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ABSTRACT

Water vapor in the lower stratosphere was measured in situ by two aluminum oxide hygrometers mounted on the nose of an RB57 aircraft. Data were taken nearly continuously from January to May 1974 from an altitude of approximately 11 km to 19 km as the aircraft flew between 70° N and 50° S over the land areas in the Western Hemisphere. Pseudomeridional cross sections of water vapor and temperature are derived from the flight data and show mixing ratios predominantly between 2 and 4 μgm/gm with an extreme range of 1 to 8 μgm/gm. Measurement precision is estimated by comparing the simultaneously measured values from the two flight hygrometer systems. Accuracy is estimated to be about ±40 percent at 19 km. A height-averaged latitudinal cross section of water vapor shows symmetry of wet and dry zones. This cross section is compared to other aircraft measurements and is related to meridional circulation models.

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WATER VAPOR IN THE LOWER STRATOSPHERE MEASURED FROM AIRCRAFT FLIGHT

INTRODUCTION

Water vapor plays an important role in the radiative balance and the photochemistry of the upper atmosphere. Information on the temporal and spatial variability of this atmospheric constituent can be useful in the understanding of dynamical as well as chemical stratospheric processes. Water vapor measurements in the stratosphere have been limited to relatively few balloon and airplane flights. The more recent measurements indicate fairly invariant dry sky conditions (mixing ratios of less than 5 μgm/gm) with respect to latitude and time. Data on the vertical distribution to about 30 km have been obtained from in situ balloon soundings by Mastenbrook (Reference 1) and by the radiometric techniques of Hyson and Platt (Reference 2) and Goldman et al. (Reference 3). Data on the latitudinal variability of water vapor have been derived by McKinnon and Moorewood (Reference 4) and Kuhn et al. (Reference 5) on an aircraft using radiation detectors. The columnar amounts of water vapor above the aircraft were measured and local concentrations were inferred.

The data presented in this paper were obtained from an in situ sensor aboard an RB57 aircraft operated for the Department of Transportation's Climatic Impact Assessment Program (CIAP). The measurement was performed by an aluminum oxide hygrometer mounted on the nose of the aircraft. The hygrometer performance, flight results, and the validity of the data will be discussed. A more detailed discussion of the aluminum oxide performance in aircraft flight has been reported earlier by Hilsenrath (Reference 6).

INSTRUMENTATION AND DATA BASE

The instruments flown in this aircraft flight series were aluminum oxide hygrometers provided by Panametrics, Inc. The aluminum oxide hygrometer performance is described in detail by Goodman and Chleck (Reference 7). Sensor calibrations were performed under conditions expected in flight with simulated airflow and ambient temperature conditions providing the required temperature compensation as reported by Hasegawa et al. (Reference 8). When possible, the hygrometers were calibrated before and after each flight series. The errors in calibration are approximately ±3°C in frost-point temperature and are equivalent to about ±40 percent in the vapor pressures or mixing ratios measured at 19-km flight levels. The hygrometers were mounted in Rosemont air scoops, which are used routinely in aircraft flight, and offer significant advantages for in situ water-vapor measurements by allowing only uncontaminated ambient air to reach the sensor (Reference 6). The hygrometer and air scoop are shown in Figure 1. Two separate measurement systems, each consisting of an air scoop, a hygrometer, and electronics, were mounted on the left and right sides of the aircraft in order to provide redundancy and an indication of precision. The forward location allowed the air scoops to extend above the aircraft boundary layer to assure sampling of the ambient air. The two hygrometer sensor elements were periodically interrupted by known impedances during the flight, simulating sensor outputs to provide calibration through the entire data acquisition and processing system.

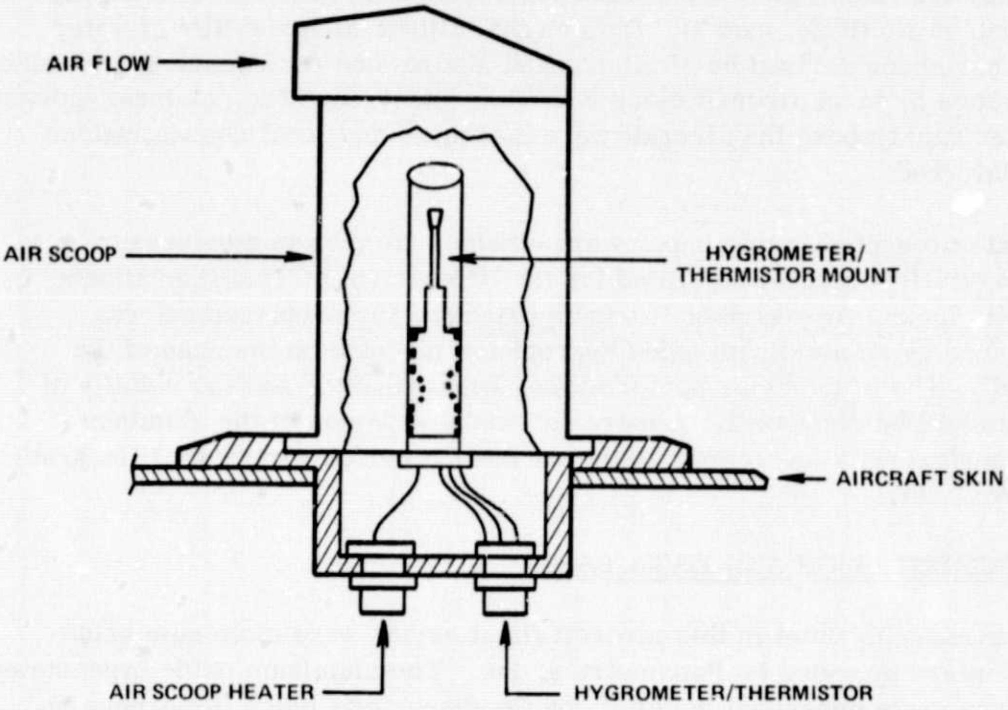

Figure 1. Aluminum Oxide Hygrometer in Air Scoop

An independent measure of air temperature was obtained from a standard aircraft total air temperature sensor. These data, as well as data from the inertial navigation system (INS) were used to derive ambient air temperature by:

$$T_r/T_a = 1 + (\gamma - 1) M^2 / 2 \qquad (1)$$

where

T_r = measured total air temperature.

T_a = computed ambient air temperature.

γ = ratio of specific heats for air.

M = aircraft Mach number.

The ambient air temperature data provided a useful diagnostic tool in evaluating the measured water-vapor distributions.

A data base was formed from the measurements taken from flights between January 1974 and May 1974 as the aircraft flew from the northern shore of Alaska to southern Argentina (70°N to 50°S in the Western Hemisphere). The aircraft flight path is shown in Figure 2. Flight series were initiated from Fairbanks, Alaska; Albuquerque, New Mexico; Panama City, Panama; and Mendoza, Argentina. The data were sampled every 15 minutes to generate a data base which included long spatial and temporal (hourly) effects only. Additional editing of the data was performed in those regions of the flight where the hygrometer was known to be saturated for extended periods of time.

Water-vapor partial pressure was determined from the measured frost-point temperature using the Smithsonian Meteorological Tables (Reference 9). The partial pressure was then corrected for aircraft ram effect by

$$P_r = P_a (1 + 0.2 M^2) \gamma/\gamma - 1 \qquad (2)$$

where

P_r = water-vapor partial pressure from measured frost-point temperature.

P_a = ambient water-vapor pressure.

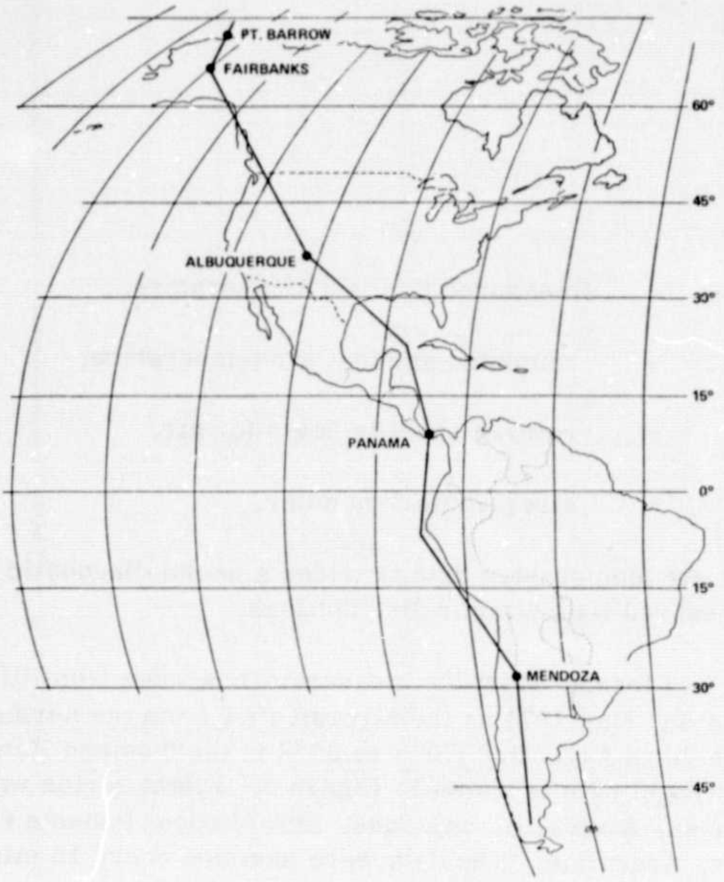

Figure 2. Aircraft Flight Path, January 1974 to May 1974

Water-vapor mixing ratios were then computed from the aircraft altimeter reading and the U. S. Standard Atmosphere, 1962 (Reference 10). Wind-tunnel tests and the measured temperature at the hygrometer sensor element confirmed the validity of this correction. At aircraft cruise speed, $P_a \approx 0.7\,P_r$.

MEASUREMENT ERRORS AND DATA BASE VALIDITY

The measurement precision was determined by comparing the simultanecus measurements of the two hygrometer systems. In Figure 3a, the left-side and right-side systems are compared over the measured range of frost-point temperatures and the standard deviations are shown by the vertical bars. Perfect correspondence would be given by the straight line. Figure 3b is a histogram of the number of occurrences between the left and right side, where the differences range from 0° to 10°C in frost point. These results

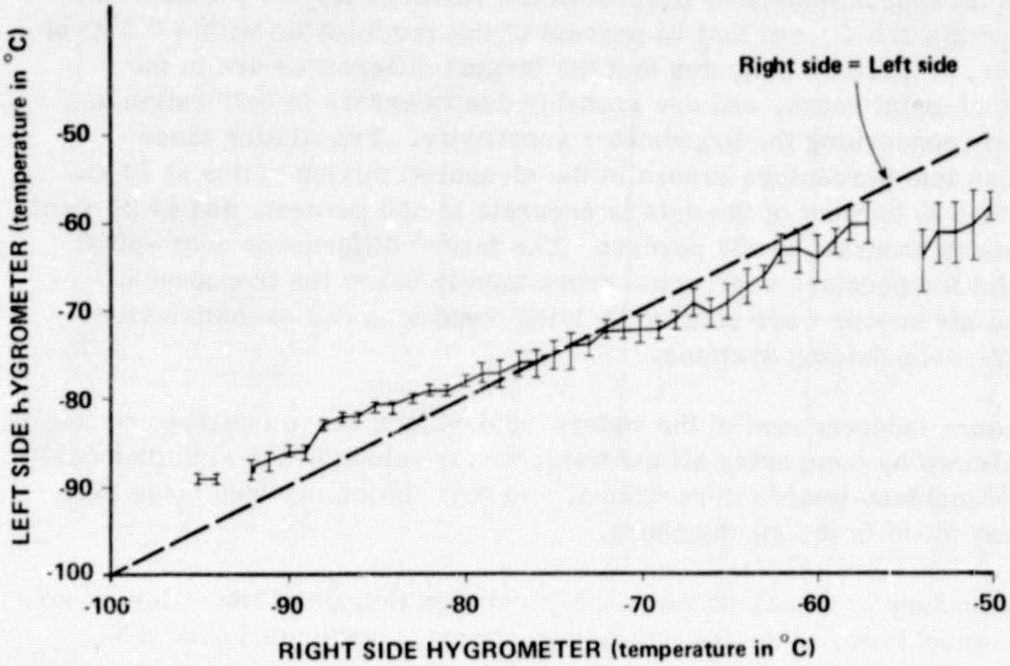

Figure 3a. Hygrometer System Comparison - Left Side versus Right Side

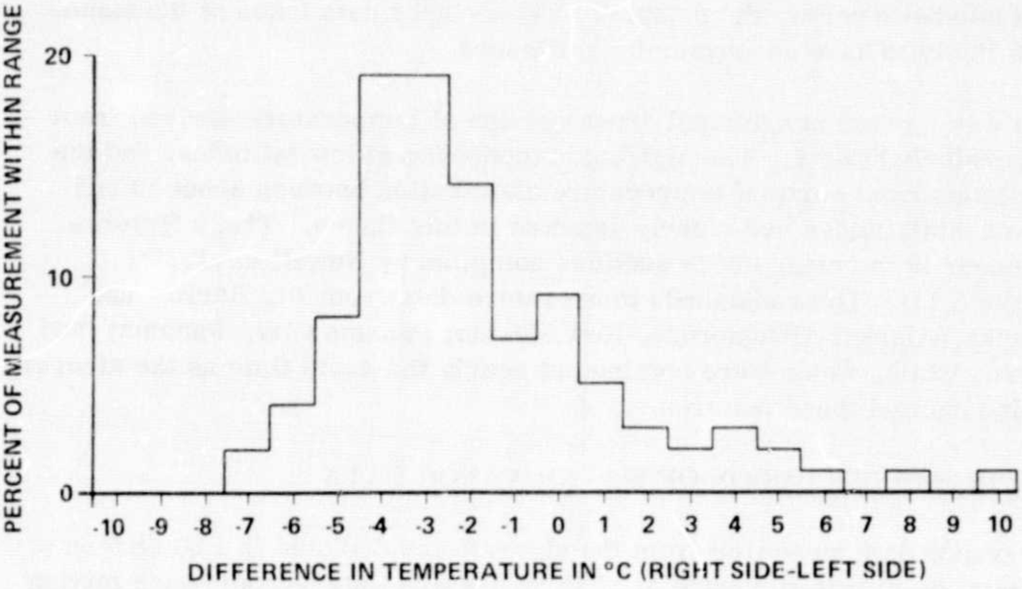

Figure 3b. Hygrometer System Difference Histogram—Percent of Measurements versus Difference in Measured Frost-Point Temperature

indicate that approximately 60 percent of the readings for the two hygrometers lie within 3.5°C, and that 95 percent of the readings lie within 6.5°C of each other. Figure 3a indicates that the largest differences are in the lowest frost-point range, and are probably due to errors in calibration and uncertainty concerning the hygrometer sensitivity. Translating these differences into percentage errors in the measured mixing ratios at 19 km suggest that 95 percent of the data is accurate to ±50 percent, and 60 percent of the data is accurate to ±30 percent. The larger differences near -50°C frost-point temperature represent errors mostly below the tropopause, where the air scoops were plagued by icing conditions due to malfunctions in the air-scoop deicing systems.

Temperature independence of the water-vapor values above the tropopause was confirmed by comparing all the water-vapor values to the simultaneously measured ambient-temperature values. No correlation between these two values was found in the stratosphere.

It was necessary to establish the geophysical significance of the water-vapor data presented here, since the measurements were performed over a 5-month period and over a 75° range in latitude. Since the ambient air temperature was derived independently from the hygrometer measurement, and since the compiled temperature data reproduce a reasonable temperature field, as will be shown below, the sample of water-vapor data taken at the same time is likely to have geophysical significance.

Figure 4 is a pseudomeridional cross section of temperature derived from the aircraft flight data. The high cold tropopause at low latitudes, and the nearly isothermal vertical temperature distribution between about 10 and 20 km at midlatitudes are clearly depicted in this figure. These features also appear in the mean cross sections compiled by Newell et al., (Reference 11). The radiosonde temperature data from Pt. Barrow and Fairbanks, Alaska; Albuquerque, New Mexico; Panama City, Panama; and Quintero, Chile, which were obtained at nearly the same time as the aircraft data also showed these features.

RESULTS AND DISCUSSION OF WATER-VAPOR DATA

Water-vapor data measured from the aircraft are depicted in Figure 5 on a scale similar to that of Figure 4. The values are water-vapor mass mixing ratio multiplied by one million, where mixing ratio is computed from the

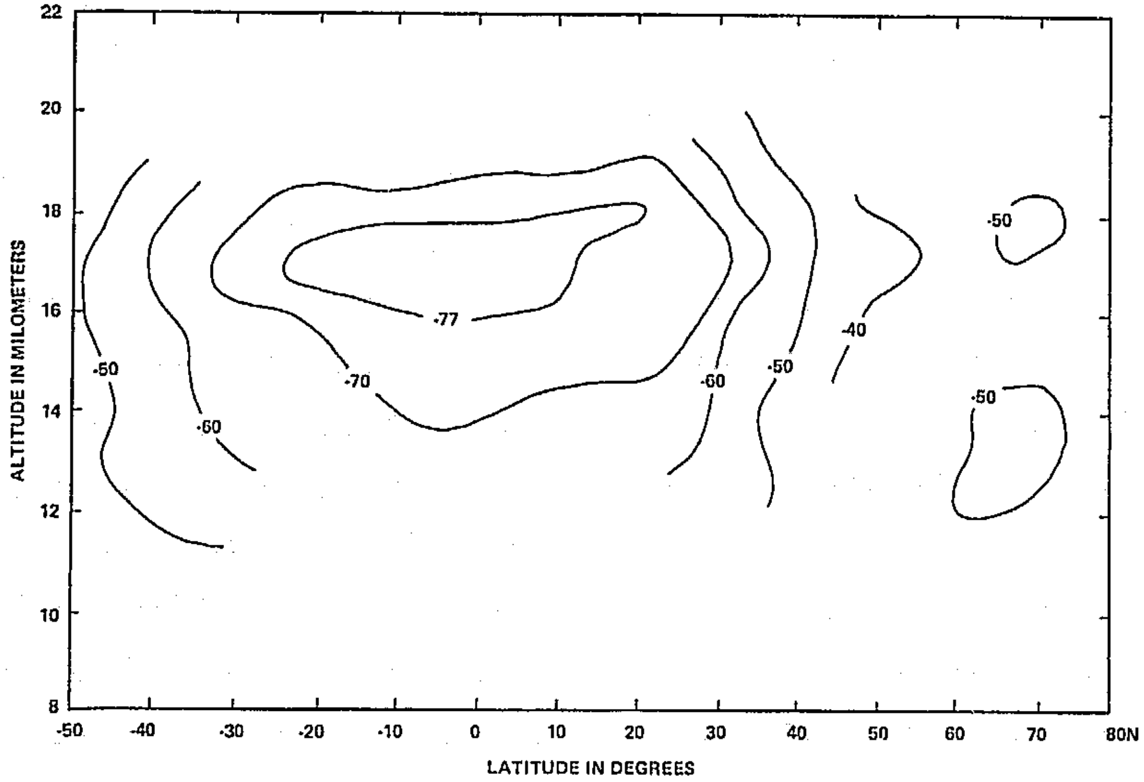

Figure 4. Pseudomeridional Cross Section of Measured Ambient Air Temperature (°C)

measured partial pressure and the pressure altitude. Each value represents an average mixing ratio at an average height in a square 1 km by 1 degree in latitude. In most cases, each depicted value represents a single measurement. The flight data are too infrequent to yield seasonal variability (January to May) at a given latitude. In general, the mixing ratio values range from 2 to 4 μgm/gm with extreme values of 1 to 8 μgm/gm. Above the tropical tropopause, the mixing ratios are generally 2 to 3 μgm/gm, which compare well with the tropopause-saturation mixing ratios obtained from the nearly simultaneous radiosonde temperature data from Panama. If the principal source of water vapor in the stratosphere at low latitudes is tropical upwelling or the ascending branch of the Hadley circulation, the very few values above 3 μgm/gm cannot be explained. All values from about 30° north and south of the Equator below about 17 km are below the tropopause, as determined from the radiosonde data. The results shown in Figure 5 are in agreement with those of Mastenbrook (Reference 1),

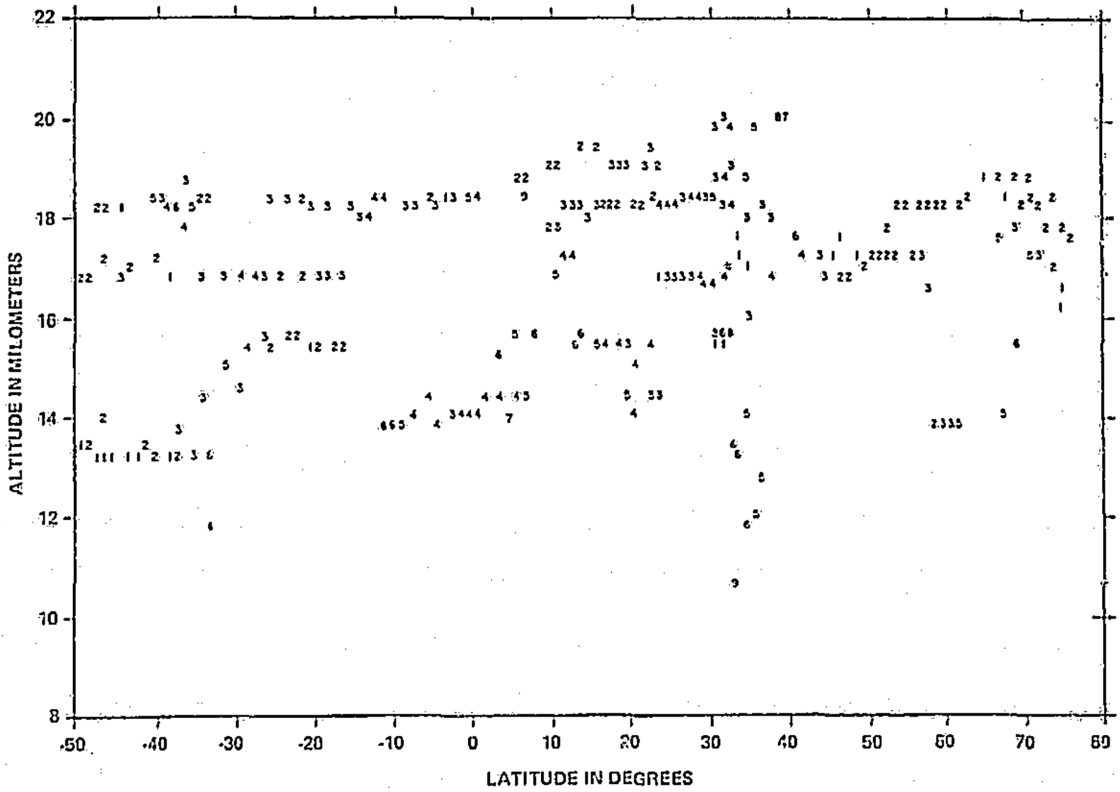

Figure 5. Pseudomeridional Cross Section of Measured Water-Vapor Mixing Ratio (μgm/gm)

whose balloon measurements from Trinidad, West Indies (11°N), Washington, D. C. (39°N), and Thule, Greenland (76°N) showed a nearly constant mixing ratio from about 16 to 22 km. Above 22 km, the Mastenbrook data show an occasional increase in the mixing ratio. Increasing mixing ratios of water vapor were also measured by Hyson and Platt (Reference 2) in the Southern Hemisphere. Measurements by Goldman et al. (Reference 3) indicate a dry layer above the tropopause with a maximum of 4 to 6 μgm/gm near 25 km over New Mexico.

From these results (Figure 5), height-averaged water-vapor mixing ratios were computed for all latitudes above the altitudes of 13 km and 17 km and are shown in Figure 6. The latitudinal data are obtained by a 5-degree moving average of the data in Figure 5, with a standard deviation of about

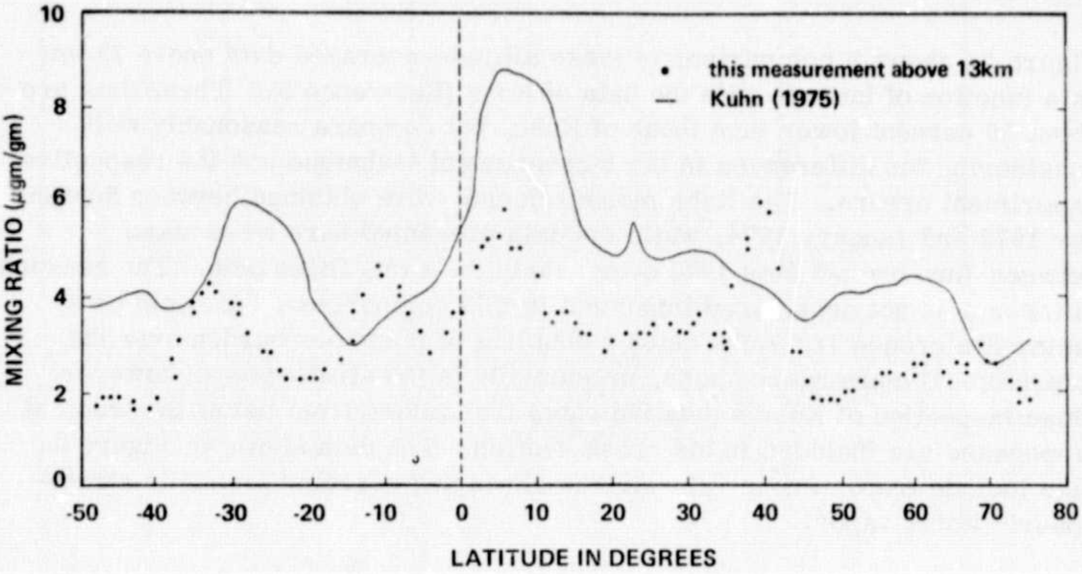

Figure 6a. Latitudinal Cross Section of Height-Averaged Water-Vapor Mixing Ratio Above 13 km

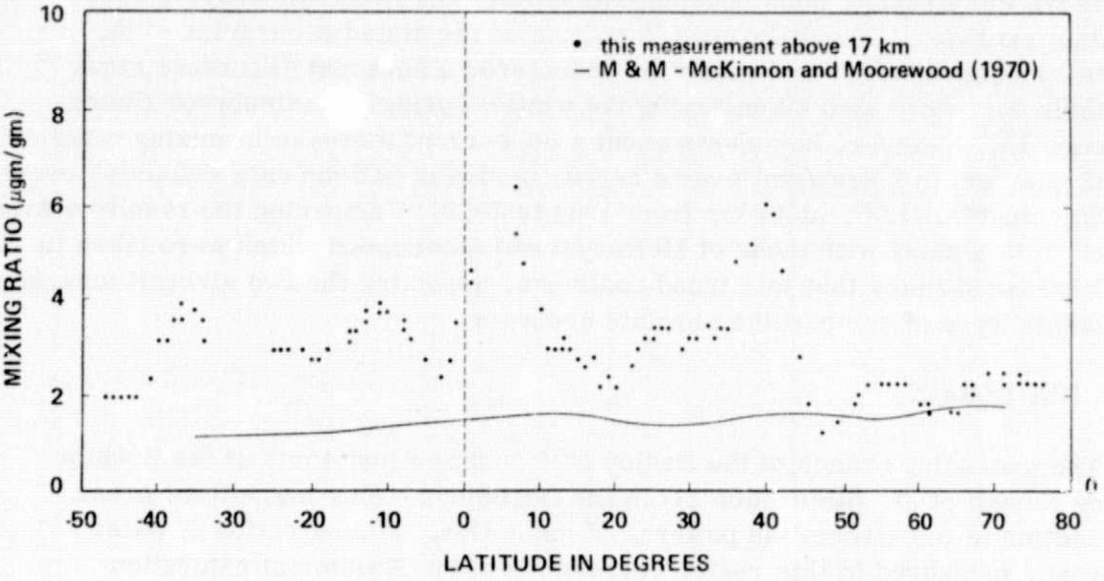

Figure 6b. Latitudinal Cross Section of Height-Averaged Water-Vapor Mixing Ratio Above 17 km

±50 percent at all latitudes. Presentation in this manner allows both a comparison with other aircraft measurements and an evaluation of the dependence of stratospheric water-vapor data on latitude.

Figure 6a shows a comparison of these altitude-averaged data above 13 km as a function of latitude with the data of Kuhn (Reference 5). These data are about 50 percent lower than those of Kuhn, but compare reasonably well considering the differences in the measurement technique and the respective experiment errors. The Kuhn measurements were obtained between September 1973 and January 1974, while the data presented here were taken between January and May 1974 over nearly the same flight path. The seasonal difference is not considered important in this comparison, but could be a factor (Reference 1). Kuhn notes a doubling of the vapor burden over the intertropical convergence zone, presumably in the stratosphere; however, close inspection of Kuhn's data indicates that values from below the tropical tropopause are included in his cross section. The data shown in Figure 6a also include tropospheric values, thus obscuring seasonal trends in stratospheric water vapor.

In Figure 6b, data above 17 km are averaged in the same manner as the data in Figure 6a, therefore data from the low latitude troposphere are excluded. Agreement with the averaged mixing ratios above 17.7 km, which were computed by McKinnon and Moorewood (Reference 4) from columnar amounts above the aircraft, does not improve appreciably even with tropospheric data excluded. The difference is not within the stated accuracies of the two measurements, and cannot be considered a seasonal difference since their data were also taken during the winter-spring. Mastenbrook (Reference 12), however, has shown about a 50-percent increase in mixing ratio (2 μgm/gm to 3 μgm/gm) over a 6-year period of balloon data collection over Washington, D. C. at 18 km from 1964 to 1970. Comparing the results obtained in this study with those of McKinnon and Moorewood which were taken in 1968 could imply that this trend continued, assuming the two aircraft measurements were of comparable absolute accuracy.

CONCLUSION

The ascending branch of the Hadley cell is shown just south of the Equator by Newell et al. (Reference 11) in the December - May meridional cross section of the streamline patterns of mass flux. Mixing ratios of water vapor measured in this region correspond to the Equatorial saturation mixing ratios. The higher values near 10° N are the result of a few data points near 19 km where increases in water-vapor mixing ratios have been detected by other measurements.

Figure 6 shows hemispheric symmetry of wet and dry zones. The water-vapor mixing ratios are at a minimum at about 20° north and south of the Equator and at a maximum at about 40° north and south of the Equator. This is also consistent with Newell's (Reference 11) cross-sectional analysis where there is hemispheric symmetry of meridional and vertical mass flux in the winter-spring at mid-latitudes in the lower stratosphere. It is also evident from these data that neither indirect cells (mid-to-high-latitude meridional cells), nor convective processes associated with the active tropopause at midlatitudes, nor even diffusive processes at high latitudes where saturation mixing ratios range from 10-30μgm/gm, are very effective in transporting water vapor upward at midlatitudes. Earlier aircraft results, also taken at midlatitudes (Reference 6), showed horizontal structure in the measured water vapor and often near-saturated conditions at the tropopause with very dry conditions (well below saturation) just above the tropopause. Though the results presented here show an increase in water vapor by nearly a factor of two in a midlatitude zone in both hemispheres, the distribution in the lower stratosphere appears to be dominated by the ascending branch of the Hadley cell and poleward meridional transport.

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