Passive Microwave Spectrum Measurements of Atmospheric Water Vapor and Clouds

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ABSTRACT

Ground-based microwave measurements of atmospheric emission at 5 wavelengths near 1 cm have enabled separate determinations of the water vapor and liquid water contents of the atmosphere. Observations during a frontal passage, in August 1966, yielded humidity estimates within 10% of conventional measurements, and cloud-type estimates compatible with the cloud structure of normal frontal systems.

1. Introduction

The techniques of microwave spectroscopy and radio astronomy offer new methods for studying the atmosphere. Meeks and Lilley (1963) and Lenoir (1965) have discussed the use of oxygen resonances near 0.5 cm for probing the atmospheric temperature profile. Barrett and Chung (1962), Staelin (1966) and Gaut (1968) have discussed the determination of atmospheric water vapor profiles by means of the 1.35-cm wavelength resonance, and Staelin (1966) has discussed the use of the same wavelength interval for estimation of the integrated liquid water content of the atmosphere. The principal advantage of microwave sensing is the ability of microwave radiation to penetrate many types of aerosols and clouds and still permit accurate remote sensing from ground or space.

Earlier microwave measurements of atmospheric water vapor (Staelin, 1966; Gaut, 1968) were absorption measurements against the sun. The present measurements are of the atmospheric emission spectrum. Emission measurements avoid dependence on the sun and permit more accurate and extensive measurements during precipitation. To demonstrate some of the potential of multi-frequency emission measurements of atmospheric water vapor, an extensive series of observations was undertaken during the summer of 1966. One frontal passage was selected for detailed analysis and is described here. It indicates that the integrated water vapor abundance can be determined even during moderate rain, and that the liquid water content of the atmosphere can be estimated simultaneously.

2. Theoretical microwave spectrum of the atmosphere

Theoretical microwave spectra were computed for a large number of model atmospheres in order to match the spectra actually observed. Each model atmosphere assumed a surface temperature of 300K, a lapse rate of 4K km^{-1}, a surface pressure of 760 mm Hg, hydrostatic equilibrium, and an exponentially decaying water vapor distribution with 2.2-km scale height. To simplify the calculations, the atmosphere was stratified into 60 homogeneous layers, each 250 m thick. The expressions for the absorption coefficients of water vapor and clouds were those given by Staelin (1966), and the absorption coefficient of oxygen was that given by Meeks and Lilley (1963). In every case the brightness temperature, measured or computed, corresponded to an elevation angle of 30°. Two such sets of theoretical spectra are shown in Figs. 1 and 2, in which the basic differences between the resonant absorption of water vapor and the nonresonant absorption of clouds are illustrated. Fig. 1 illustrates the great sensitivity of the microwave spectrum to changes in atmospheric water vapor. A receiver accuracy of 1K is sufficient to yield an approximate accuracy of 0.15 gm m^{-3} water vapor, in terms of the equivalent ground-level humidity. Fig. 2 shows the effects of various cloud models superimposed upon the same model atmosphere containing 10 gm m^{-3}

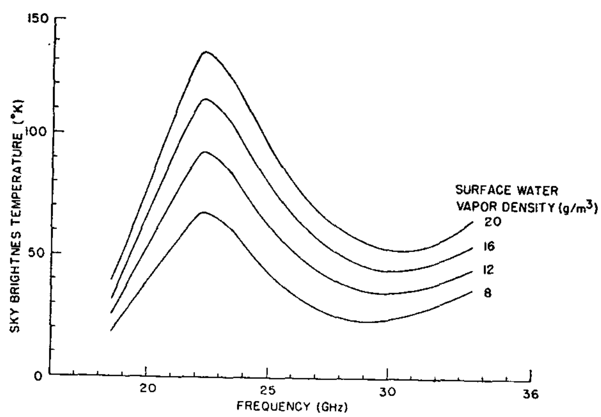

FIG. 1. Theoretical emission spectra of atmospheric water vapor distributed exponentially in altitude, with a scale height of 2.2 km. The spectra are viewed from the ground at 30° elevation angle.

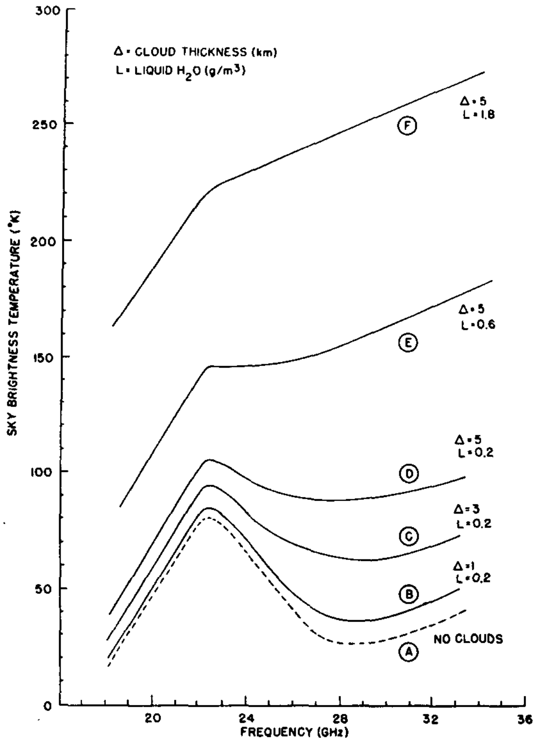

FIG. 2. Theoretical emission spectra for various cloud models combined with a single water vapor model with 10 gm m^{-3} at the terrestrial surface. The spectra are viewed from the ground at 30° elevation angle.

water vapor at the surface. Model B corresponds to a typical cumulus congestus. All cloud bases were assumed to be at 1 km. Examination of Figs. 1 and 2 should make clear the separability of water vapor and cloud information. A mathematical argument to the same effect has been given by Staelin (1966).

3. Instrumentation

The sensing equipment consisted of a multi-channel microwave radiometer which received five frequencies simultaneously. It operated in the region of the 22.235-GHz water vapor resonance (1.35-cm wavelength) at specific frequencies of 19.0, 21.9, 22.235, 23.5 and 32.4 GHz. Each radiometer channel was a conventional Dicke-switched superheterodyne system with an i.f. frequency of 30 MHz, and an i.f. bandwidth of 8 MHz. Two shielded 20-dB standard gain horns served as antennas, one operating at K band, and the other at Ka band. The antenna assembly, exclusive of the shields, had dimensions of the order of inches and was mounted indoors where it viewed the sky 60° from the zenith through an open window. Thus, the antenna remained dry even during heavy rain. The gains of the radiometer were calibrated by gas-discharge tubes referenced to thermal loads. The radiometer baselines were calibrated by means of reference loads immersed in liquid nitrogen. The liquid nitrogen and sky were viewed by the radiometer during alternate half-minute intervals. The rms sensitivity of the radiometer system was ~0.2K for a 100-sec integration period, and the absolute accuracy of the radiometer is estimated to be 2K. Except for the antennas and calibration procedure, the system was similar to that described by Staelin (1966).

4. Observations

Observations were made on many days, but all were consistent with the results obtained during the passage of a cold front over Boston, 2–3 August 1966. This cold front was selected for detailed study because it was quite typical, and involved a wide variety of humidity, rain and cloud conditions. The motion of the front was perpendicular to the antenna beams.

Representative observed spectra are presented in Fig. 3. Each spectrum represents an average of several minutes of data taking, and has been interpolated between the observed points for ease of comparison with the theoretical spectra. These observed spectra represent antenna temperatures at 30° elevation, and correspond to an average of the atmospheric brightness temperature within approximately 7° of 30° elevation. Although the theoretical spectra were not averaged over elevation angle, the error introduced by this omission is believed small.

These observed spectra were then empirically matched to spectra computed for various model atmospheres in an effort to determine the atmospheric humidity and the liquid water content of the clouds. The theoretical spectra were generated for 10, 15, 17.5 and 20 gm m^{-3} water vapor at the surface, and for a variety of cloud models at each humidity. The bases of the model clouds were 1 km, and the tops were at an altitude consistent with the liquid-water content assumed for the cloud. Cloud thickness and density cannot be separately determined from the microwave spectra. Agreement within 3K was usually obtained in this way, and still closer agreement could have been obtained with more care or by statistical estimation procedures such as regression analysis.

The discrepancy between the theoretical and experimental spectra is most significant for spectrum 4, which corresponds to heavy rain. In this case, the observed spectrum is decidedly flatter than the theoretical spectrum. Since the theoretical spectrum is dominated by clouds, which absorb approximately as the square of the frequency, this implies that the effective interaction with rain is less dependent upon frequency. Field measurements and theoretical studies of the cross section of rain (Goldstein, 1951) have both shown decreased wavelength dependence for smaller wavelength-to-drop-size ratios, and thus it is reasonable that the discrepancy should be greatest for the largest rain rates. Although we have not used this effect to separately estimate rainfall rate, it would appear to be

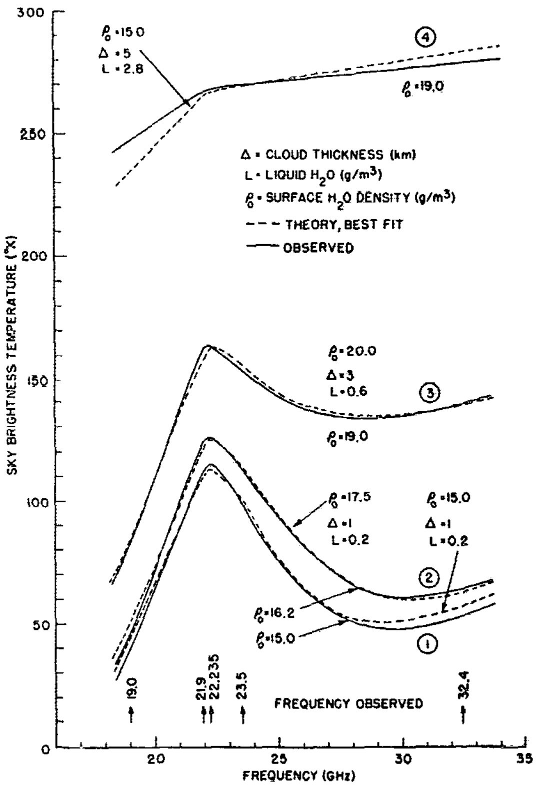

Fig. 3. Comparison of observed spectra and the corresponding best-fit theoretical spectra, showing the model parameters and, for comparison, the directly measured surface water vapor densities. The observed spectra have been interpolated between the observed frequencies.

within the realm of possibility, particularly for very heavy rainfall. Observations at 2-cm and 3-mm wavelengths might increase the accuracy with which the frequency dependence of the nonresonant contribution could be determined, and would thus augment any such attempt at rainfall estimation. If spectrum 4 were due entirely to rain, the equivalent rainfall rate would be approximately 5 mm hr^{-1}.

The model atmospheres providing the best match to the observed spectra are represented in Fig. 4, in which

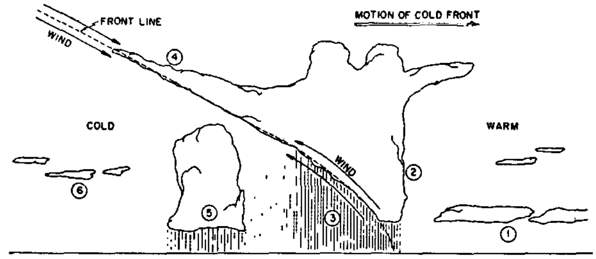

Fig. 5. Model of a cold front showing features observed visually or by the microwave radiometer.

the inferred surface water vapor density, cloud thickness, and cloud density as a function of time are indicated. Also shown are the local rainfall rate and the average surface water vapor density observed at three sites which were within 10 mi of the radiometer and located in a line approximately parallel to the front. The time scale in Fig. 4 is not linear and, of course, the discontinuous atmospheric and cloud parameters that are pictured are only an approximation to the actual continuum situation.

The validity of these inferred water vapor and cloud parameters is difficult to evaluate because accurate meteorological data are difficult to obtain under these circumstances. The best test of the procedure is a comparison of the inferred surface level humidity and the humidity measured by conventional techniques. Such a comparison is not ideal because the surface water vapor density is imperfectly related to the water vapor density at higher altitudes. Nonetheless, comparison of the inferred and true surface water vapor densities indicates that the method is moderately accurate. The true surface humidity was examined only after the inferred values had been determined.

The validity of the inferred cloud models cannot easily be tested except by comparison with a standard model for a cold-front passage. For example, Petterssen (1940, 1941) discusses typical frontal systems, one of which is illustrated in Fig. 5. Key features shown include: 1) cloud systems that sometimes extend far into the warm air ahead of the front at the ground; 2)

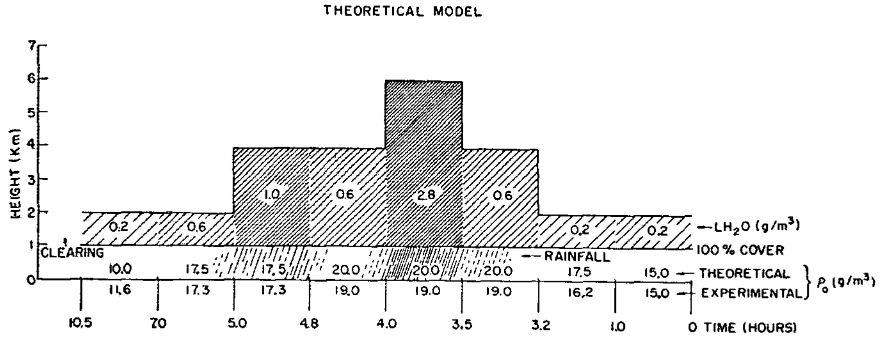

Fig. 4. Histogram of best-fit model parameters during the frontal passage. The experimental surface humidity was derived from conventional sensors, and the theoretical humidity from the best-fit atmospheric models.

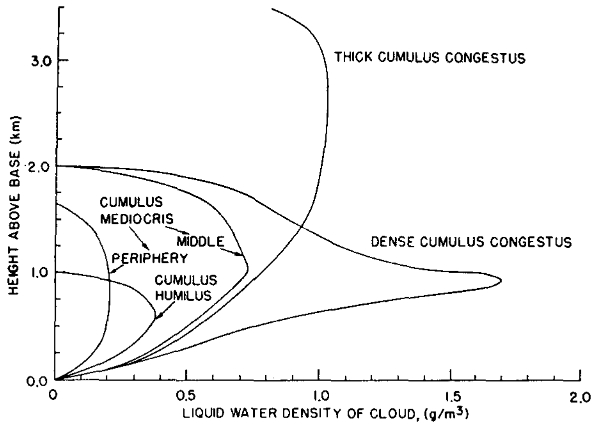

FIG. 6. Liquid water densities of typical clouds as a function of height, for comparison with the cloud parameters derived from the microwave observations.

rapid advent of the cold-front rain, accompanied by a sharp increase in cloud thickness; 3) cold-front precipitation, usually of short duration and variable intensity; 4) clouds along the frontal surface that may extend far behind the front position at the ground; 5) instability showers behind the front, if the cold air is unstable; and 6) clouds of secondary importance that also may form under the frontal surface but not contribute materially to the precipitation. All of these features, except 2), were observed visually.

On the basis of Fig. 5 it may be inferred which cloud types correspond to features of the observed frontal passage. These typical cloud types may then be compared with those inferred from the microwave observations, as illustrated in Fig. 4. In order to facilitate this comparison liquid water profiles of typical clouds are presented in Fig. 6 (after Borovikov, 1963). The inferred clouds are quite consistent with those expected for the standard cold-front model. For example, the most dense rainless cloud observed, that at hour 4.5, was comparable to a thick cumulus congestus, and only during heavy rain was the indicated cloud water content in excess of the typical value for such clouds.

5. Summary and conclusion

Measurement of the emission spectrum of atmospheric water vapor has allowed us to determine integrated water vapor abundance and liquid water content under varying meteorological conditions. Theoretical spectra were generated for many different model atmospheres, taking into account the combined effects of the mutual absorption of water vapor concentration and cloud liquid water content. These models demonstrate the separability of the resonant absorption of water vapor and the nonresonant absorption of clouds. Of the many observations recorded with the 5-channel radiometer, a particular 10-hr period corresponding to a cold-front passage was chosen for detailed study. Agreement within 3K between observed and theoretical spectra was obtained by empirically matching the two. The largest discrepancy between theoretical and observed spectra occurred during heavy rainfall, when the observed spectrum was flatter than predicted. A composite picture of the cold-front passage was then assembled, using the inferred values of surface water vapor density, cloud thickness, and cloud density as functions of time. This picture agrees (in nearly all respects) with typical frontal characteristics that have been described, thereby demonstrating the ability of this procedure to yield reasonable estimates of water vapor and cloud parameters. Although scattering effects and the absorption coefficient of rain were not included in the computations, the interpretation of cloud and water vapor contributions to the spectra remain relatively unaffected except in heavy rainfall. It is evident from these results that passive microwave spectroscopy offers an interesting approach to the study of the terrestrial atmosphere.

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