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THE VERTICAL DISTRIBUTION OF WATER VAPOR OVER HYDERABAD, INDIA, AND COMPARISON WITH MID-LATITUDE DISTRIBUTION

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CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
INSTRUMENTATION AND FLIGHT TRAIN	1
RESULTS	2
COMPOSITE DISTRIBUTION	8
DISCUSSION	9
ACKNOWLEDGMENTS	13
REFERENCES	14

ABSTRACT

Three stratospheric soundings over India with a balloon-borne frost-point hygrometer in April 1961 provided data which have been analyzed subjectively to resolve inconsistencies in the data observations. The lack of any other data for the vertical distribution of water vapor at low latitudes justifies the effort to resolve the inconsistencies to provide a best estimate of the water-vapor distribution over India during the period of observation. Subsequent flights and laboratory studies of the instrumentation have provided reasonable explanations for the inconsistencies, and a composite distribution has been derived based upon these explanations.

The composite distribution shows a mixing ratio minimum of 0.003 g/kg, a condition of near saturation in a 5000-foot interval which includes the tropopause. Above this level, the mixing ratio increases with altitude and at the 20-millibar level becomes six times greater than the minimum value. The distribution is in substantial agreement with mid-latitude observations for April and June of the previous year.

The Hyderabad potential temperature vs mixing ratio distributions for levels above the 100-millibar level is in substantial agreement with mid-latitude distributions for April and June of the previous year. At levels between 200 and 100 millibars, the Hyderabad distribution (April) agrees closely with the mid-latitude distribution for June; however, the April mid-latitude distribution showed substantially lower potential temperatures than the Hyderabad distribution for corresponding values of mixing ratio. This region has been further examined using the large amount of frost-point data collected by the British Meteorological Research Flights over southern England. Monthly mean potential temperature-mixing ratio distributions show a seasonal shift to lower potential temperatures in winter, and daily distributions for spring and fall show a monthly range of potential temperature shift for corresponding values of mixing ratio which is comparable to the annual range of the monthly means. Day-to-day shifts of the potential temperature for the potential temperature-mixing ratio distributions are evidence of mixing ratio gradients along potential temperature surfaces; the comparison of mid-latitude distributions with the low-latitude Hyderabad distribution suggests the existence of a latitudinal gradient.

PROBLEM STATUS

This is an interim report on these problems; work on these and other phases is continuing.

AUTHORIZATION

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THE VERTICAL DISTRIBUTION OF WATER VAPOR OVER HYDERABAD, INDIA, AND COMPARISON WITH MID-LATITUDE DISTRIBUTION

INTRODUCTION

A balloon-borne frost-point hygrometer has been used to measure the vertical distribution of water vapor in the stratosphere and upper troposphere. Observations have previously been described (1) for locations within the United States close to the 40th parallel. These observations, together with mid-latitude observations by others, show minimum frost-point temperatures in the lower stratosphere which are not too different from air temperatures at the tropical tropopause. Since the air temperature sets an upper limit for the frost-point temperature, air ascending through the tropical tropopause could be expected to have a frost-point temperature near that of the tropopause temperature. The northward transport of this air to mid-latitudes could account for the observed mid-latitude minimums of frost point. This hypothesis has been advanced by Brewer (2), Dobson and Brewer (3), and Dobson (4) to explain the dryness of the stratosphere at mid-latitudes.

This explanation reasonably accounts for the frost-point minimums at mid-latitudes; therefore it is desirable to examine directly the distribution at the proposed tropical source region for comparison with observations at mid-latitudes. The opportunity to do this was afforded by the Joint United States-India Balloon Flight Program in 1961, and a series of vertical frost-point soundings were made in April from Hyderabad, India (latitude 17^{0}) near the time when the thermal equator attained the latitude of this city.

INSTRUMENTATION AND FLIGHT TRAIN

The basic instrumentation is essentially the same as that used for the mid-latitude flights (5), namely, a mirror surface maintained at the dew-point temperature (or frost-point temperature below $0^{\circ}C$) by a heat sink and a heating coil controlled by a servo loop containing a phototube to observe the condensate on the mirror. The following exceptions were made from the previous instrumentation:

1. The sampling cavity and intake duct were fabricated from stainless steel, replacing aluminum and plastic, to minimize contamination of the air sample by absorbed water vapor in the walls of the cavity and intake duct.

2. The AN/AMT-6B dropsonde transmitter was used in place of the T-304A/AMT-4A transmitter for the transmittal of data to a ground receiving station because of greater reception range and greater portability of the ground receiving equipment.

The measurement of atmospheric moisture content using vertical sounding techniques is made difficult in that the absolute humidity of the lower stratosphere is four to five orders of magnitude lower than in the surface layers. Moisture from the lower levels is carried aloft on the balloon and instrumentation, and the extent to which this moisture may enter into the measurement of stratospheric moisture must be considered. The adsorption of moisture by the surfaces of the sampling duct is minimized by the use of stainless steel, as stated above, and accretion of moisture on the surfaces is prevented by exposure of the duct to solar radiation. Contamination from the balloon and other

components of the flight train cannot be avoided on the ascent flight. Steps are taken, however, to minimize contamination from external components by positioning the instrumentation 900 feet beneath the balloon and parachute. Since it is unavoidable that the instrumentation encounter some of the wash from the flight train, major emphasis has been placed on the descent flight for data collection. For this reason, the frost-point hygrometer is given the lowest position on the flight train. The side location of the intake duct is used in an effort to provide good exposure for both the ascent and descent flights. For the India flights, it became necessary to insert a metal mesh shield between the antenna and the rest of the instrumentation because the unshielded dropsonde transmitter used for these flights caused radio interference with the control circuit of the frost-point instrument. The location of the metal shield and transmitter below the level of the sampling duct introduced the possibility of contamination of the sample during descent.

Except in the case of balloon failure, the balloon was used to support the instrumentation for both the ascent and descent. The reversal in direction of flight was achieved by opening a gas port at the base of the balloon, using a pressure switch. The time-altitude record shown in Fig. 1 is typical of the flight performance. The use of a balloon for the descent flight, in preference to a parachute, provides slower descent rates and consequently longer sampling periods at stratospheric levels.

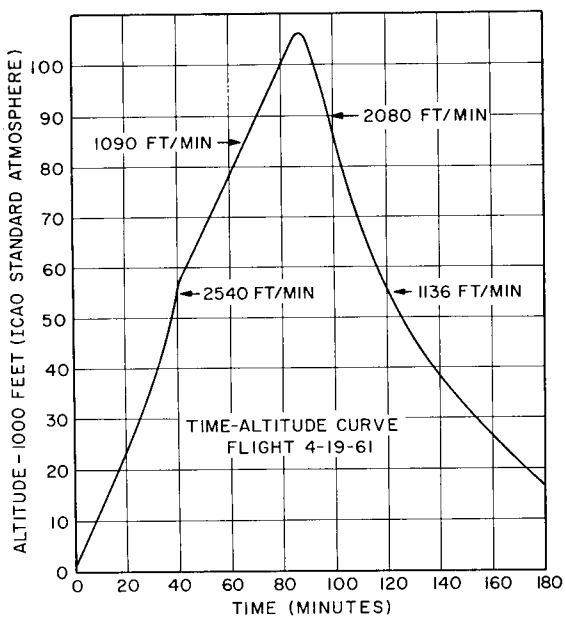

Fig. 1 - Typical time-altitude curve for an ascent and descent balloon sounding

RESULTS

The vertical distribution of ambient and frost-point temperature measurements for three flights from Hyderabad, India, are shown in Figs. 2-4. Comparison of the ascent and descent records for each flight provides a criterion of estimating the reliability of the observations. Marked differences between the ascent and descent curves for these flights make it apparent that the data cannot be interpreted directly in terms of frost-point temperature. A systematic aspect of the differences, however, suggest that they are amenable to resolution, and the attempt is here made to determine the most reliable features of all the data for the three flights and arrive at a composite distribution of water vapor for the period of observation.

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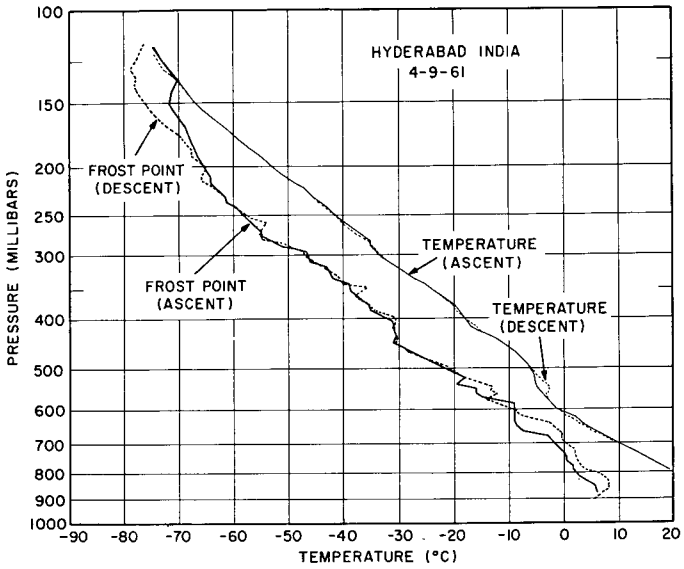

Fig. 2 - Frost-point and ambient temperatures for flight 4-9-61

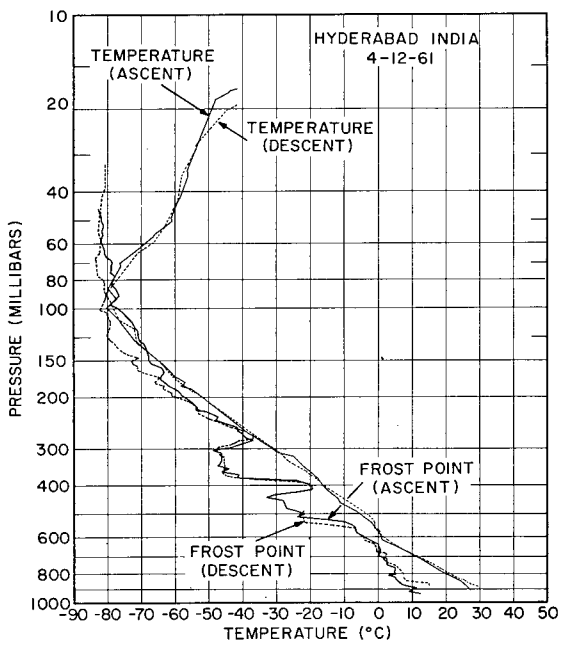

Fig. 3 - Frost-point and ambient temperatures for flight 4-12-61

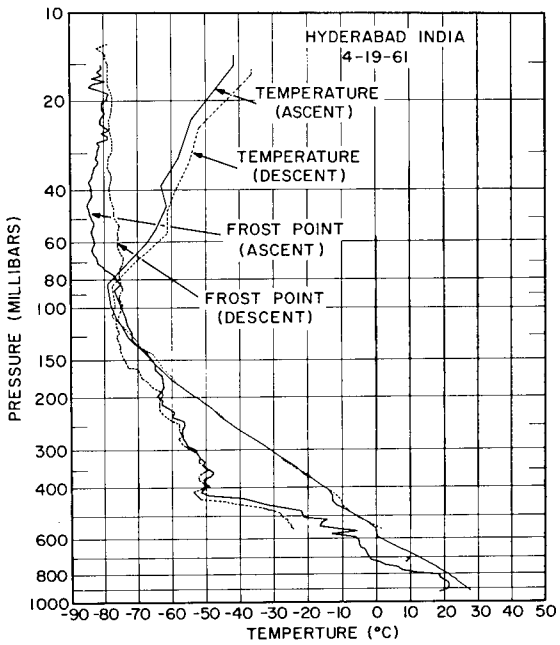

Fig. 4 - Frost-point and ambient temperatures for flight 4-19-61

The data are now examined to estimate the effects of contamination. The possible contamination may be considered, in terms of source regions, as that encountered during ascent from sources above the intake and that encountered during the descent from sources below the intake. In the lower troposphere there is good agreement between the ascent and descent curves of frost point, and the effect of contamination appears to be negligible compared to the total moisture content in this region. At about the 200-millibar level, the ascent and descent curves of frost-point temperature diverge noticeably for all flights, with the separation becoming 5 to 10 degrees at the 150-millibar level. At this level the absolute humidity is four orders of magnitude lower than the surface humidity and the rate of decrease at the flight level is an order of magnitude in 5 minutes of flight. Levels of apparent supersaturation clearly indicate that the ascent frost-point values are too high in this region of flight. Further indication that the ascent frost points are too high in this region is supplied by the frost-point loop generated by flight 4-9-61 when the direction of flight changed abruptly at the 115-millibar level due to balloon rupture.

Figure 5 considers the disagreement in this region in terms of a possible moisture excess observed for flight 4-19-61 as the balloon ascended from 40,000 to 60,000 feet. Curve A is the water-vapor density as determined from the ascent frost-point data. Curve B is the water-vapor density as determined from the composite distribution (discussed later) considered to approximate the true distribution of water vapor. Curve C is the water-vapor density excess obtained by subtracting corresponding time points of curve A from B. The water-vapor density excess curve has the shape of a decay function with the exception of the region between 39 and 40 minutes of flight, where there appears a step increase in the vapor density excess. This region includes the tropopause level, where the ascent rate of the balloon decreases from 2540 feet per minute to 1090 feet per minute (see Fig. 1) due to the change in temperature lapse rate. The dashed line of Curve C extends the portion of the curve before the step increase at the same decay rate. At time 40 minutes, the ordinate of the dashed curve may be compared with that of the actual curve after the step increase, and the latter is observed to be greater by a factor of nearly 2. The step increase in the water-vapor density excess is concurrent with the sudden change in ascent rate at the tropopause, and a direct correspondence between the

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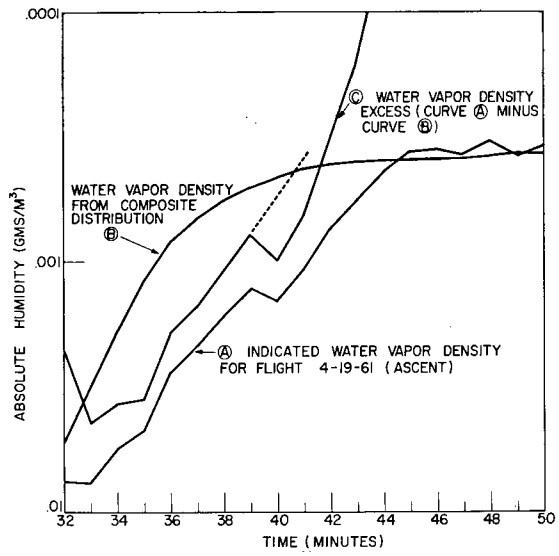

Fig. 5 - Examination of possible contamination effects for ascent of flight 4-19-61

two events is indicated. Flights 4-9-61 and 4-12-61 were examined in the same manner and were found to exhibit similar decays of the water-vapor density excess, and flight 4-12-61 also showed a strong correspondence with ascent rate.

The observations are readily explained if one hypothesizes the evolvement of moisture from the flight train above the intake of the frost-point instrument. The position of the battery pack 10 feet above the instrumentation constitutes a likely source of excess moisture. On previous flights the pack was located beneath the instrument, but in these flights it was moved to the higher position to favor the descent flight. Referring to Fig. 5, it may be noted that the water-vapor density excess curve decays rapidly, becoming insignificant after 45 minutes and does not affect the ascent observations at higher levels (above the 70-millibar level).

Looking now at the descent frost-point curve of flight 4-19-61 (Fig. 4), a departure relative to the ascent curve is observed which increases with decreasing altitude down to the 70-millibar level. At lower levels, between 80 and 100 millibars, the descent curve, like the ascent curve, indicates supersaturation, and frost points in this region are considered too high. Above the 70-millibar level, it has been previously argued that the ascent curve is not significantly affected by contamination and from this point of view may be indicating a correct frost-point value. Both the ascent and descent records of flight 4-12-61, above the 70-millibar level, agree more closely with the ascent frost points of flight 4-19-61 than with the descent frost points, further suggesting that the descent record of frost point for flight 4-19-61 is too high at all stratospheric levels.

This departure is first examined in terms of a possible moisture excess from contaminating sources beneath the intake. The water-vapor density excess was determined using the composite curve as the best estimate of true frost point. The resulting distribution of water-vapor density excess (Fig. 6) increases with decreasing altitude until the tropopause level is reached; below the tropopause the excess decreases sharply. When considered in conjunction with the descent rate, the implication is that of a near constant or increasing rate of moisture evolvement from sources below the balloon during the stratospheric descent. The absence of an observable decay in the excess moisture supply makes the argument of contamination from beneath untenable. This is further supported by flight 4-12-61 which had an identical flight configuration but did not exhibit the same degree of departure of the descent frost points.

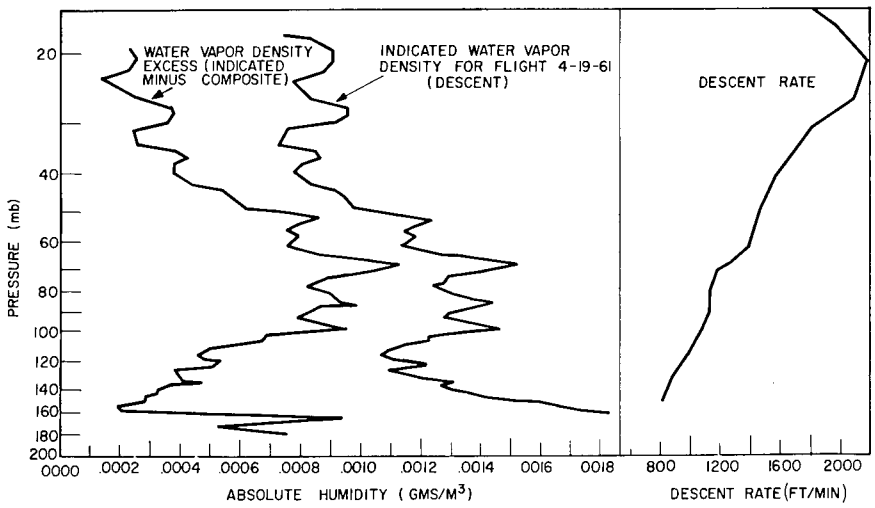

Fig. 6 - Examination of possible contamination effects for descent of flight 4-19-61

Instrumental characteristics are next examined for an explanation for the frost-point departure during the stratospheric descent of flight 4-19-61. The frost-point servo control circuit derives the control error signal from the phototube bridge circuit, which operates in a slightly unbalanced condition. It follows that as the temperature differential between the cold sink and frost point increases, the unbalance of the bridge (or error signal) must also be slightly increased to maintain equilibrium between the mirror condensate and the vapor phase of water. This slightly increased error signal can only be obtained by a slight increase in spot size to which the phototube circuit can respond. It is apparent then that the size of the deposit is, to some extent, a function of the differential temperature between the cold sink and the mirror under conditions of servo control. Since this differential temperature is constantly varying during flight, the size of the deposit must also vary slightly to maintain the equilibrium temperature condition. The extent to which this necessary variation in spot size can affect a proper control depends upon the response characteristic of the sensor circuit, the distribution of condensate upon the mirror, and the time required to acquire or evolve condensate upon the mirror (this time being a function of the frost point). At the higher frost-point temperatures, condensate may be quickly acquired or evolved and the departure of the mirror temperature from the true frost-point temperature, due to a lag in area adjustment of the condensate, is within tolerable limits. At the lower frost-point temperatures of the stratosphere, the lag is much greater and the departure from the true frost-point temperature may assume more significant proportions.

Cold-sink temperature and frost-point temperature as a function of altitude are shown in Fig. 7. The temperature difference between cold sink and frost point reaches a minimum at the 110-millibar level, and the corresponding error signal and spot size are also minimum at this level. At all other levels the diffential temperature is changing as the instrument ascends or descends through the atmosphere. An increasing differential temperature calls for an increasing spot size and a mirror temperature slightly below frost-point temperature; conversely, a decreasing differential temperature calls for a decreasing spot size and a mirror temperature slightly above the frost-point temperature.

A descent flight at stratospheric levels involves a decreasing differential temperature and the area effect would cause a positive frost-point error. For a stratospheric ascent the effect is reversed and would cause a negative frost-point error. An ascent and descent

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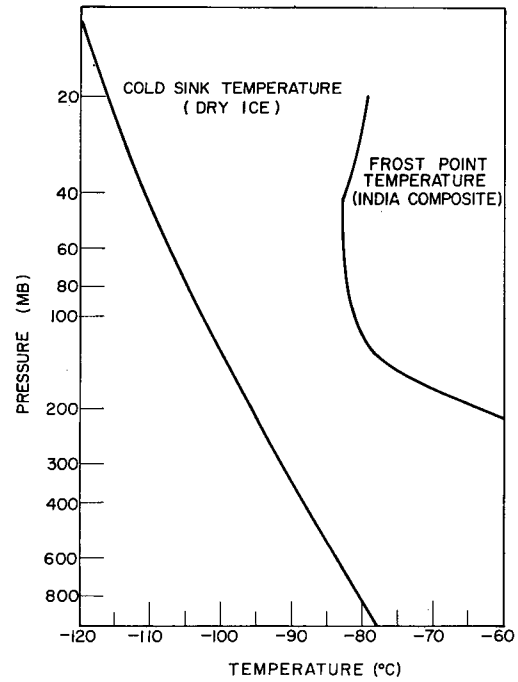

Fig. 7 - Vertical distribution of frost-point and cold-sink temperatures

flight in the stratosphere should then generate an error loop in the frost-point record, (the width of the loop being dependent upon control characteristics of the particular instrument). At tropospheric levels the effect is reversed and a loop may also be expected but with a positive error during ascent and a negative error during descent. A complete sounding record should then exhibit two frost-point loops due to the area effect with a crossover in the vicinity of the tropopause.

Except in the vicinity where the rate of change of the difference in the frost-point and cold-sink temperatures is changing sign, the true frost-point temperature can be expected to lie between the ascent and descent curves of indicated frost point; where the sign reverses, the crossover point of the ascent and descent curves need not correspond to the true frost point due to the lag in the adjustment of condensate area.

The indicated frost-point distribution of flight 4-19-61 (Fig. 4) shows the two loops with a crossover near the tropopause, which is consistent with the area effect hypothesis. The crossover point may be assumed to lie to the warm side of the true frost-point distribution, since the crossover temperature is warmer than ambient and would represent a condition of supersaturation.

To further establish that the area effect can have significant proportions, flight equipment has been operated in the laboratory under conditions for which only the difference in the frost-point and cold-sink temperatures, was varied. At a frost point of -75°C, the effect was observable, and the departures appeared of sufficient magnitude to offer a plausible explanation for the frost-point departures observed in flight 4-19-61.

The magnitude of the area effect depends upon many factors and these factors may vary considerably from flight to flight and between different portions of the same flight. The effect becomes appreciable only at the low frost points, where the rate of acquiring or evolving condensate is very slow. Consideration of all the flights suggests that it is easier to acquire enough condensate to provide an incremental amount of reflected light than it is to drive off enough to effect the same change, and that the older the condensate

the more difficult it is to provide an incremental change of reflected light. A probable explanation is that a deposit once acquired continues to increase in thickness for a time, and for the long-period trends of area change, a thicker layer of condensate must be driven off to effect a change in reflected light than has to be acquired for the same amount of change. An aged condensate also increases in thickness toward the center, and consequently the longer the trend of spot size decrease, the thicker the condensate which must be driven off.

Basic to the problem is the response characteristic of the instrumentation, particularly with respect to the ratio of condensate area change to frost-point and cold-sink temperature difference change, for it is this area dependence which brings about the problem of area adjustment.

However, the immediate concern is for an understanding of the factors which resulted in discrepancies in the India flights, and to arrive at a composite distribution of frost point for the period of the Indian operation which is the best possible estimate from the available data. The discrepancies have been considered in two different lights: first, with the assumption that the instruments always indicate the true frost point and that the discrepancies are the result of moisture contamination, and, second, that the discrepancies can be explained in terms of an instrumental characteristic. A good case for contamination can be made for the ascent flight, but the same arguments do not provide a reasonable explanation for a drift to warmer mirror temperatures upon descent through the stratosphere. The area effect, on the other hand, provides an acceptable explanation for the descent warming as well as the ascent warming near the tropopause, with the exception of the marked dependence of the warming on ascent rate. Both contamination and the area effect are probably operative in causing the ascent warming.

COMPOSITE DISTRIBUTION

The indicated frost-point temperature distributions for all the India flights appear in Fig. 8 together with a composite distribution deduced from a consideration of all the flight data. The composite reflects a number of considerations which will be discussed separately.

The frost-point curves for the ascent flights all show a departure from the descent curves starting at about the 200-millibar level. For several minutes thereafter the time plots of these data (see Fig. 5) have the appearance of a decay function; the indicated frost-point temperatures, which are the actual mirror temperatures, at times exceed the ambient temperature within this region for two of the flights. These factors were taken as grounds for disregarding the ascents in this region in deriving the composite distribution.

In the higher stratosphere, the area effect is considered to be operative, resulting in negative frost-point errors during ascent and positive errors during descent. The magnitude of the errors differs for the two flights extending into the stratosphere, although the same instrument was used for both flights. Between the 32-millibar level and the 68-millibar level the true frost point is taken as bounded by the ascent curve of flight 4-19-61, which should have a negative error due to the area effect, and the descent curve of flight 4-12-61 which should have a positive error. In this interval the maximum spread between the two curves is not over 3 degrees. Above the 32-millibar level there is data only from flight 4-19-61. Between the 32-millibar level and 18-millibar level the spread between the ascent and descent curves does not exceed 4-1/2 degrees. The lower interval just considered indicates that the ascent curve error is considerably less than the descent curve error, and so the composite curve is positioned closer to the ascent curve in the higher interval. Above the 18-millibar level the ascent curve exhibits erratic fluctuations, induced possibly by the opening of the balloon valve and the injection of extraneous moisture into the slip stream of the balloon. The composite curve is not drawn above the 18-millibar level; however, the descent curve of flight 4-19-61 places a useful upper bound on the frost-point distribution to about the 14-millibar level.

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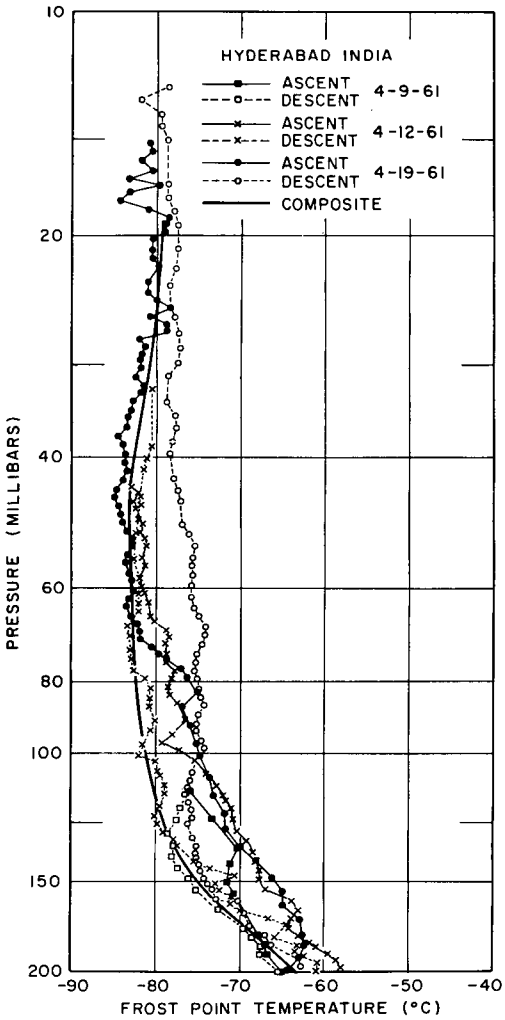

Fig. 8 - Frost-point temperatures for all flights and composite distribution

Between the 125-millibar level and the 68-millibar level, only the descent curves may be considered, since the ascent curves are to be disregarded in this area. The descent flights in this interval are subject to the area effect, which can give rise to positive frost-point errors. For flight 4-19-61, the error of the descent curve obviously remains large, crossing the ambient temperature curve at the tropopause, (Fig. 4). In the interval between the 50- and 68-millibar level, the descent curve of flight 4-12-61 and the ascent curve of flight 4-19-61 are in juxtaposition, and since the errors due to the area effect of each of the two curves should be oposite in sign, the errors of both curves can be taken as near zero in this interval. For the continued descent of flight 4-12-61 to the 125-millibar level, error due to the area effect is considered to remain small, since the rate of change of the frost-point and cold-sink temperature difference, which gives rise to the area effect, reaches a null value at the 110-millibar level.

The interval from the 125-millibar level to the 200-millibar level lies within the troposphere, where the moisture distribution becomes more variable. In this region the ascent curves are to be disregarded and descent data was used to position the composite distribution. The resulting composite distribution for the India flights appears separately in Fig. 9, and corresponding mixing ratio distribution in Fig. 10.

DISCUSSION

The Hyderabad composite distribution may best be discussed in terms of the water-vapor-to-air mixing ratio (Fig. 10). The minimum mixing ratio is slightly lower than the saturation mixing ratio for the tropopause level and is nearly constant over an interval of 5000 feet which includes the tropopause. Above this interval the mixing ratio increases and attains, at a level 12,000 feet above the tropopause, a value corresponding to the saturation mixing ratio for the tropopause. The increase in mixing ratio with increasing altitude continues at the higher levels; and at the 20-millibar level, the mixing ratio is six times greater than the minimum value.

In Fig. 11, the Hyderabad distribution is compared with two flights of the preceding year at the Chesapeake Bay Annex (CBA) of the Naval Research Laboratory, near Washington, D. C. (1). Potential temperature is used as the common reference for comparing the mixing ratio distributions. The pressure levels are indicated at intervals along the curves. The general features of the curves are similar, showing minimums of mixing ratio in the potential temperature interval 370^0 to 420^0K, which includes the 100-millibar level for all three flights. Above this inverval, all three curves show an increase in mixing ratio with potential temperature, or altitude. The spread in mixing ratio values at all levels with pressures below 110 millibars corresponds

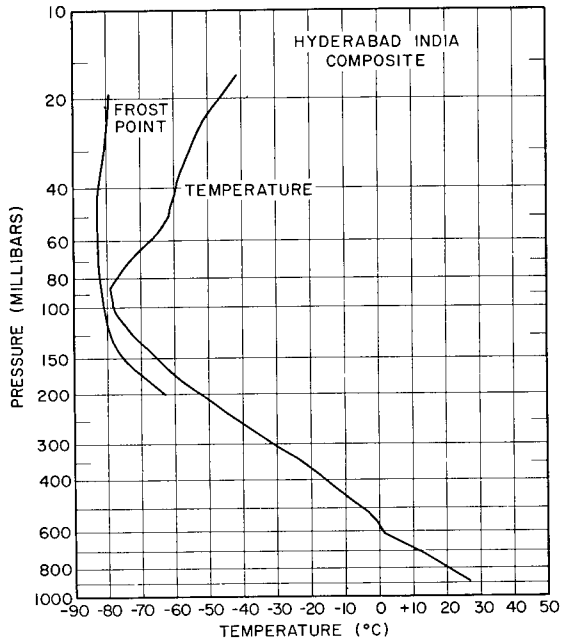

Fig. 9 - Composite distribution of frost-point and ambient temperatures

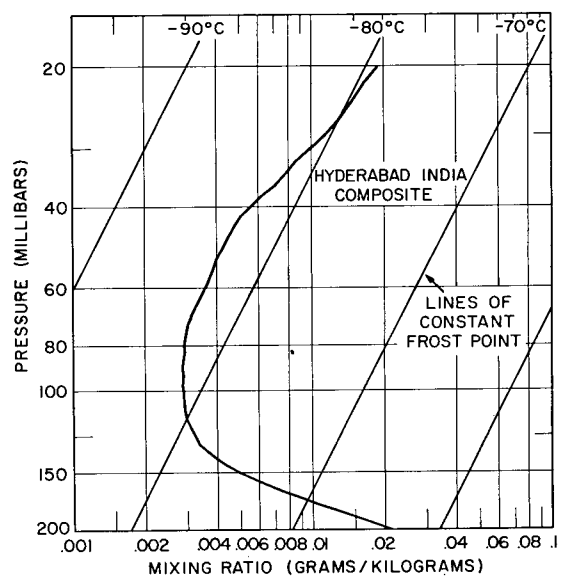

Fig. 10 - Composite distribution of mixing ratio

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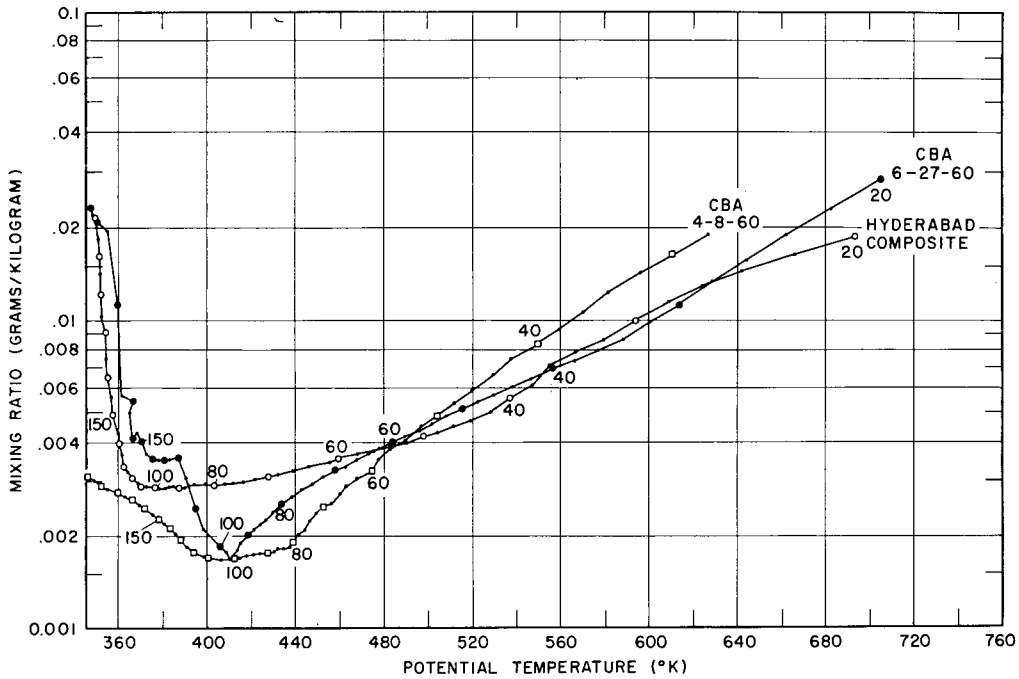

Fig. 11 - Comparison of water-vapor distributions for Hyderabad, India, and the United States

to frost-point spreads of 3 degrees or less. The discrepancies in the region between the 100- and 200-millibar pressure levels are more pronounced, with the Hyderabad distribution agreeing closely with the June mid-latitude distribution but showing much higher mixing ratios for corresponding potential temperatures than the April mid-latitude distribution.

The largest quantity of frost-point data for the lower stratosphere is that collected by the British Meteorological Research Flights (MRF) over southern England and this data may be used to further compare the potential temperature distribution of the mixing ratio for middle and low latitudes. Of particular interest here are the potential temperature levels, which are in the low stratosphere at mid-latitudes and the high troposphere at low latitudes. Distributions of mixing ratio with potential temperature have been prepared by month from tabulations of this data (6) (excluding the anomalous distributions of August 5, 1954, May 9, 1955, and March 10, 1955) together with balloon sounding distributions (Fig. 12). Presented in this manner, the mid-latitude distributions divide into two somewhat distinct groups, which appear to distinguish summer distributions from those of winter.

The two groups differ in that the potential temperatures observed for corresponding values of mixing ratios are some 15°C colder for the winter months. The mid-latitude balloon soundings are consistent with the MRF distributions in this respect. The Hyderabad distribution for April is found to fit most nearly with the summer group of mid-latitude distribution, with the exception of the region of mixing ratio minimum; here the mixing ratios for Hyderabad appear higher than either of the mid-latitude groups by an amount corresponding to about 4°C of frost point. While this portion of the Hyderabad distribution is determined by the descent of only one flight (a meager amount of data compared to mid-latitude observations), the frost-point temperatures in this region are at least 2°C lower than the ambient temperature and therefore entirely plausible.

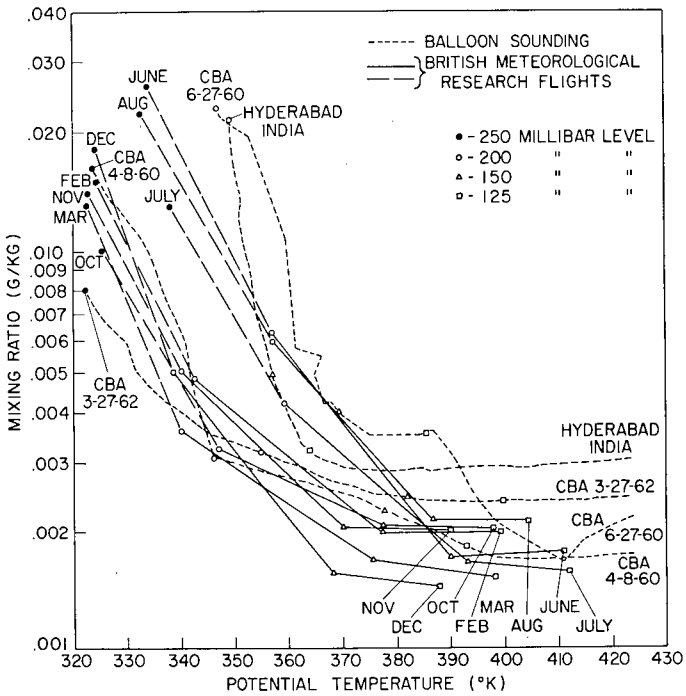

Fig. 12 - Monthly mean mixing ratio distributions with potential temperature for the British Meteorological Research Flights; also vertical balloon soundings for the United States and India

The Hyderabad distributions cannot be compared with MRF distribution for the same time of year, since there are no MRF data reported above the 200-millibar level for April. It may be compared, however, with the April mid-latitude balloon sounding for the previous year. This April ballon sounding is observed to fit the winter group of MRF distributions (Fig. 12) whereas the Hyderabad distribution for the month of April fits the summer group of MRF distributions. The marked difference of potential temperatures for corresponding mixing ratios for these two flights suggests the existence of substantial latitudinal mixing ratio gradients along potential temperature surfaces.

The large amount of MRF data provides a means of examining this question further. Daily distributions of mixing ratio versus potential temperature have been prepared for all the MRF flights which reached the 125-millibar level, and these distributions have been examined by months. The daily distributions for the midwinter months show consistently lower potential temperatures than the Hyderabad distribution for corresponding values of mixing ratio and for the summer months the potential temperatures are near to, or somewhat higher, than the Hyderabad distribution. All months show day-to-day displacements of the distribution to higher or lower potential temperatures. The range of variation is least for the midwinter and midsummer months. Figure 13 presents the daily distributions for one of the months for which the range is large. The range in this case embraces the entire range of monthly means shown in Fig. 12. Of particular interest are the distributions for the 22nd and 23rd, which are separated in time by only one day yet lie at opposite extremes in the distribution range for the month.

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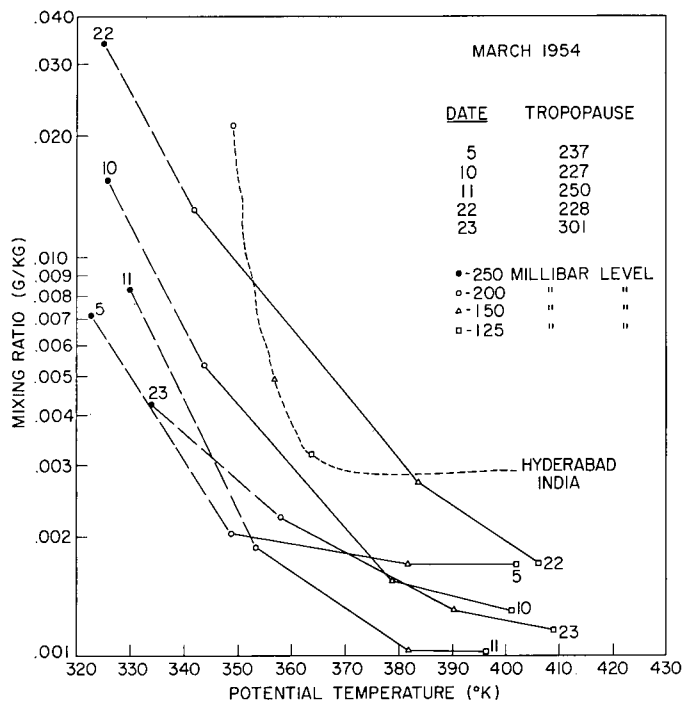

Fig. 13 - Daily mixing ratio distributions with potential temperature for the British Meteorological Research Flights for March 1954

It is evident from the MRF data that there are mixing ratio gradients along potential temperature surfaces in the low stratosphere at mid-latitudes, and the comparison of observations at Hyderabad with mid-latitude observations suggests that the observed gradients are indicative of mean latitudinal gradients. If the Hyderabad distribution is representative of the tropical distribution throughout the year, then the mixing ratio gradient is minimum in summer and maximum in winter, with the winter gradient directed toward higher latitudes.

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