Spectroscopic Observations of Water Vapor near the Tropopause

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1. Introduction

In August 1968 the National Aeronautics and Space Administration Ames Research Center CV-990 aircraft carried instrumentation aloft for measuring the absolute solar flux in the far infrared region. The apparatus, consisting principally of a gyroscopically stabilized heliostat, directing solar radiation into a scanning Michelson interferometer, has been described elsewhere (Eddy *et al.*, 1970), as have been the flux measurements (Eddy *et al.*, 1969a). In the spectral region examined (30–100 cm^{-1}) the solar radiation is partially absorbed by the various constituents of the atmosphere, including O_2, O_3, H_2O, etc., but principally by the pure rotation lines of water vapor. Analysis of the absorption due to these lines provides us with information concerning the quantity of water vapor present above the flight altitudes (12.3–12.6 km). In this note we present and briefly discuss observations of the absorption due to water vapor obtained during the flights of 2, 6 and 7 August 1968. The flight paths followed 42N, with the data obtained from longitudes 100–120W, over the period 1800–2000 GMT.

2. Data

The Fourier transform of the interferograms obtained during the flights yields solar spectra, modified by telluric absorption, in the spectral region 30–100 cm^{-1}. The interferometer path difference allowed a spectral resolution of 0.25 cm^{-1}; after apodization the effective resolution is near 0.4 cm^{-1} (Eddy *et al.*, 1969b). The absorption lines due to atmospheric water vapor were then compared with theoretical H_2O spectra computed with the aid of the line parameters of Benedict and Kaplan (1968, private communication). The corrected line shape of Zhevakin and Naumov (Zhevakin and Naumov, 1963; Falcone, 1969) has been used in this computation.

Comparison of the intensity of the absorption lines in the actual and theoretical spectra allows the deduction of the total quantity of water vapor present in the atmosphere above the aircraft at the time of the observation. In the spectral region of interest several H_2O lines are sufficiently isolated from other lines of H_2O and other atmospheric constituents to allow the comparison to be made with good accuracy. It has also been shown by Eddy and MacQueen (1969) that the scattering of solar radiation by particles present in the atmosphere is negligible in the far IR. Only the scattering by large particles in a cirrus cloud (water droplets or ice crystals) could have a slight influence on the level of the continuum in the spectra; but all the observations were performed with visually clear sky above the aircraft.

The detector noise (principally microphonic on the initial two flights) and the distortions of the interferograms due to the motions of the airplane which perturbed the gyroscopic tracking system introduce some uncertainty in the water vapor quantity deduced. This error is estimated to be on the order of 5–15%, with the former figure applying to the last flight, when the system was optimized. The results obtained are presented in Fig. 1.

Also in Fig. 1 is the height of the tropopause above the aircraft, as determined from U. S. Weather Bureau balloonsonde data. The data that we used are those of the sounding balloons launched from North Platte, Neb., Lander, Wyo., and Medford, Ore., at 2400 GMT on the days of our flights. The altitude of the airplane was given by a pressure altimeter; it has been employed in the computations because it did not differ from the true altitude by more than 1–2%, and the uncertainty so introduced is no greater than the uncertainty due to change in the tropopause height during the 4–6 hr between the time of the flights and the time of the soundings. A study of the balloonsonde records showed that on the flight days the pressure surfaces were nearly horizontal along the flight path; thus, the height of the

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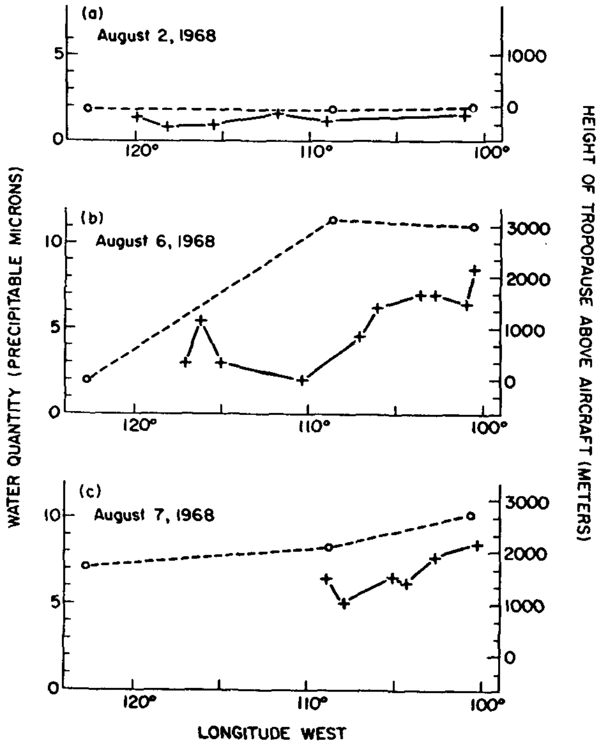

Fig. 1. Horizontal variation of water vapor quantity above 12.5 km, and of the tropopause height, on the three flight days: water vapor, solid line; tropopause height, dashed line.

tropopause shown in Fig. 1 reflects the actual mass of air between the aircraft and the tropopause.

On 2 August the flight level was practically at the altitude of the tropopause, which was nearly horizontal. The tropopause level was less well defined on 6 and 7 August than on the 2nd. A first weak break in the vertical temperature gradient appeared at, or slightly higher than, flight level. The altitude of this weak break decreased toward the west. The major break in the temperature gradient appeared some 2–3 km higher than the aircraft flight level. We have considered this major break as defining the tropopause and its altitude above the airplane is presented in Fig. 1. On 6 August, the sharp slope of the tropopause between longitudes 110–120W is probably not real. More likely the tropopause in this region was characterized by a complex structure not resolved by the balloonsonde data.

3. Analysis of the observations

Three things are apparent from Fig. 1:

1) The total quantity of water vapor above the aircraft varied greatly from day to day, and (especially on 6 August) along the flight path.

2) On the last two flight days the quantity of water vapor decreased significantly from east to west (from Nebraska to the Oregon coast); on these days the height of the tropopause also decreased from east to west.

3) On the first flight day the water vapor quantity was low and almost constant; the tropopause height (relative to the aircraft) was low and nearly constant too.

The variability is large. In the eastern part of the flights the total amount of water quadrupled from 2 to 6 August. On the latter day the water quantity above 12.5 km changed by a factor of 3 over a range of 5° of longitude. Thus, the horizontal scale length for the change in water quantity near the tropopause can be as small as 200 km.

The points 2) and 3) above clearly suggest a correlation between the total quantity of water above the aircraft and the height of the tropopause. Let us discuss this in more detail.

4. Water quantity and tropopause height

To explore the correlation between the height of the tropopause above the aircraft and the measured quantity of water vapor, it will be assumed that the quantity of water vapor decreases exponentially with height as it does in the lower tropopause (Reitan, 1963; Smith, 1966). The water distribution is thus described by the familiar expression

$$w = a \exp(-h/b),$$

where w is the water quantity above the aircraft, in precipitable microns, h the distance between the flight level and the tropopause, in kilometers, and a and b are constants, the former the total quantity of water present in the stratosphere and the latter the scale height for water vapor near the tropopause.

A regression calculation has been performed employing the data illustrated in Fig. 1. Using all three days' observations together (22 observations), we find $a = 1.69\,\mu$, $b = 2.2$ km. The correlation coefficient is $r = 0.83$, significant at the 1% level (Crow *et al.*, 1960). Thus, for all three days the average scale height for water vapor is 2.2±0.5 km. The standard error of estimate, $s_{\ln w, h}$, which represents the mean deviation of $\ln w$ from the regression line, is 0.37. It is interesting to note that these values are similar to those found by Bolsenga (1965) in correlating the total quantity of water in the atmosphere and the mean daily dew-point temperature at the ground ($r = 0.85$ and $s_{\ln w, t} = 0.40$).

If, following Smith (1966), we express the water quantity in terms of the pressure, we can write

$$w = w_0 (p/p_0)^{\lambda},$$

where from our observations we obtain $\lambda = 3.6 \pm 0.8$ near the tropopause. Smith finds for the troposphere $\lambda = 2.77$ in summer at 45° latitude.

The computed scale height varied from day to day. On 6 August it is found to be 4.8 km, but this value is not too significant because of the weak correlation between $\ln w$ and h ($r = 0.4$) due to the uncertain

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definition of the tropopause. For the data of 7 August the correlation is very good ($r=0.89$) and the scale height is found to be 1.7±0.3 km. On 2 August the water quantity and the tropopause height were essentially constant along the flight path. In Fig. 2 are shown the measured water vapor quantities vs height, and the computed regression lines. (It should be noted that the point representing the observations of 2 August is actually the superposition of six independent observations giving essentially the same result. This gives this point a stronger weight, which counteracts the scattering of the observations of 6 August and justifies the high value of the correlation coefficient for the three days together.)

5. Small-scale features

In Fig. 1, it is apparent that there are horizontal variations of the water quantity which remain to be explained. We have shown that the large-scale variation of water quantity can be correlated with changes in the height of the tropopause. It is tempting to correlate the small-scale variations of the water vapor quantity with a small-scale structure of the tropopause region, not resolved by the radio soundings. Unfortunately, the data necessary to support this do not yet exist.

Recently, Kuhn *et al.* (1969) reported variations of the water vapor in the lower stratosphere and correlated them with lower level meteorological features, i.e., frontal zones. In our case the synoptic situation was as follows. On 2 August 1968 the flight path followed a weak high pressure ridge with an east-west orientation near 42N. In the eastern portion the surface ridge lay between two frontal systems; the northernmost front was near the Canadian border and the southernmost extended from near Denver into the Great Plains. On 6 and 7 August, a surface high pressure cell was centered near the northwest corner of New Mexico, with a weak low pressure area over Nebraska and the Dakotas. A slow moving frontal system lay east-west along the Canadian border on the 6th and penetrated southward to the vicinity of 47N by the 7th. On none of the days was there any apparent manifestation of a surface frontal system at flight altitude. Yet our observations indicate water quantity variations almost of the same magnitude as those noted by Kuhn *et al.* in the presence of fronts below the flight path. Although our observations cannot rule out the possibility of interaction between frontal zones and the water quantity near the tropopause, they show that other, equally important factors must also be involved. Clearly, more extensive observations of the type reported herein, and by Kuhn *et al.*, will prove valuable in understanding the fine structure of the tropopause region and the transport of water vapor into the lower stratosphere.

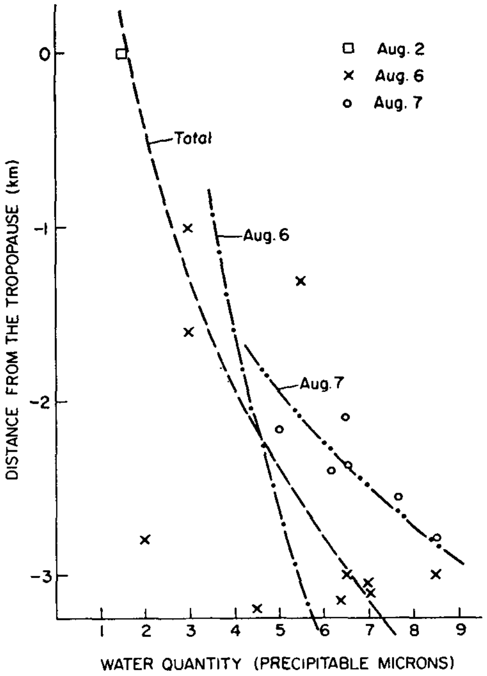

FIG. 2. Regression lines of water vapor vs distance of the aircraft from the tropopause level for the primary two flight days and the combined total. One observation on 2 August is also included.

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