. Sounding, 25 April 1966, Chico, California

To further verify this relative maximum in humidity at about 25 km with a decrease above, an additional sounding was made 26 April 1967 (see Figure 7). The results of this flight were a disappointment. Due to an apparent equipment malfunction early in the sounding, in either the heat sink, the electronics, or both, frost-point temperatures appear to be 5 to 10°C too warm at all altitudes. However, the vertical gradients in the frost-point profile appear to be valid. They are very similar to those in Figure 6. After a humidity minimum above the tropopause, the frost-point increases gradually to a maximum at about 22 km. (In Figure 6 the maximum is at 25 km.) Above this maximum, the frost-point gradient is about -1°C per km up to the top of the sounding, 32 km. The frost-point lapse rate in the top portion of this 26 April 1967 flight is essentially the same as that depicted above 25 km in Figure 6. The descent data was valid only down to about 27 km, but in the 5 km descent the frost-point temperature trace closely followed the ascent profile.

Figure 8 is presented as further support for the tendency of a humidity maximum at 25 km, at least over mid-latitudes. (This is also the altitude of nacreous clouds. Such clouds generally form to the leeward of mountains during periods of strong upper air flow across the range.) This 14 June 1965 sounding was obtained at Holloman AFB in New Mexico during investigations of the frost-point sounding system contamination (Ballinger et al, 1965b). The alpha radiation, frost-point hygrometer was flown on the load bar in these studies (rather than at 2000 ft beneath it as in Chico), and usually showed much less contamination than in the flight pictured in Figure 8. Presumably this is because of the drier surface and troposphere conditions of the New Mexico desert. However, both ascent and descent of this Holloman flight also showed a tendency for the slight increase in moisture at 25 mb.

How this gradient in frost-point of -1°C per km above 25 km is related to water vapor at the mesopause was next considered. Probably the only information in which one can place great confidence regarding water vapor in a layer at high altitude, was derived from an experiment in which noctilucent cloud particles, captured by a rocket at the 80 km mesopause level, included ice (Soberman, 1963; and Michaels, 1965). This finding implies the existence of saturated water vapor through a layer at this high altitude. Such clouds are not found at tropical and mid-latitudes where temperatures are seldom colder than -100°C (Cole and Kantor, 1963) at this level. They are only seen at high latitudes in the summer where extremely cold mesopause temperatures are usual. During one experiment (Anonymous, 1963), at which such clouds were physically sampled, the temperature observed was -143°C. During another sampling, when the clouds had dissipated, a temperature of -120°C was measured. If the mixing ratio at 30 km, the top level of our highest sounding, 27 ppm (Figure 6), were considered to hold uniformly up

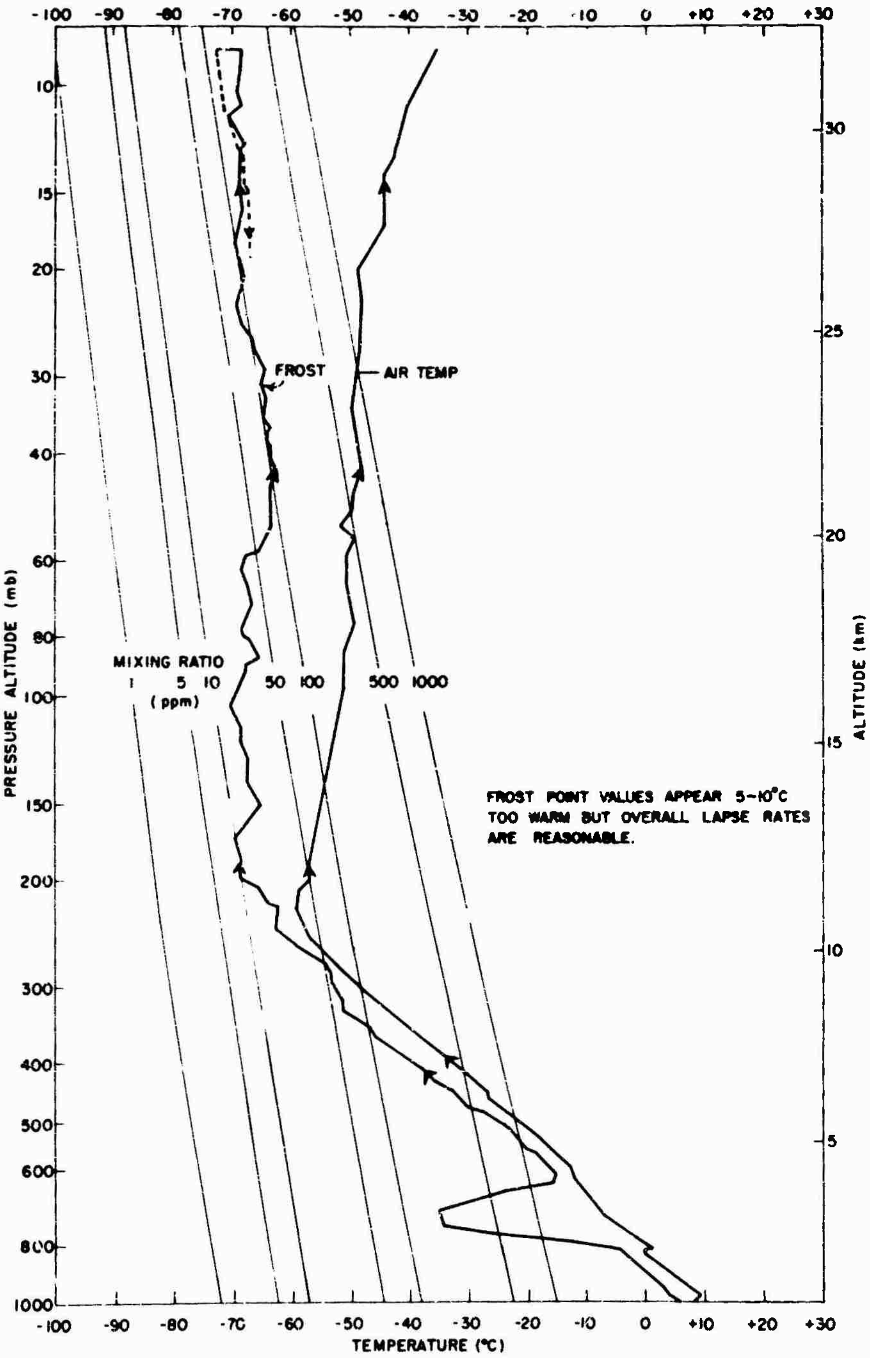

Figure 7. Sounding with Bias Due to Malfunction, 26 April 1967, Chico, California

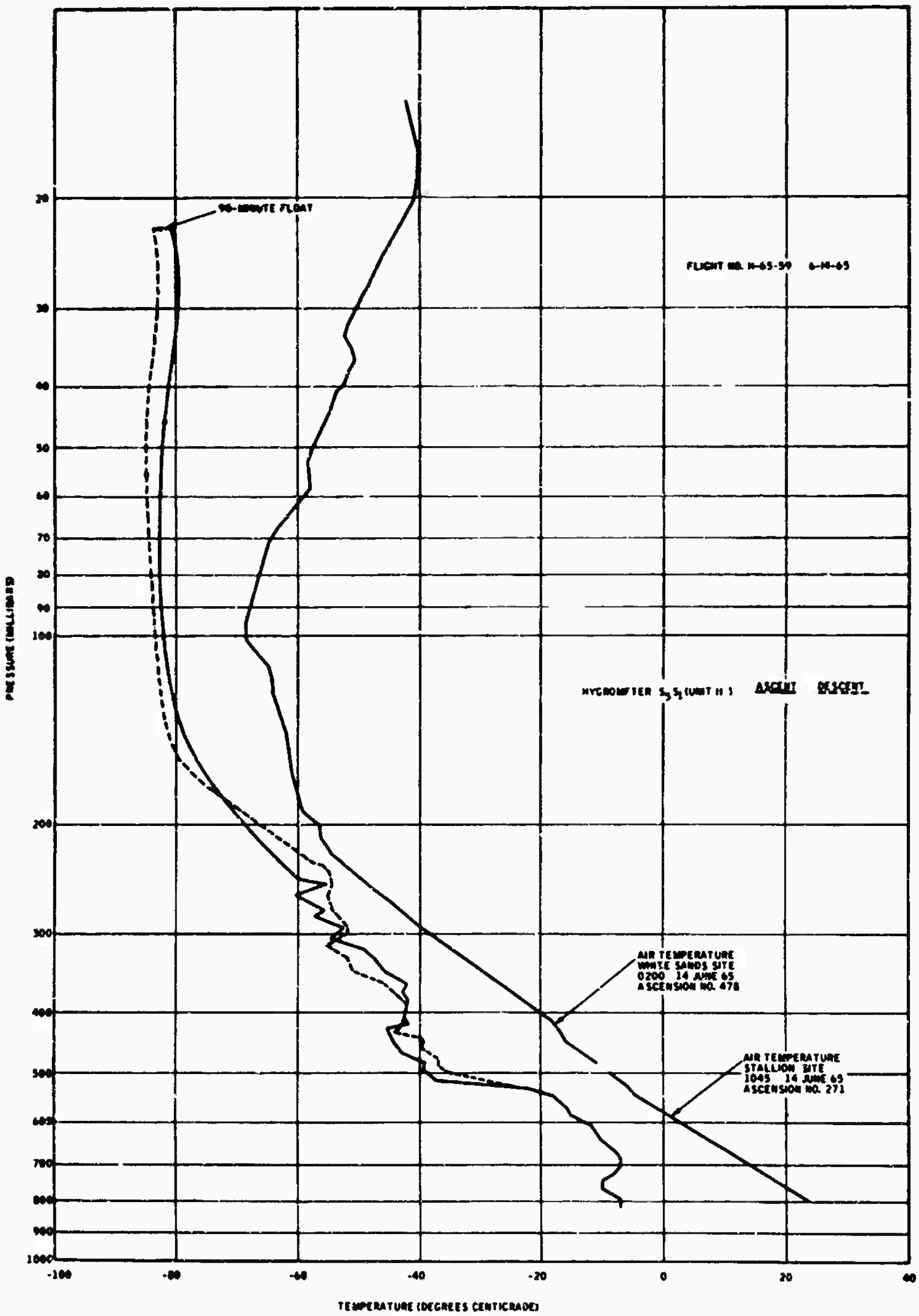

Figure 8. Contamination Study Sounding, 14 June 1965, Holloman, New Mexico

to 80 km, 10^{-2} mb (COESA, 1966), the frost-point would be -115°C, not cold enough. However, the frost-point in this sounding had fallen 7°C in the highest 6.5 km, a gradient of about 1°C per km. At this rate 48 km are required to lower the frost-point from -82°C (the value at 32 km in Figure 6) to -130°C, a nominal value for noctilucent clouds suggested by the experimental data of "clouds at -143°C, and clouds dissipated at -120°C." Since these clouds are found about 48 km above the top of this sounding, the trend in humidity in the 25 to 32 km altitude region provided by the Chico sounding appears to support the values of humidity which must be present at altitudes of noctilucent clouds.

Now the problem remains of explaining the relatively moist layers at 20 to 25 km. Mixing ratios in this layer are five times those at the base of the stratosphere, and can only be considered credible if a source for such a "spiking" of the stratosphere can be presented. The British and other investigators (Mastenbrook, 1965b) had noted near saturation in the upper troposphere, and a sharp drying out upon passing upward through the tropopause. The Chico data corroborates these findings. In Figure 9 the average change in depression in frost point below free-air temperature during penetration of the tropopause for this series of soundings, is shown. The drop in frost point from -63.9°C at the tropopause to -80.4°C in 2.8 km, lowers the water content by a factor of 12. The tropopause certainly seems to act as a barrier.

However, there are exceptions which, if not present, would have made these average rates of decrease even more dramatic. In Figure 10, the graph at the left displays a sharp temperature tropopause (the solid curve). With it there is a very sharp decrease in the frost-point (the dashed curve). At the right of Figure 10, for another weather situation, the tropopause is not well defined (solid curve). The parallel frost-point decreases were far less dramatic (dashed curve). This example suggests that with less intense tropopause inversions, such as encountered frequently at mid-latitudes when there is overlapping or leafing of tropical and polar tropopauses, there will be occasional transfer of moister troposphere air into the stratosphere. For example, over the Gulf of Alaska where such leafing action could be forced by well-developed cyclones regularly entering the Aleutian Low (the tropopause is known to rise and fall as cyclones pass), the tropopause temperature remains between -50°C and -55°C (Ratner, 1957, 1958) throughout the year. This air is about 25°C warmer than in equatorial regions, and can contain nearly 100 times more vapor before becoming saturated. Small amounts of saturated tropospheric air being mixed upward could add considerably to the water vapor of higher level warmer air, even if most of this higher altitude air had entered the stratosphere over the equator, as suggested by Brewer (1949). Corroborating this speculation, extensive cloudiness through a deep layer well above the tropopause over Anchorage, Alaska, was noted by an Air Weather Service

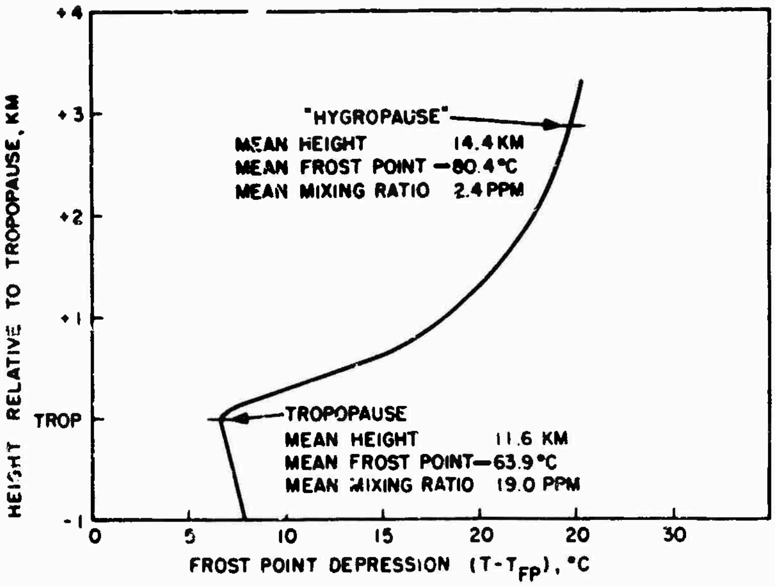

Figure 9. Mean Frost-Point Spread in Vicinity of Tropopause Level

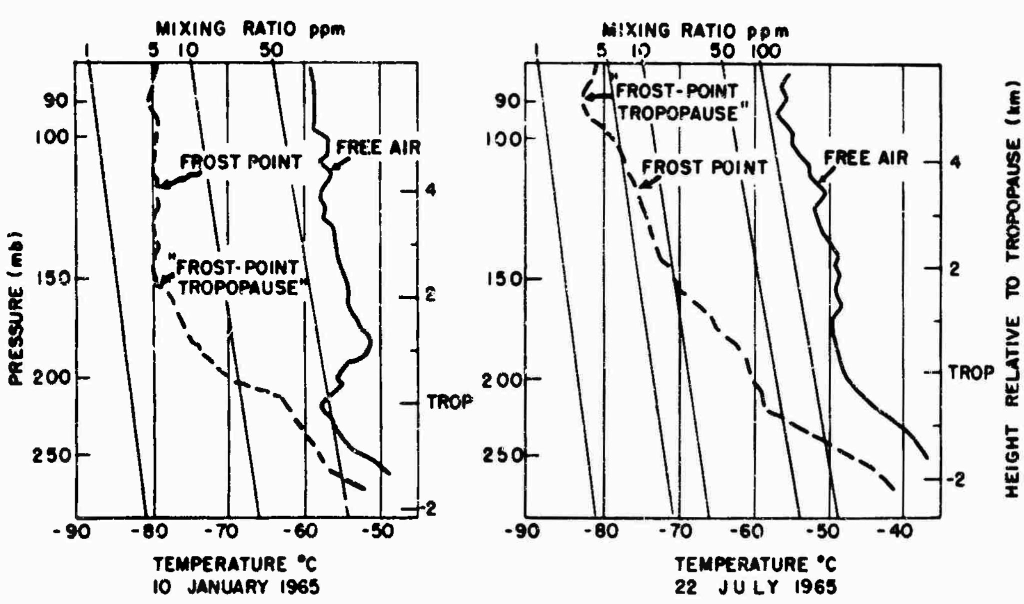

Figure 10. Frost-Point Profiles in Vicinity of Tropopause

forecaster (Ehrlich, 1966). Though a well-defined polar tropopause was present at 25,000 ft, jet aircraft were unable to top all cloudiness after climbing to 39,000 ft. This happened during a transition season, and was associated with passage of a not unusually-strong extra-tropical cyclone. Crutcher (1963) also summarized much evidence of clouds in the stratosphere in an address on problems of supersonic aircraft. He quoted Captain Joseph W. Kittenger, a USAF investigator/parachutist who upon jumping from a balloon at 102,800 ft stated: "I am making an exciting discovery. There are clouds at my altitude. They are so thin I see them only when my vision comes within 30 degrees of the sun, but they reflect the sun with dazzling whiteness."

Passage of water vapor into the stratosphere during leafing of multiple tropopauses at mid-latitude and higher is a possibility, but not necessarily an exclusive explanation. Another possibility is vaporization of the ice crystals of convective clouds, which penetrate into the stratosphere over continental mid-latitudes in the warmer half of the year. These have been observed to attain altitudes of 22 km by aircraft and radar (Grantham and Kantor, 1967; and Long, 1966) over the center of the United States with greater frequency than has heretofore been considered likely. They must evaporate to dissipate, and thus also add vapor to the air. Since at this level the upper winds flow from the east during the summer, this water vapor could very well be carried over Chico.

There are no known reliable direct measurements of humidity in the upper stratosphere and mesosphere, consistent with noctilucent cloud data, which can be compared to the suggested extension of the Chico profile. However, comparison to indirect measurements such as spectrographic analysis are possible. A balloon-borne spectrometer experiment was conducted from Holloman AFB, New Mexico in September 1965 by Johns Hopkins University. Special care was taken to remove the influence of the water, being outgassed from the floating balloon, from the reduced data. The results of this experiment, based on analysis of absorption of solar energy in 50 cm^{-1} wide spectral intervals, indicated mean mixing ratio of 10.5 ppm above the 34 mb float level (Zander, 1966). This value was later revised (Zander and Bottema, 1967) to 5.4 ppm after stronger emphasis was placed on individual spectral line analysis. In order to compare these findings to the extension of the Chico data to the mesopause suggested by the discussions of frost-point in noctilucent clouds, a nominal humidity profile was developed for Chico, Figure 11. Up to 25 km, it is the average of all soundings. Above 25 km, the frost-point lapse rate is that provided by the two soundings attaining 32 km. The British "Dry Sky" and Gutnick's (1962) average of data available before 1962, is also shown. Because of decreasing atmospheric pressure with altitude, the mean mixing ratio for each layer above 34 mb in Figure 11, extrapolated to 80 km, had to be weighted to obtain the mixing ratio comparable to that determined in this

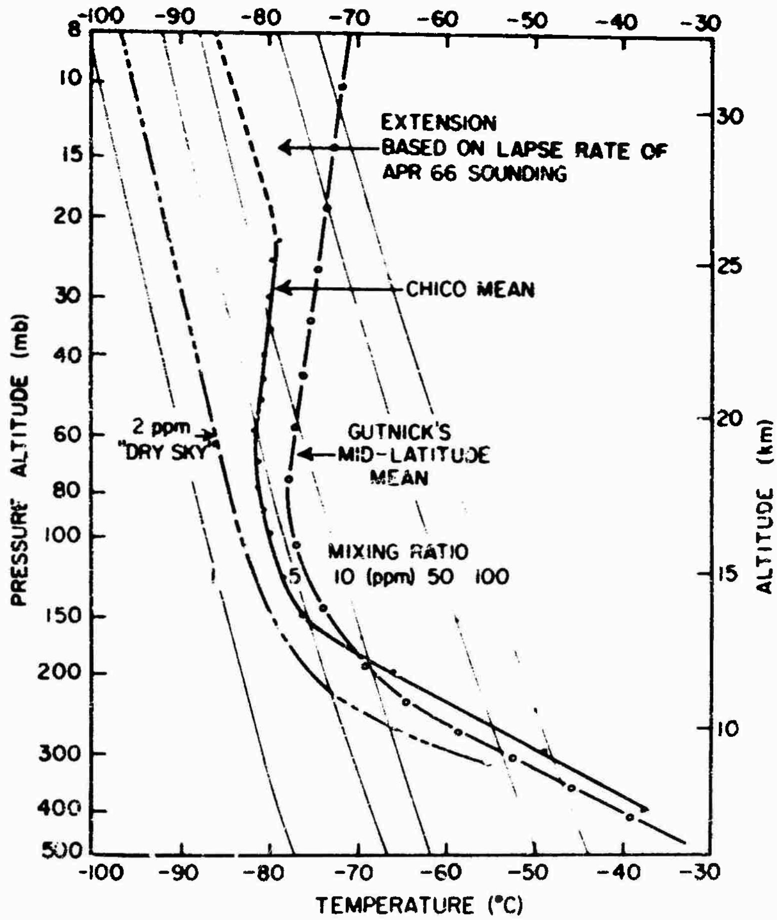

Figure 11. Comparison of Frost-Point Profiles

spectrographic experiment. Eight layers were chosen. The respective weighting factor and mean mixing ratios are shown in Table 2. The mean mixing ratio for the layer 34 to 0.01 mb (25 to 85 km), based on the extension of Chico data, is 14.7 ppm. Although this value is higher than the revised value of 5.4 ppm, it is only slightly higher than the original value of 10.5 ppm. Regardless of which of the two New Mexico values are accepted, it cannot be considered in great conflict with Chico findings. There is far less likelihood that water vapor injected into the stratosphere through the tropopause over Pacific cyclones will reach New Mexico in September, than will reach Chico on a year round basis. Also, though the New Mexico sounding, Figure 8, does show a tendency for a slight maximum near 25 km in June, the Zander sounding at 24 km in September may have been above such a maximum, or near the top of it. Chico soundings revealed that this slight maximum had a range in altitude of a few kilometers, although average

Table 2. Basis for Obtaining Mean Mixing Ratio Above 34 mb at Chico, California

Layer (mb)	Weighting Factor	Mean Mixing Ratio (ppm) Chico, extended
34 to 25	9	13.0
25 to 15	10	17.0
15 to 10	5	17.0
10 to 6	4	15.5
6 to 3	3	14.0
3 to 1	2	10.4
1 to 0.5	0.5	6.8
0.5 to 0.01	0.5	1.8

altitude was 25 km. Therefore, the arguments for explaining the small, but measureable, amount of water vapor up to 25 kilometers at Chico, can be logically used to estimate a lesser amount over New Mexico, where the tropopause inversion is stronger.

3. CONCLUSIONS

(1) A nominal mid-latitude yearly average humidity profile is provided by the average of 17 Chico, California soundings, Figure 11. The dashed extension is a result of only one sounding plus corroboration in the gradient from a malfunctioning second attempt to reach this 32 km. The curve reveals a stratospheric humidity minimum above the tropopause near 15 km, a slight maximum near 25 km, and a gradual decrease upward. This rate of decrease provides a frost-point of -130°C at the mesopause (80 km), which is in reasonable agreement with temperatures observed while trapping noctilucent cloud particles which contained water. The mid-latitude maximum required a physical explanation, a water source to make it plausible. Two mechanisms have been suggested.

(2) The curve on the left of Figure 11 is representative of the frost-points that could be expected if the mixing ratio remained constant at 2 ppm, the value suggested by early British investigators and still considered valid by many. This curve yields a frost-point of -125°C at the altitudes of noctilucent clouds, which is still within the range for agreement with experimental noctilucent cloud data of "-120°C no cloud, and -143°C cloud present," obtained by the 1963 United States-Swedish rocket experiments. Having a nominal profile of humidity such as this over the tropical areas would not be inconsistent with the nominal mid-latitude profile inferred from the Chico soundings, if the suggested mechanism for injection of water vapor into the stratosphere in the mid-latitudes is acceptable.

(3) The curve on the right, prepared by Gutnick (1962), shows the mean conditions observed up to that tune, after screening out data thought to be erroneous through subjective examination. This water-content profile could not be reasonably extrapolated upward since it would require noctilucent clouds over most of the earth, and result in a partial pressure of water vapor which exceeds the total pressure of the atmosphere at the same altitude.

(4) Finally the processes that introduced water vapor into the stratosphere are sporadic, so that there is variability of nearly ten-fold in the lower stratosphere at mid-latitudes. Systematic variability, such as associated with seasons, also appears to be present but much more evidence is required to substantiate it.

(5) None of the Chicc experimental data support speculation that the lower-to-middle stratosphere is sometimes nearly saturated.

Acknowledgments

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Lt. Col. Robert W. Cowne was responsible for monitoring development and procurement of the instrument package and in supervising some of the early flights. The efforts of M/Sgt John E. Bowers, Instrument Technician, in preparing and maintaining flight instruments also merit special recognition. Special thanks are due to Messrs. S. Rohrbough and J. Ballinger, of Honeywell, Incorporated for design of the sensor package and field aid during initial flights. The Balloon systems were designed by AFCRL's Balloon Research Branch, and flown under the supervision of the Balloon Flight Requirements Analysis Branch.

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Appendix to Part I

Graphs of the 14 soundings which were not discussed in the text, plus an edited version of the first sounding, are provided in this appendix (Figures 12-26). Ascent is shown by the upward pointing arrows, and descent by the downward pointing arrows. Air temperature was measured by 10-mil bead thermistors exposed about 1 meter from the humidity sensor. The height ordinate of the attached graphs is expressed in pressure (mb), and corresponding geopotential altitude (km) is based on the "U. S. Standard Atmosphere, 1962." Mixing ratio is given in parts per million, 10^{-6} grams of water vapor, per gram of dry air.

Some portions of the attached soundings are not considered valid and are questionable as explained below:

(1) The cross-hatched portions of the frost-point profiles are when the hygrometer was being contaminated by extraneous moisture, and are not considered valid.

(2) The dotted portions of Flight 11, 14, 15, and 18 are periods of missing data due to equipment malfunction, illegible recorder traces, etc. The dotted curves are merely linear interpolation between the bracketing valid data and, although these appear reasonable, they are open to question.

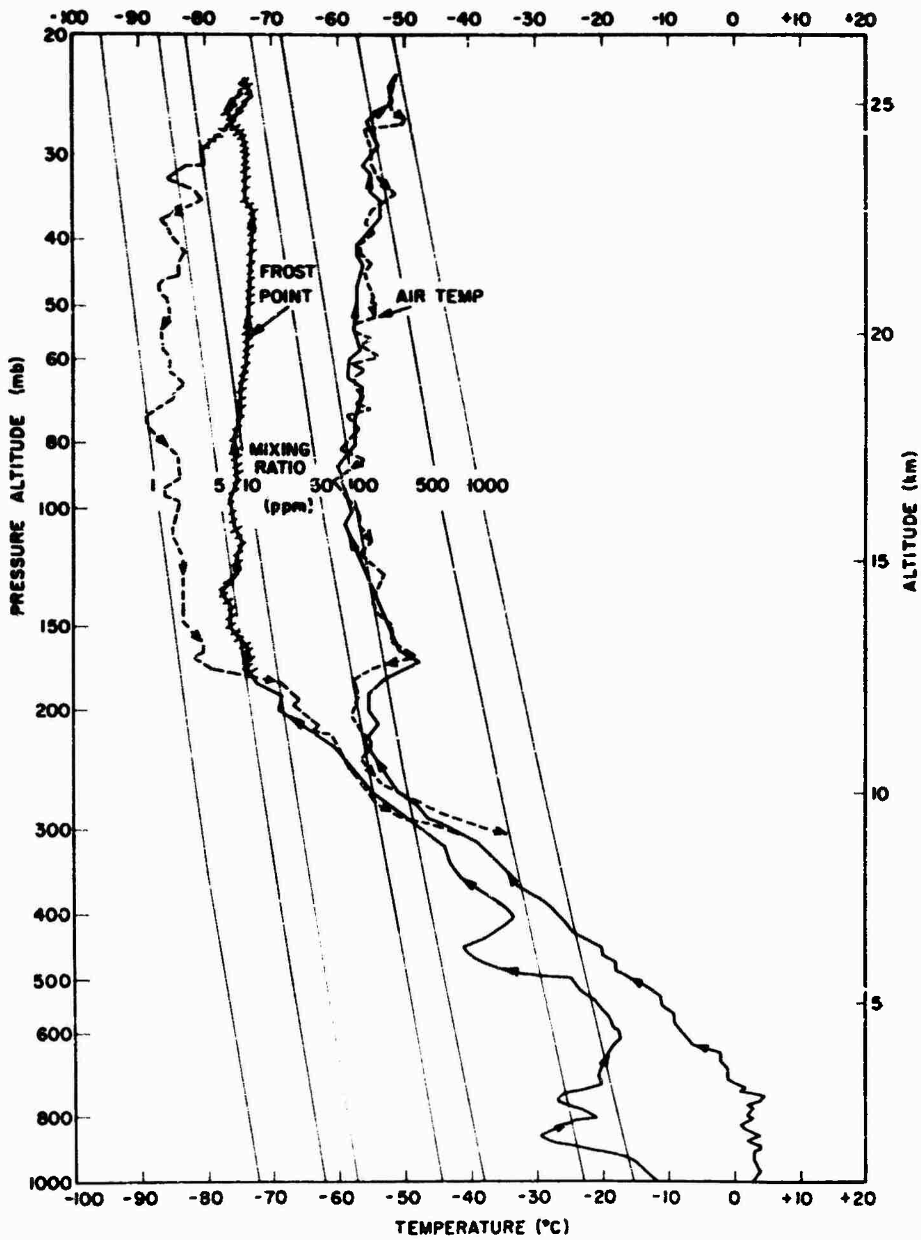

Figure 12. Flight 1, 8 January 1965

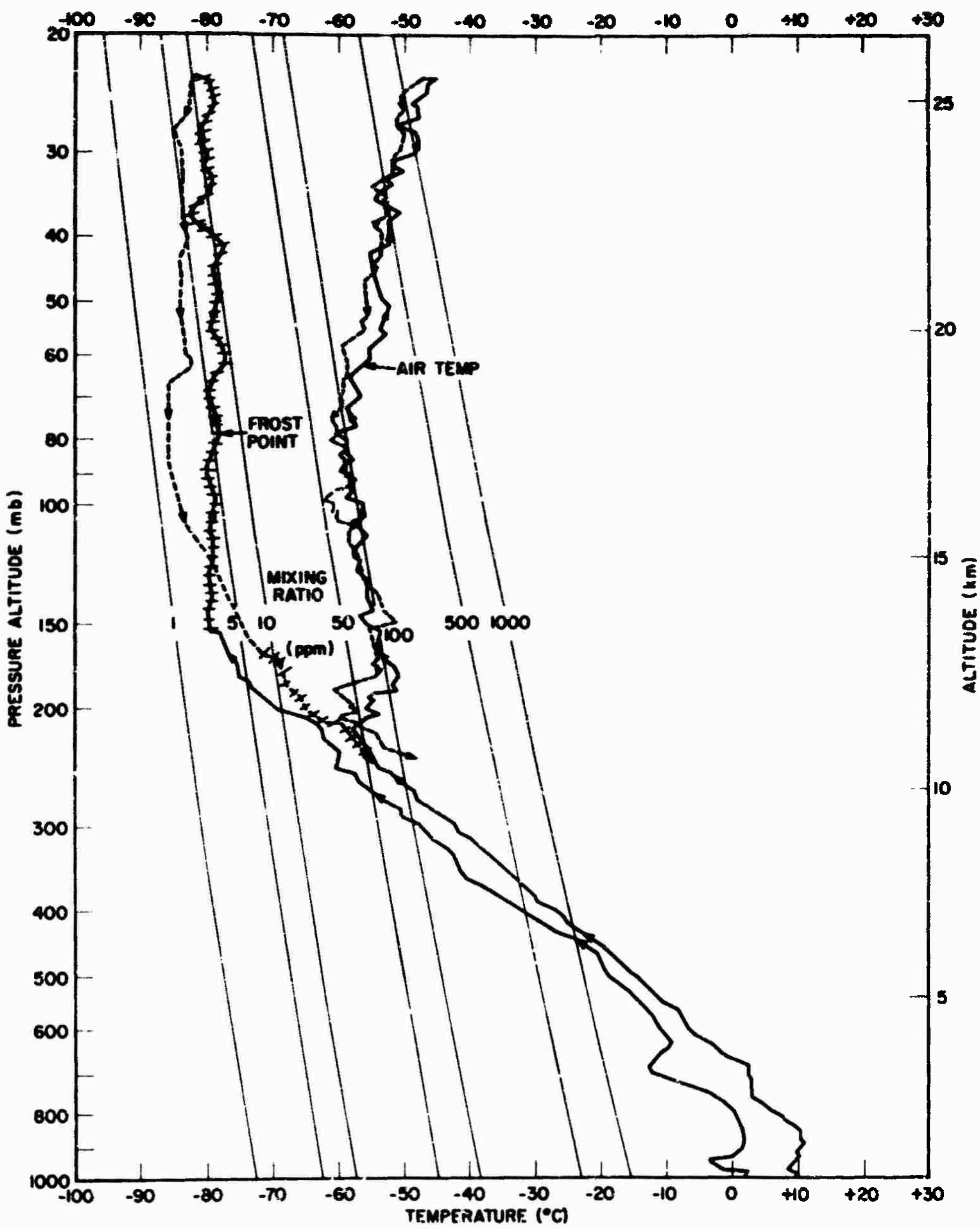

Figure 13. Flight 2, 10 January 1965

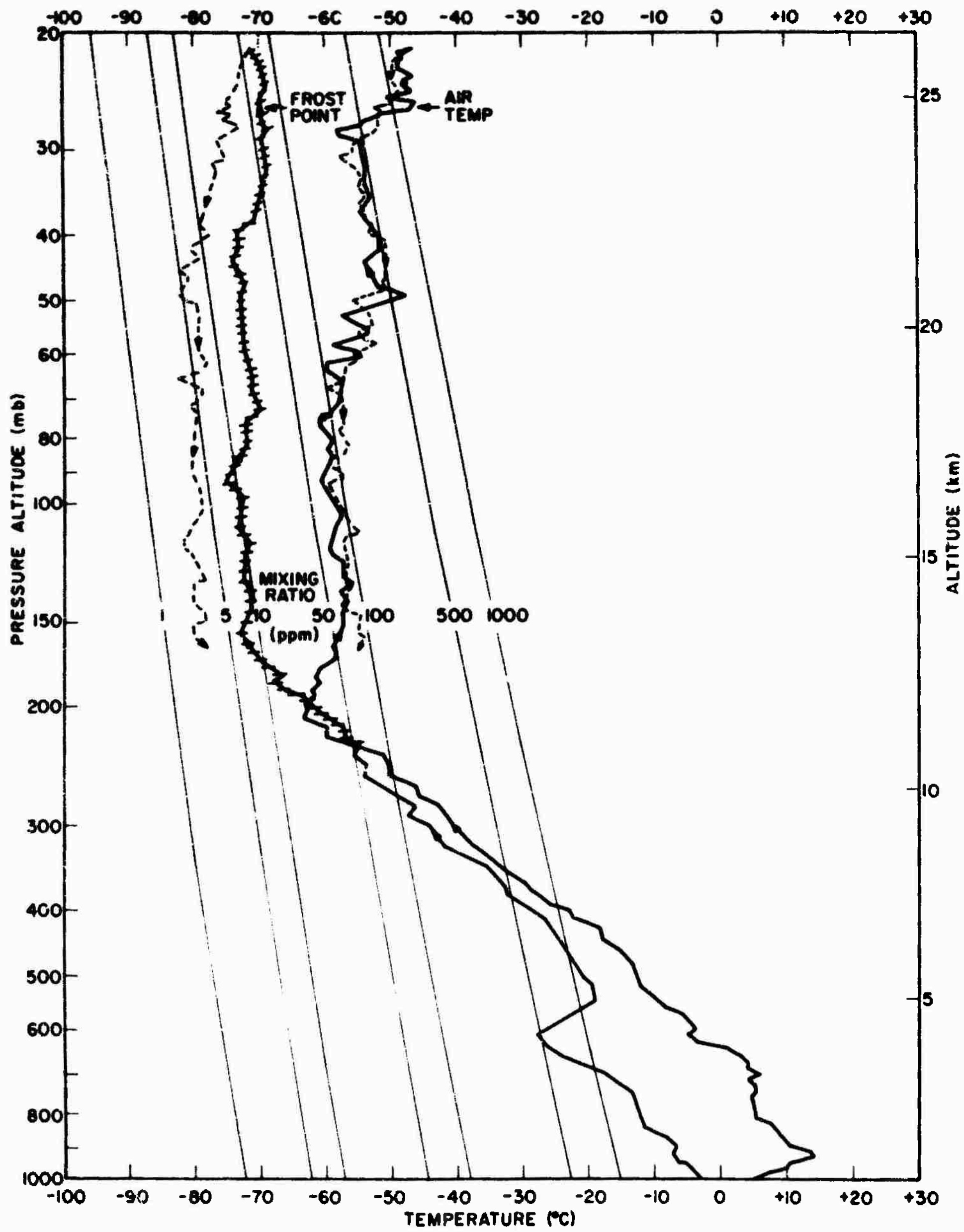

Figure 14. Flight 4, 24 February 1965

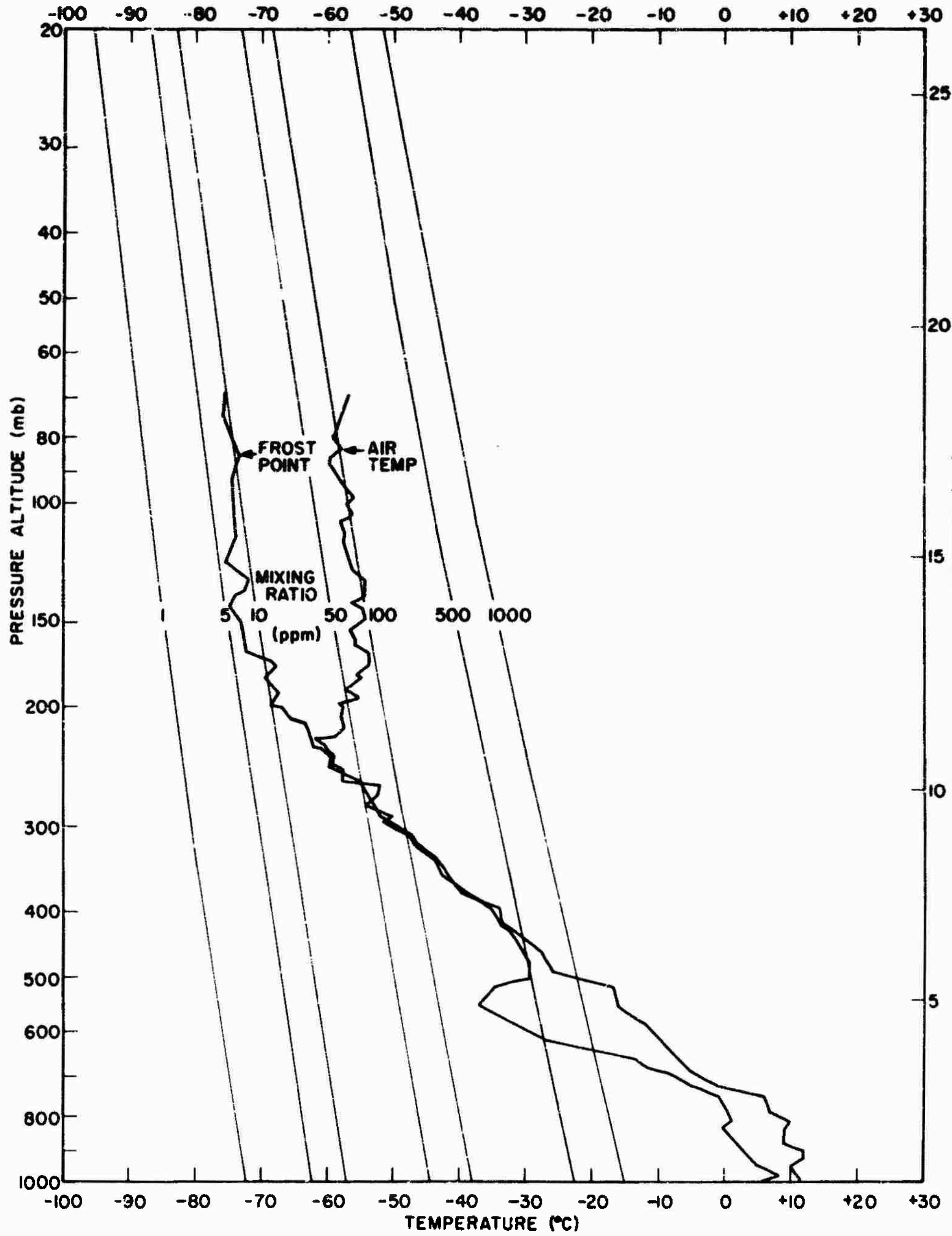

Figure 15. Flight 5, 23 March 1965

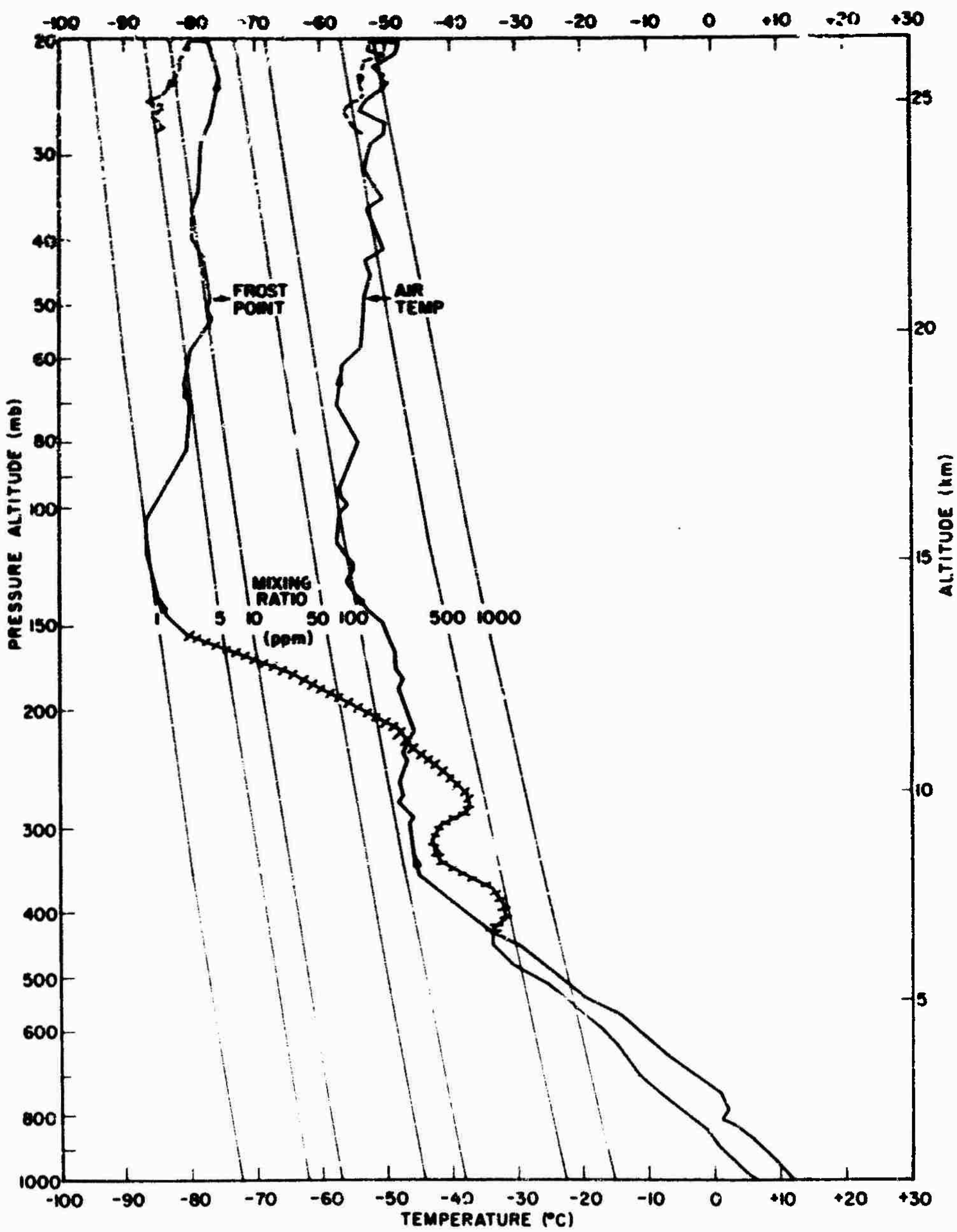

Figure 16. Flight 8, 22 May 1965

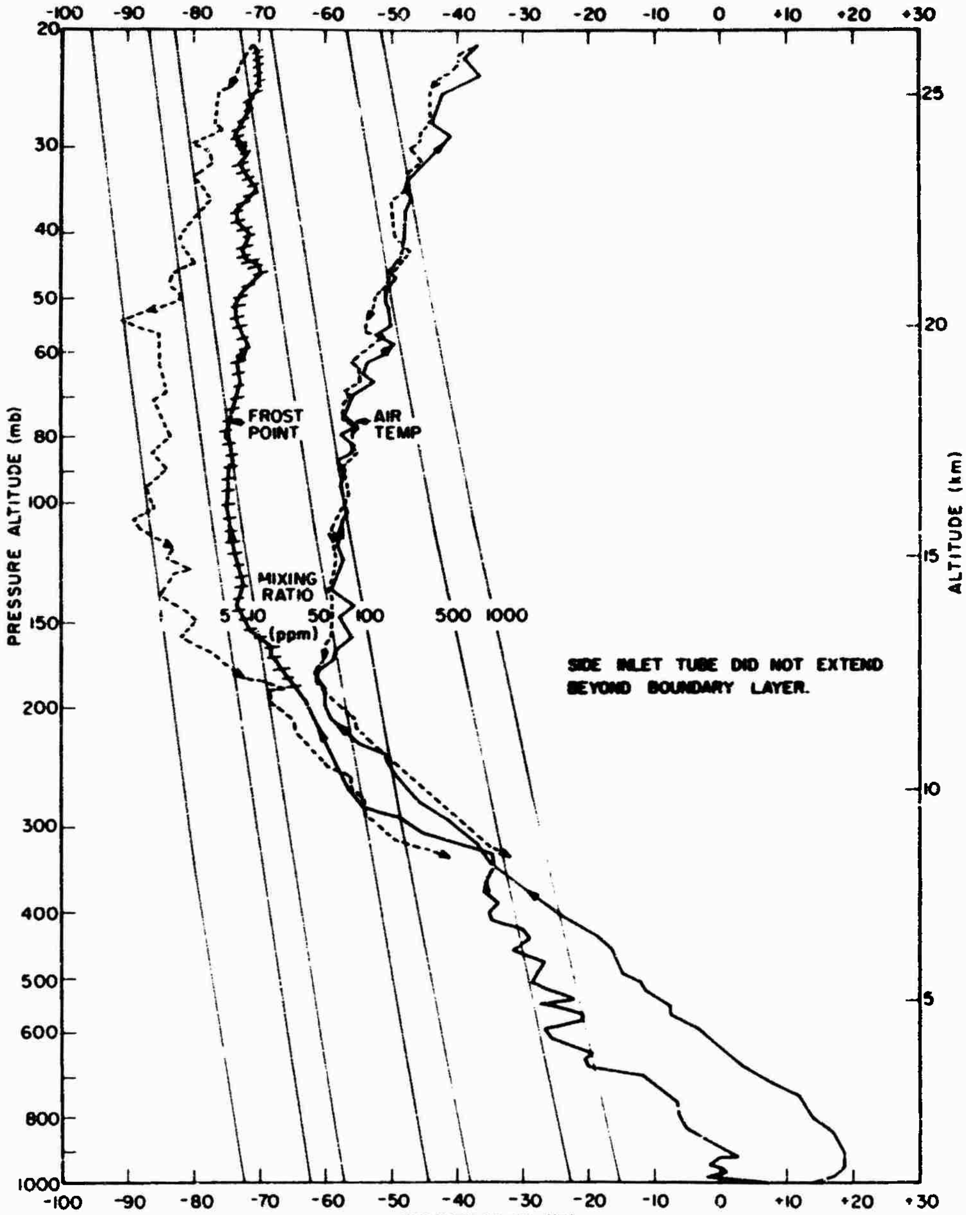

Figure 17. Flight 10, 22 June 1965

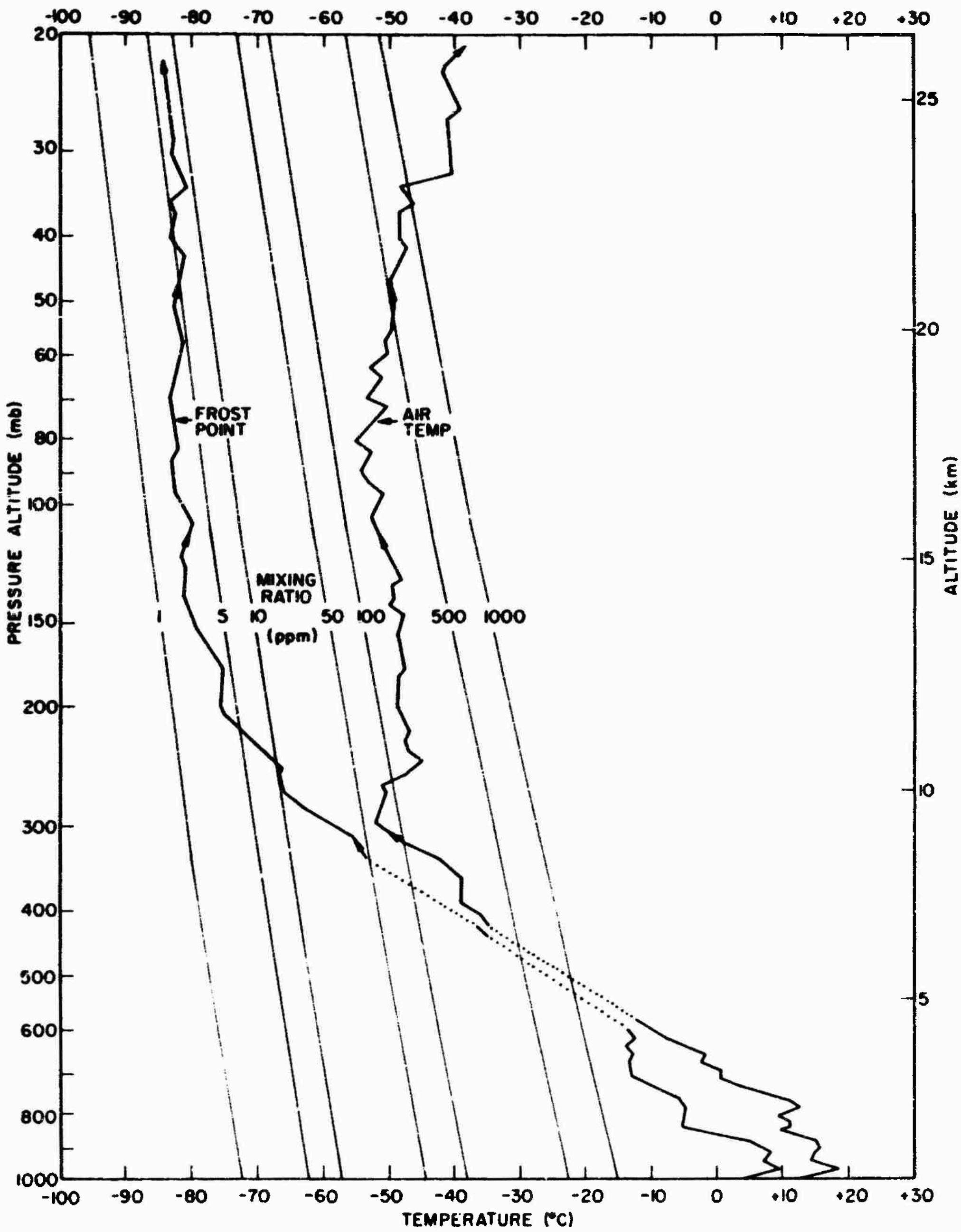

Figure 18. Flight 11, 25 June 1965

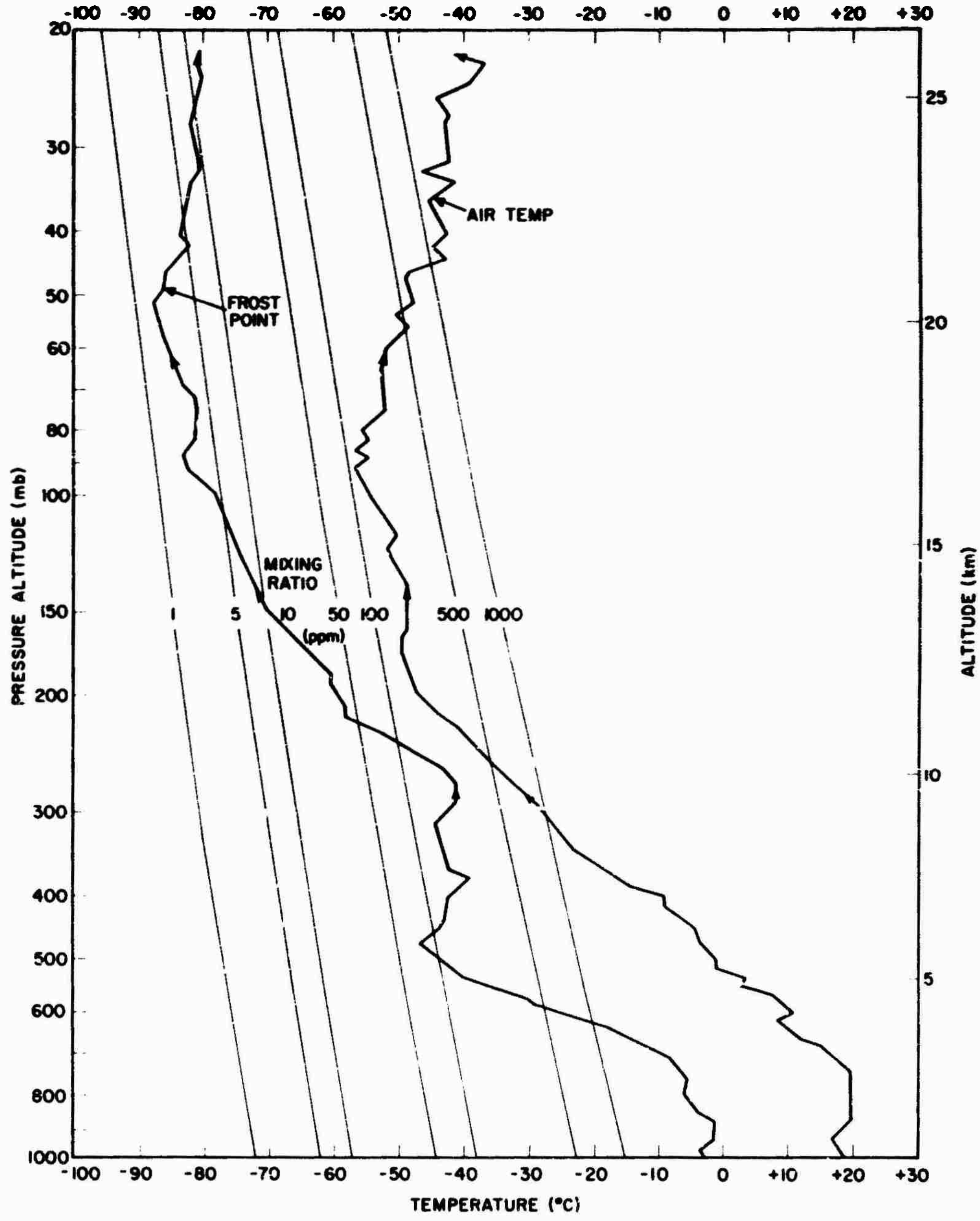

Figure 19. Flight 13, 22 July 1965

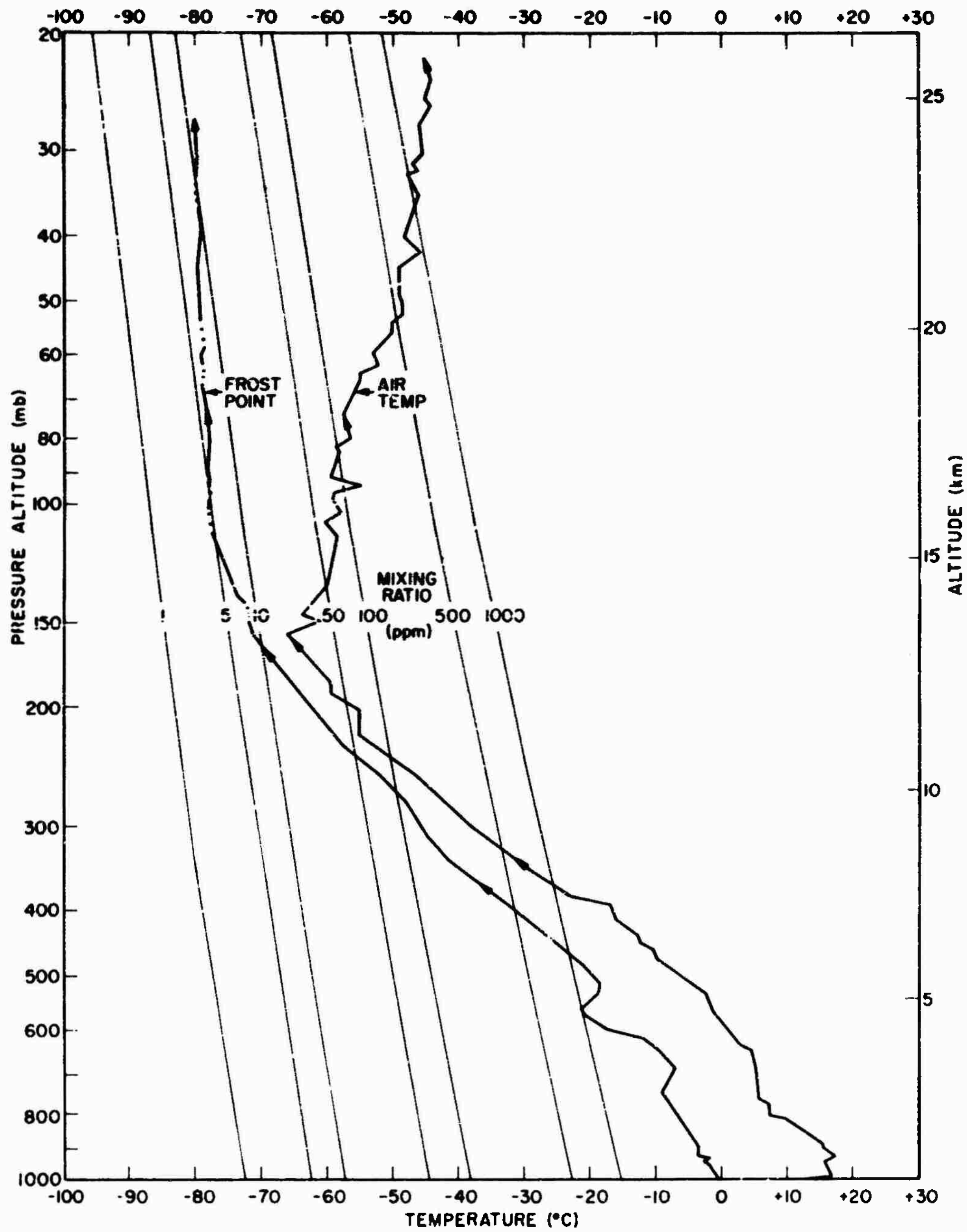

Figure 20. Flight 14, 21 September 1965

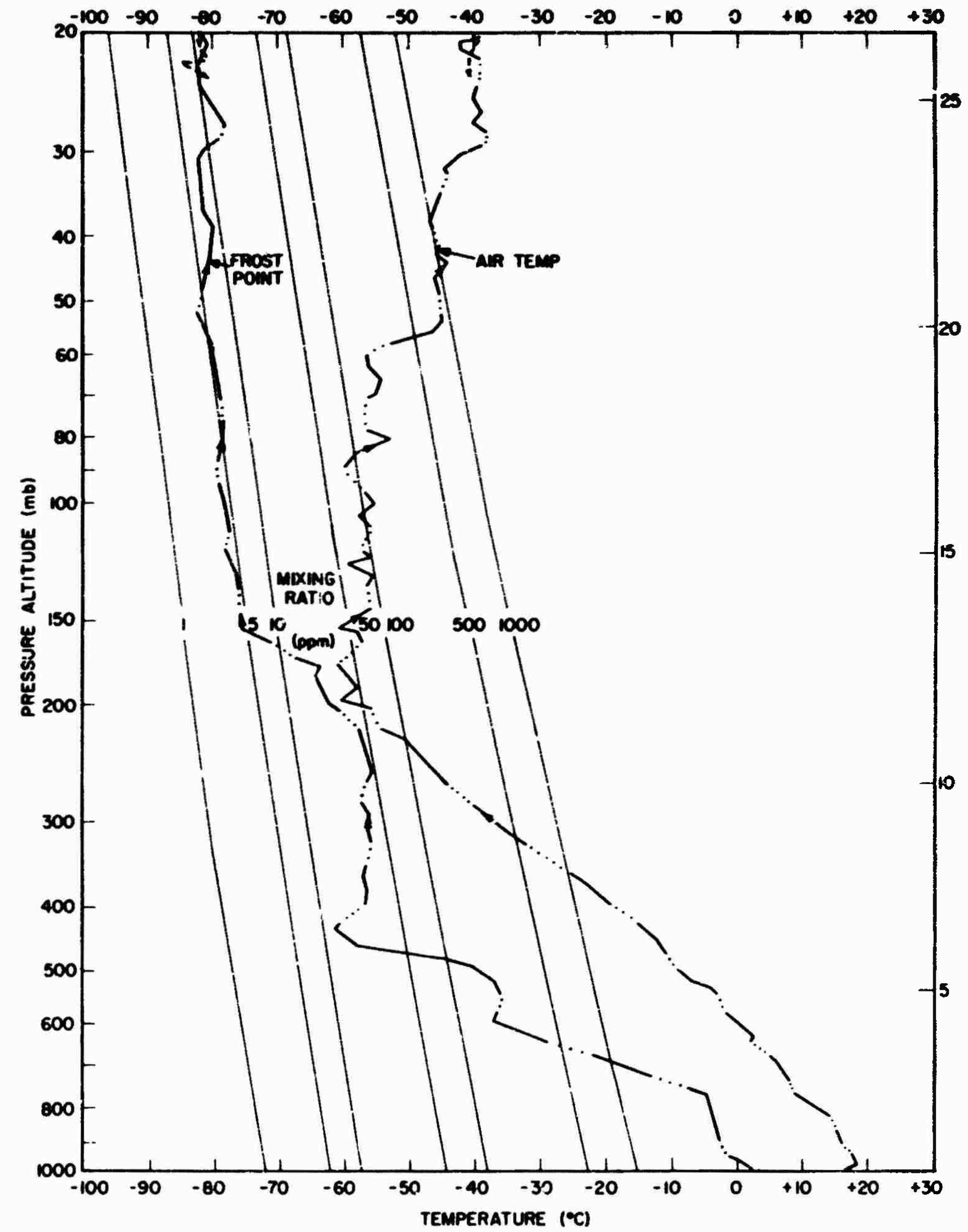

Figure 21. Flight 15, 23 September 1965

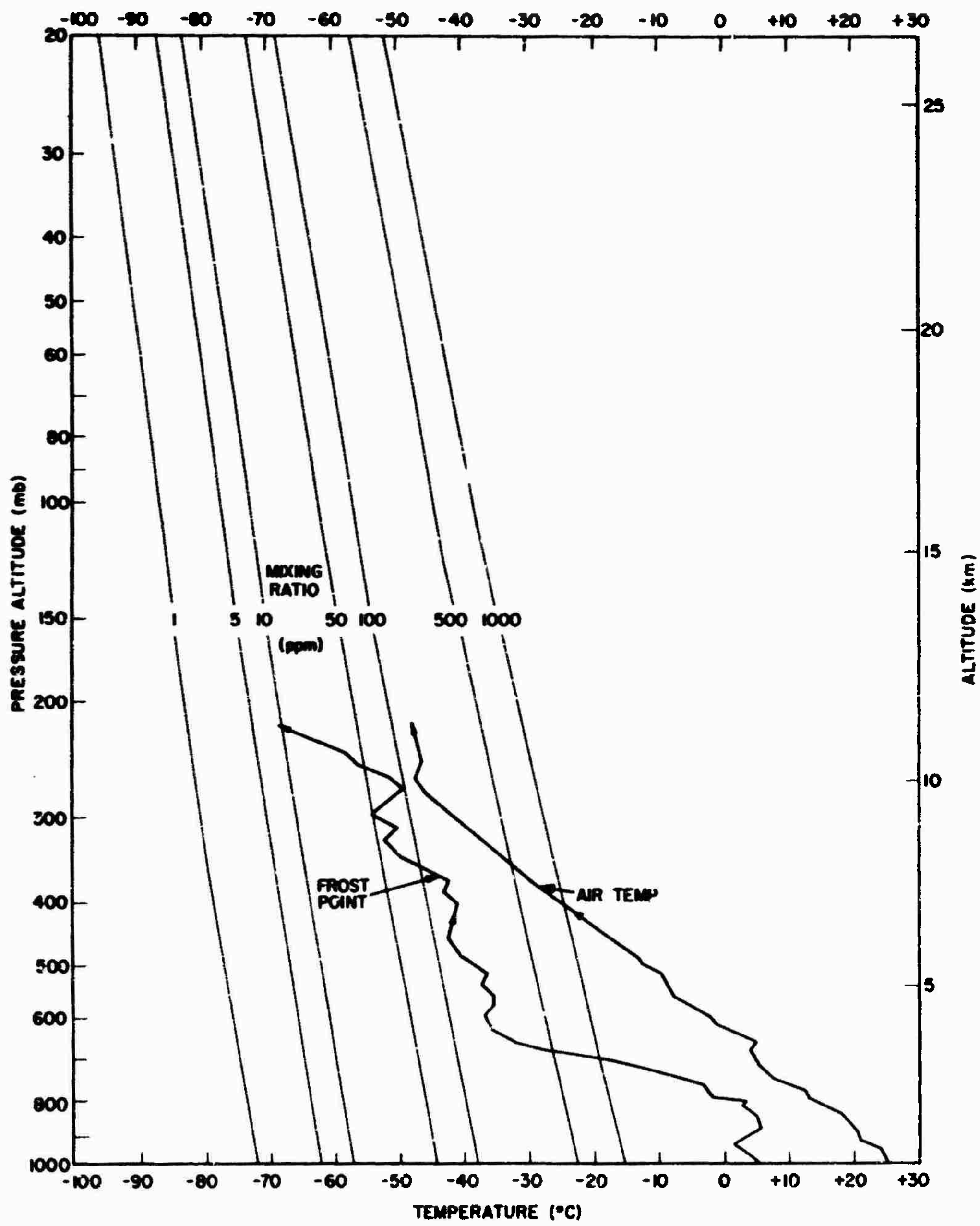

Figure 22. Flight 16, 25 October 1965

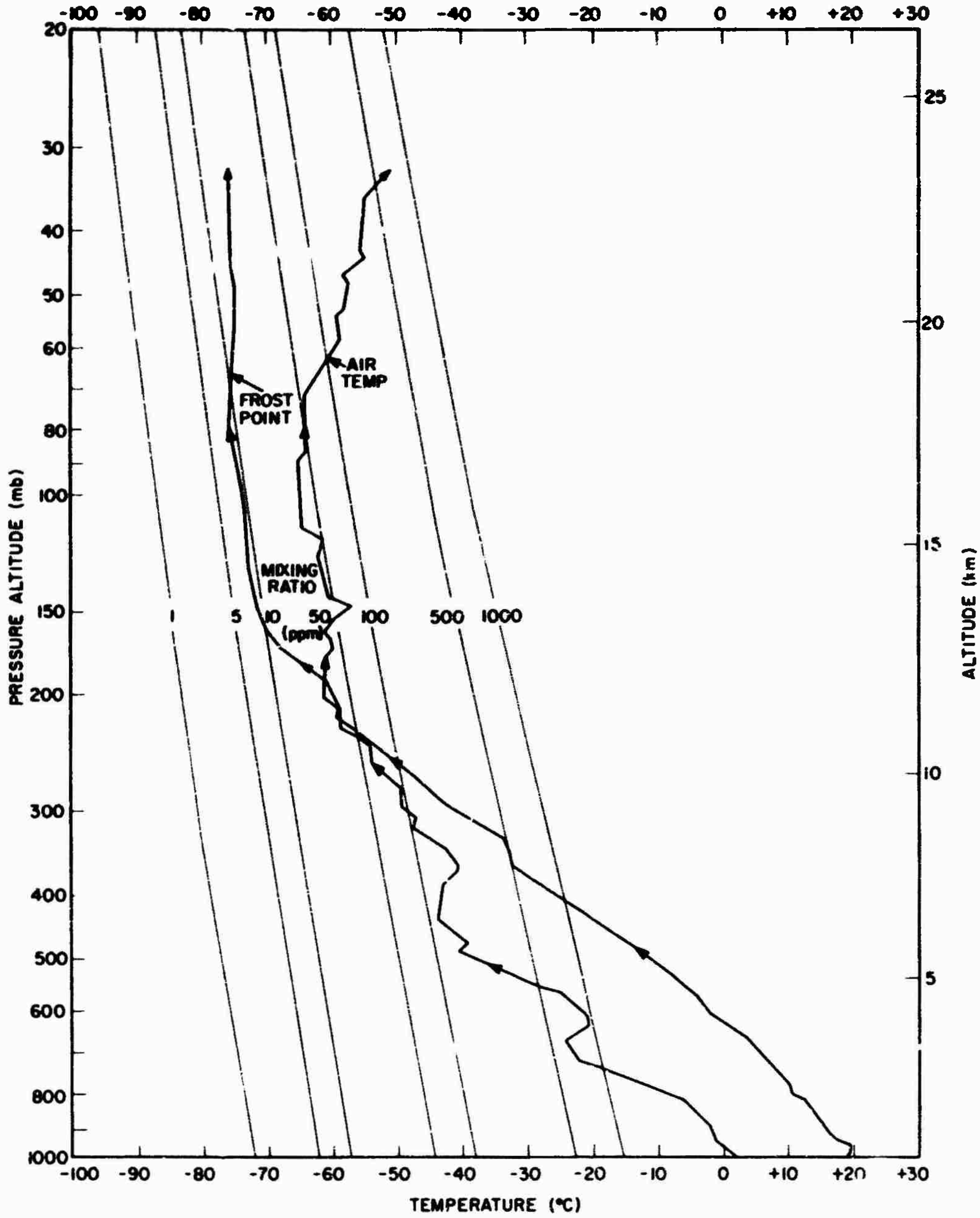

Figure 23. Flight 17, 27 October 1965

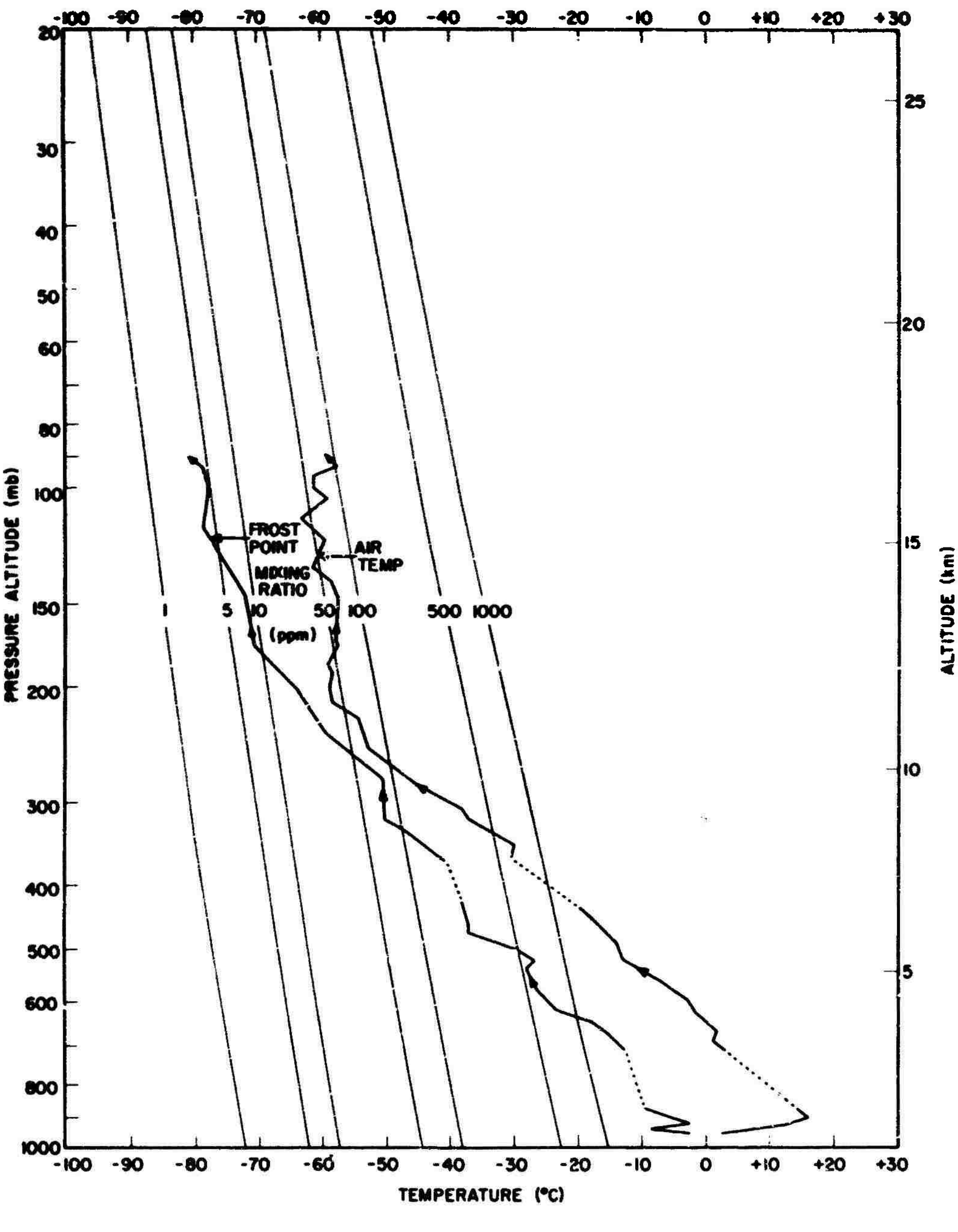

Figure 24. Flight 18, 7 December 1965

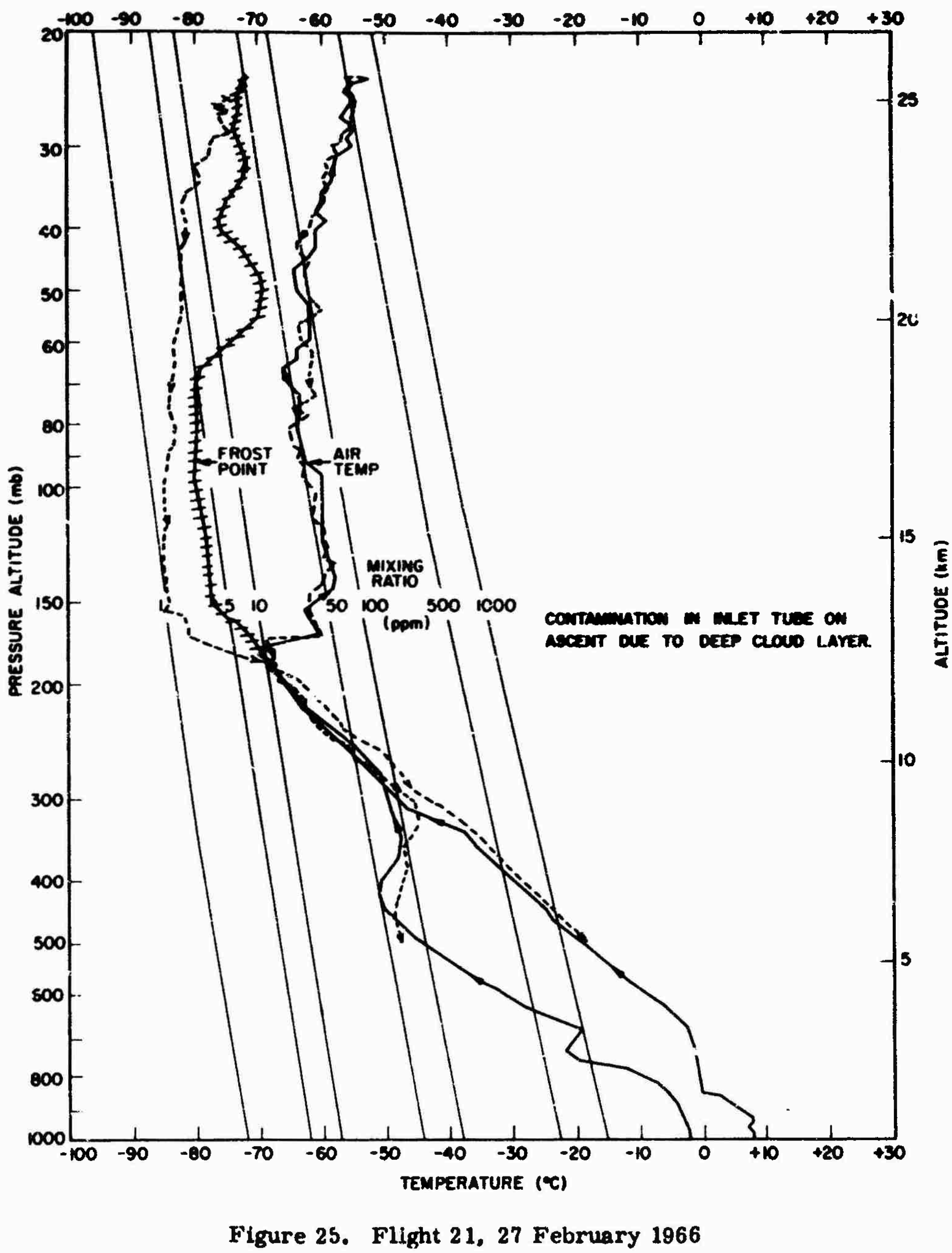

Figure 25. Flight 21, 27 February 1966

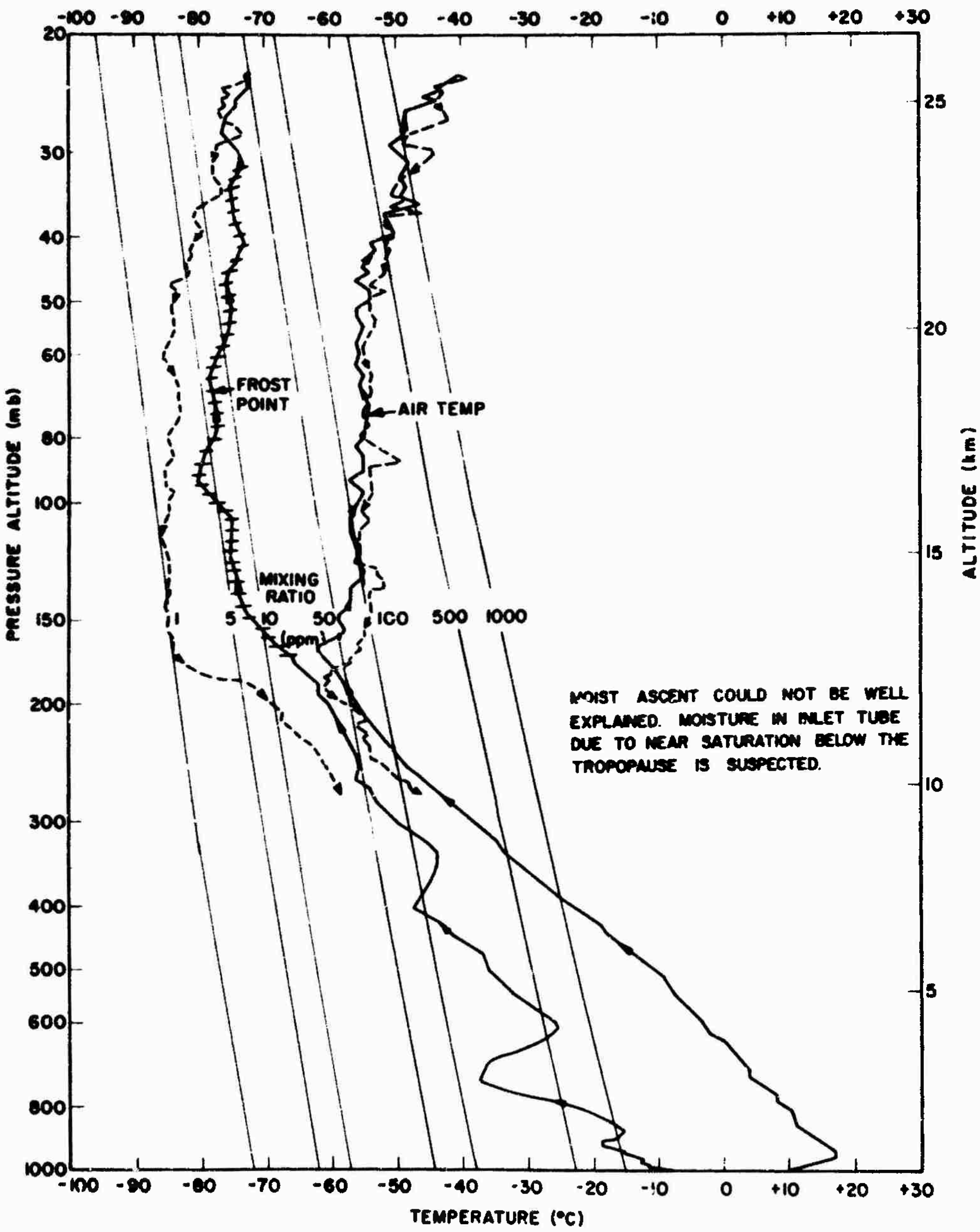

Figure 26. Flight 23, 27 April 1966

Part II. Model Mid-Latitude Moisture Profile to 80Km

1. INTRODUCTION

Needs to understand the amount and distributions of water vapor in the upper troposphere and through the stratosphere have been described in the introduction, Part I of this report. Gutnick (1962) provided "Mean Annual Mid-Latitude Moisture Profiles to 31 Km" which was reevaluated by Gutnick and Salmela (1963). The Gutnick profile was a subjectively determined mean of data that were considered valid measurements. These were obtained by several investigators using various experimental equipment at different locations. In subsequent reevaluation of the "wetter data", contamination is strongly suspected.

Gutnick's humidity profile was an attempt to establish guidelines for Air Force designers who required basic guidance in high altitude humidity for various systems designs. This need continues. It is the aim of Part II to present a more realistic mid-latitude average annual humidity-profile than what was possible when attempted by Gutnick and Salmela in 1963.

2. DEVELOPMENT OF MODEL

The 1968 humidity profile to 80 km is based upon three sources of humidity data: surface to 400 mb (about 7 km) from a humidity atlas (Gringorten et al, 1966);

7 km to 32 km from the annual humidity-profile average for (40°N) described in Part I; and 32 km to 80 km from hypothesis based on observations of noctilucent clouds.

The recently published humidity atlas (Gringorten et al, 1966) provides an excellent basis for a mid-latitude humidity profile. This atlas was prepared from carefully edited radiosonde for the period 1958-1962. The 50 percentile dew points for each 10 degrees longitude at 45 degrees North were summed for each season. The average of this total was designated as the mean-seasonal dew point. The average of the four seasons for the surface, 850, 700, 500, and 400 mb levels were computed and used to determine annual mean profile up to 400 mbs, about 7 km.

The frost-point at the top, 400 mbs, closely approximated that at 400 mb in the Chico profile, Figure 10, Part I. The Chico profile was added by graphical smoothing to give a frost-point profile up to 32 km. Above this level, the extrapolation of the frost-point profile from 32 to 85 km is described in Part I of this report.

The model, Figure 27, is presented as the best estimate of a typical dew-point (or frost-point) profile from the surface to 80 km for mid-latitudes. It is based on the latest compilations of tropospheric and stratospheric humidity data up to 32 km, and experimental rocket samplings of noctilucent clouds. Figure 28 is the comparable mixing ratio profile. The mixing ratios from the surface to 7 km were derived from seasonal 50 percentile dew points used for the dew-point (or frost-point) profile. The mixing ratio was computed for each 10 degrees of longitude at 45 degrees North for each season. This resulting mixing ratio is a true representation of the 50 percentile dew-point from which it was computed. However, when summed and averaged around the hemisphere for the four seasons to obtain an annual 50 percentile value, the averaged mixing ratio is no longer truly representation of the 50 percentile. It is too low by about 20 to 30 percent. No attempt is made to adjust these resulting mixing ratios.

From 7 to 32 km, the average mixing ratio of all Chico soundings was used. From 32 to 80 km, mixing ratios were computed from each 5 km from the frost-points in Figure 27 and the pressures of the standard atmosphere. A smoothed mixing ratio curve was graphically fitted to these points.

Tabular data for the model mid-latitude moisture profile are provided in Table 3. Mean annual dew-points (or frost-points) for every 2 km up to 32 km and for every 5 km from 35 to 80 km are included. Dew-point (or frost-point) values corresponding to those in Figure 27 are provided in the first column in the portion of the table under "Mean Frost-Point." Mixing ratio values from Figure 28 are given in the first column in the portion of the table under "Mean Mixing Ratio." "U. S. Standard Atmosphere, 1962" values for temperature, pressure and density

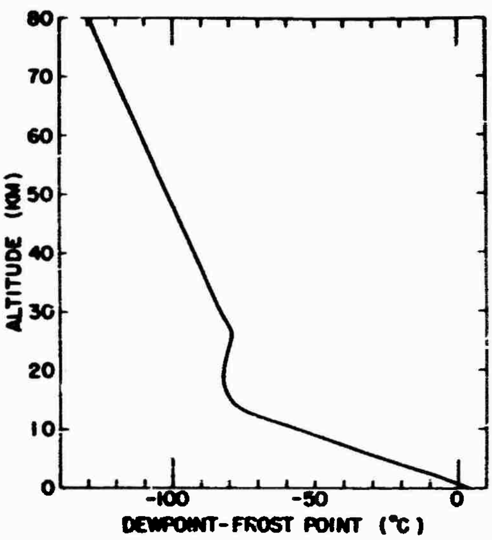

Figure 27. Model Mid-Latitude Mean Annual Dew Point (or Frost Point)

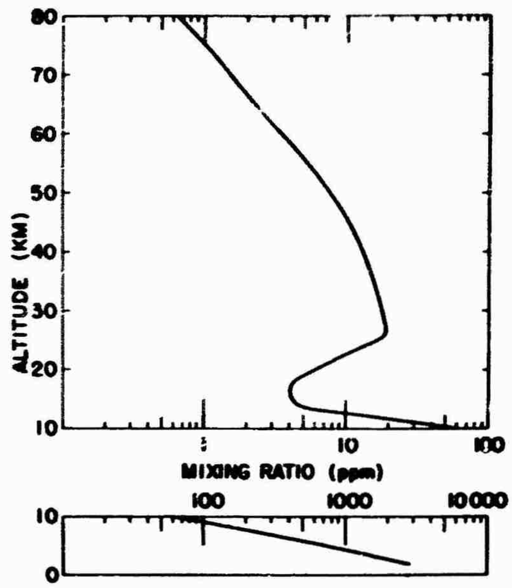

Figure 28. Model Mid-Latitude Mean Annual Mixing Ratio

are also presented with corresponsing values of vapor pressure, vapor density and mixing ratios at saturation conditions.

Mixing ratios corresponding to the mean dew-points (or frost-points) under the "Mean Frost Point" heading, and dew-points (or frost-points) corresponding to mean mixing ratios under the "Mean Mixing Ratio" heading were computed for comparison purposes, assuming Standard Atmosphere conditions. These are different since dew point and mixing ratio are not related linearly, and a mean mixing ratio obtained from a mean dew point will not be the same as the mean obtained from mixing ratios for each dew point used to get the mean dew point. Finally, precipitable water, vapor pressure, vapor density, and relative humidity were computed from each of the independently determined profiles, dew-point (or frost-point) and mixing ratio. Appropriate formulas together with explanation of the method of calculation are provided under the notes for Table 3. Saturation-vapor pressure and water-vapor density correspond to a water surface up to 8 km (-40°C to -50°C), and an ice surface for values above that altitude. Asterisks indicate the values recommended for general use; values obtained directly from one of the two independent profiles, dew-point (or frost-point) and mixing ratio.

Table 3. Mid-Latitude Mean Annual Dew Point (or Frost Point) and Mixing Ratio Related to the U. S. Standard Atmosphere, 1962 (USSA)

Alt	STANDARD ATMOSPHERE						TYPICAL MOISTURE CONTENT FROM:											
	Basic			Derived			Mean Dew Point (or Frost Point)						Mean Mixing Ratio					
(km)	T (°C)	P (mb)	ρ (g/m³)	e_s (mb)	ρ_s (g/m³)	w_s (ppm)	$\bar{T}_f$ (°C)	e_v (mb)	ρ_v (g/m³)	U (%)	$\bar{w}$ (ppm)	W_s (μ)	$\bar{w}'$ (ppm)	e_v (mb)	T_f' (°C)	ρ_v' (g/m³)	U' (%)	W' (μ)
sfc	15.0	1.012 (+3)	1.225 (+3)	1.704 (+1)	1.283 (+1)	1.047 (+4)	3	7.675 (+0)	5.947 (+0)	76	4.886 (+3)	2.898 (+3)	8.840 (+3)	1.018 (+1)	7	7.75 (+0)	80	1.004 (+4)
2	2.0	7.950 (+2)	1.006	7.055 (+0)	6.669 (+0)	5.528 (+3)	-7	2.618	2.946	61	2.848	4.020	2.790	8.868 (+0)	-7	2.948	81	8.838 (+3)
4	-11.0	6.64	6.191 (+2)	2.644	2.186	2.669	-20	1.254	1.074	47	1.268	1.468	1.200	1.188	-21	2.884 (-1)	48	1.281
6	-24.0	4.716	6.597	6.827 (-1)	7.576 (-1)	1.164	-22	4.206 (-1)	3.779 (-1)	48	6.848 (+3)	4.861 (+3)	4.95 (+2)	2.766 (-1)	-23	2.446	48	8.978 (+3)
8	-37.0	3.560	5.262	2.571	2.369	4.492 (+2)	-44	1.238	1.172	48	2.165	1.866	1.78	1.007	-48	8.501 (-2)	38	1.108
10	-50.0	2.644	4.127	8.925 (-2)	2.821 (-2)	9.259 (+1)	-66	1.888 (-3)	1.834 (-3)	47	4.224 (+1)	8.805 (+1)	8.00 (+1)	2.381 (-3)	-84	8.288	68	2.742 (+1)
12	-56.5	1.932	3.106	1.722	1.726	5.660	-68	3.611 (-3)	8.708 (-3)	20	1.130	4.848 (+0)	1.68	4.817 (-3)	-88	4.908 (-3)	28	8.837 (+0)
14	-56.5	1.410	2.266	1.722	1.786	7.606	-78	7.577 (-4)	8.413 (-4)	4	2.342 (+0)	1.465	4.80 (+0)	1.080	-78	1.148	8	1.872
16	-56.5	1.029	1.654	1.722	1.726	1.042 (+2)	-80	6.478	6.128	2	8.808	1.069	4.10	6.783 (-4)	-78	7.181 (-4)	4	1.188
18	-56.5	7.505 (+1)	1.207	1.722	1.725	1.429	-88	3.925	4.449	2	2.253	8.888 (-1)	4.10	4.947	-81	5.220	2	1.028
20	-56.5	5.475	6.604 (+1)	1.722	1.725	1.969	-82	3.925	4.449	2	4.468	9.678	5.80	6.184	-80	6.188	2	1.088
22	-54.5	4.000	6.373	2.222	2.216	3.476	-81	4.638	6.280	8	7.212	1.137 (+0)	8.70	5.596	-80	8.188	2	1.801
24	-52.5	2.920	4.527	2.660	2.632	6.121	-80	5.472	6.188	2	1.162 (+1)	1.323	1.22 (+1)	6.218	-78	7.181	2	1.261
26	-50.5	2.152	2.269	2.699	3.606	1.070 (+3)	-79	6.444	7.191	2	1.862	1.248	1.86	6.439	-79	7.181	2	1.052
28	-48.5	1.566	2.460	4.730	4.552	1.854	-61	4.688	6.230	1	1.819	9.008 (-1)	1.79	4.864	-81	5.230	1	7.520 (-1)
30	-46.5	1.172	1.601	6.022	5.767	2.197	-83	3.216	3.778	1	1.760	6.488	1.76	8.316	-82	3.778	1	5.228
32	-44.5	6.650 (+0)	1.328	7.635	7.235	5.473	-66	2.363	2.710	-	1.686	6.801	1.69	2.389	-46	2.710	-	5.180
35	-26.1	5.569	6.214 (+0)	1.960 (-1)	1.510 (-1)	2.203 (+4)	-86	1.388	1.624	-	1.546	6.726	1.54	1.384	-68	1.624	-	4.077
40	-22.1	2.775	3.651	6.419	7.267	1.667 (+5)	-92	5.642 (-6)	6.655 (-5)	-	1.242	8.464	1.29	5.756 (-5)	-93	6.865 (-5)	-	1.681
45	-6.1	1.431	1.661				-97	2.561	2.160	-	1.112	1.082	1.04	2.283	-87	3.150	-	6.186 (-2)
50	-2.5	7.694 (-1)	9.775 (-1)				-102	9.257 (-6)	1.176	-	7.506 (+0)	3.974 (-2)	7.61 (+0)	9.291 (-6)	-102	1.175	-	2.222
55	-6.5	4.023	5.296				-107	3.170	4.134 (-6)	-	4.901	1.461	6.20	3.853	-107	4.290 (-8)	-	8.587 (-3)
60	-16.5	2.084	2.650				-111	1.280	1.710	-	2.820	6.608 (-2)	3.49	1.169	-111	1.664	-	2.054
65	-26.5	1.041	1.533				-116	2.666 (-7)	5.220 (-7)	-	2.210	1.717	2.26	3.756 (-7)	-115	5.197 (-7)	-	1.057
70	-56.5	4.900 (-2)	7.678 (-2)	1.728 (-2)	1.725 (-2)	2.189 (+5)	-121	1.061	1.539	-	1.372	5.188 (-4)	1.50	1.182	-121	1.585	-	3.518 (-4)
75	-76.5	2.142	3.795	9.631 (-4)	1.064 (-2)	2.502 (+4)	-125	2.567 (-6)	6.262 (-8)	-	1.055	1.672	9.95 (-1)	2.427 (-6)	-126	5.017 (-8)	-	1.065
80	-92.5	6.569 (-3)	1.656	6.066 (-5)	7.330 (-5)	4.426 (+3)	-130	5.739 (-9)	1.223	-	6.326 (-1)		6.32	8.741 (-9)	-130	1.384	-	

SYMBOLS:

Basic parameters

T, P, ρ : Temperature (°C), Pressure (mb), density (g/m^3) of air (assumed dry).

e_s : vapor pressure (mb) if saturated at USSA temperature, from SMT tables 94 and 96.

e_v : vapor pressure (mb) for mean dew point (or frost point), $\overline{T}_f$.

e_v' : vapor pressure (mb) having mean mixing ratio, $\overline{w}$, for USSA pressure; $e_v' = \overline{w}P/0.62197$.

Dew point (or frost point) temperature in degrees Celsius

$\overline{T}_f$: estimated mean mid-latitude values (see Figure 27).

T_f' : from SMT tables 94 and 96, using e_v' derived from $\overline{w}$.

Absolute humidity or vapor density in g/m^3.

ρ_s : if saturated at USSA temperature and density; from SMT tables 106 and 109.

ρ_v : having dew point (or frost point) $\overline{T}_f$; from SMT tables 106 and 109.

ρ_v' : having dew point (or frost point) T_f'; from SMT tables 108 and 109.

Mixing ratio, ratio of mass of water vapor to that of dry air in mixture, in parts per million (ppm).

w_s : if saturated at ambient USSA temperature and density; $w_s = \rho_s/\rho$.

$\overline{w}$: estimated mean mid-latitude value, from e_v derived from average dew point (or frost point) $\overline{T}_f$; $\overline{w} = 0.62197\, e_v/(P - e_v)$.

$\overline{w}'$: estimated mean mid-latitude value based on actual Chico mixing ratios and extrapolation (see Figure 28).

Relative humidity, ratio of vapor pressure to saturation vapor pressure in percent (%).

U : surface; weighted average of observed relative humidities from National Atlas of the United States, ESSA.

U : 2km and higher; $U = 100\, e_v/e_s$.

U' : $U = 100\, e_v'/e_s'$.

Precipitable water, condensed water content in next higher layer in microns, μ (one micron, 0.0001 cm 0.0001 g/cm^2).

$$W_z = \frac{\rho_v(Z_1) + \rho_v(Z_2)}{2} \Delta Z,$$ where ΔZ is layer thickness in meters.

$W' = (P_2 - P_1)(\overline{w}')/g$; where ($\overline{w}$) is mean mixing ratio between P_1 and P_2 (USSA), g is 980 cm/sec^2 .

NOTES:

1. A one digit number (preceded by a plus or minus sign) between lines indicates the power of ten by which each succeeding entry of that column should be multiplied. A change of power occurring within a column is indicated by a new notation.
2. The derived values of vapor pressure, density, and mixing ratio between 45 and 65 km are not indicated, since temperature at these levels is so high that the partial pressure of the vapor would be greater than atmospheric pressure, a physical impossibility. Relative humidities U and U' at 45 to 65 km are therefore, imaginary.
3. A bar (—) above a symbol, indicates a relative humidity less than 0.5 percent.
4. An asterisk (*) above a column, indicates values in columns are recommended for scientific and engineering applications; other values of the same parameter were derived for comparison only.
5. SMT indicates Smithsonian Meteorological Tables, sixth edition, prepared by R. J. List, Washington, 1951.
6. Saturation assumed with respect to plane surfaces of liquid water below 10 km (approximately above -40°C), of ice, 10 km and above (approximately below -40°C).

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13. ABSTRACT

In Part I the results of seventeen northern California soundings of humidity up to 25 to 30 km, generally a month apart, utilizing a highly sophisticated alpha-radiation hygrometer and associated balloon sounding equipment are described. The stratosphere was never found to be near saturation as has been suggested by some investigators, nor was it as dry and completely devoid of variability as is indicated by most accepted circulation theory. A very dry layer was found above the tropopause, followed by a slight increase in humidity up to an average altitude of about 25 km. Above this level, a general decrease in water vapor with altitude was deduced. Variability in this region of the lower stratosphere approached a factor of 10. Spasmodic transfer of water vapor upward through the tropopause is suggested, and speculation related thereto provided.

In Part II a model moisture profile is presented as an engineering reference standard. Typical dew point (or frost point) and mixing ratio profiles from the surface to 80 km for mid-latitudes are provided. The model is based on latest compilations of tropospheric and stratospheric humidity data up to 32 km and experimental rocket samplings of noctilucent clouds.

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