CWV.6 A Comparison of Microwave Radiometer, Lidar, and Meteorological Balloon Observations of Water Vapor During the Ladimas Campaign

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Introduction

During the fall of 1991, the German Research vessel *Polarstern* sailed from Bremerhaven, Germany, to the Antarctic carrying a 22-GHz microwave water vapor radiometer, a Nd:YAG lidar with a water vapor Raman data channel, and meteorological balloons. This portion of the LADIMAS (LAtitudinal DIstribution of Middle Atmosphere Structure) campaign provided a unique opportunity to combine the data sets from the three observation techniques over a wide range of geographic latitudes.

The Penn State microwave radiometer was developed at CSSL as part of NASA's Network for Detection of Stratospheric Change and the UARS Correlative Measurement program (1). It remotely senses water vapor in the atmosphere by observation of the thermally excited 22-GHz resonant line. The instrument has a cryogenically cooled HEMT (High Electron Mobility Transistor) preamplifier to obtain a very low effective noise temperature to enable observations into the mesosphere. Spectral analysis of the radiometer output by a 63-channel filter bank gives the altitude distribution of water vapor. The primary data set for these LADIMAS measurements was for the 40 to 80 km altitude region; however, a 400-MHz broad-band "total power" channel centered over the line also provided a measure of the total water vapor overburden that continued between periodic "tipping curve" calibrations.

The Penn State lidar, which was designed and constructed by the faculty and staff at Penn State University's Applied Research Laboratory (ARL) and Communications and Space Sciences Laboratory (CSSL), has an output of 1.5 J/pulse at 20 Hz. The fundamental wavelength is doubled to obtain 600 mJ pulses at 532 nM and mixed to obtain 250 mJ pulses at 355 nm. The lidar was designed as part of an NSF effort to study the coupling of energetics and dynamics of atmospheric regions and to develop advanced meteorological sounders for the U.S. Navy and other users of meteorological data. The lidar obtained density and temperature profiles from molecular scatter of the gases of the middle atmosphere (25-80 km), density and temperature profiles measured from the ground upward using two-color lidar and Raman detection, molecular nitrogen profiles up to 30 km, and water vapor profiles up to 5 km altitude (2).

Microwave Radiometric Measurements of Water Vapor

Microwave radiometer measurements of water vapor in the atmosphere can generally be classified into two broad categories. "Narrow-band" systems are focused on observations of the stratosphere and mesosphere and are often intended to study the interrelationships of water vapor and ozone to better understand the chemical activity of these regions. The radiometer needs spectral resolutions on the order of 100 kHz for observations into the mesosphere (3). However, because of pressure broadening of the spectral line even a "narrow band" system must have a bandwidth of several hundred MHz to permit observations down into the stratosphere. The even higher pressures of the troposphere broaden the spectral line to several GHz, requiring a "broad-band" or even "multi-channel" radiometer system.

These "broad-band" systems can serve as "sounders" to continuously monitor meteorologic conditions without expensive balloon-borne radiosonde measurements. The development of broad-band systems came about from the need to determine the amount of "wet path" delay introduced in radio wave propagation paths by atmospheric water vapor. This wet path delay results from the change in the dielectric constant produced by water vapor in the atmosphere.

Unknown variability in the propagation delay, varying with water vapor concentration, can severely affect radio astronomy, VLBI crustal dynamics, and communication link measurements. Water exists in many forms in the atmosphere (vapor, cloud, haze, fog, rain, etc.), and the absorption coefficient for each form has a different frequency dependence (4). Dual-channel radiometers (5,6) have exploited this frequency dependence, using one frequency near the spectral line that is primarily sensitive to water vapor and a second channel frequency in the 31 GHz window that is primarily sensitive to liquid water in clouds.

The CSSL Penn State microwave radiometer was developed as a "narrow-band" system to be used primarily for studies of the stratosphere and mesosphere. However, to fully calibrate the high-altitude data, the amount of attenuation introduced by water vapor in the troposphere must be determined. Periodic "tipping curve" calibrations are done to determine the tropospheric loss. This procedure is generally done by using a "medium-band" channel that covers the full bandwidth of the spectral analysis unit. This channel operates in a total-power mode so that the absolute brightness temperature can be determined. As the stratospheric/mesospheric measurements are recorded between the tipping curve calibrations, the total-power channel is also recorded as part of the data stream. Off-line data processing then uses this total-power data to interpolate the tropospheric attenuation between the tipping curves. The LADIMAS campaign on the *Polarstern* provided the opportunity to intercompare measurements from these procedures with both lidar- and radiosonde-based measurements of tropospheric water vapor.

Microwave Observations

As the *Polarstern* sailed from the latitude of 53 N to 63 S, 65 tipping curve observations were taken by the microwave radiometer. Typically five different observation angles were used for each calibration. About ten percent of these observations were inconsistent and discarded. We believe that these inconsistencies were produced by variations in the cloud cover viewed by the antenna as its elevation angle was changed. For many of the tipping curve observations, a good fit to the expected dependence on air mass ($1/SIN(\theta_{elev})$) was obtained. Ninety-nine weather balloons were launched from the deck of the *Polarstern* during this portion of the LADIMAS campaign. The resulting profiles of temperature, pressure, and relative humidity have been used in a forward model calculation to predict the expected amounts of tropospheric attenuation. These predicted attenuation factors agree well with the tipping curve values obtained by the microwave radiometer. The amount of attenuation depends on the viewing elevation angle; the comparison shown in Fig. 1 is for zenith observation (air mass = 1).

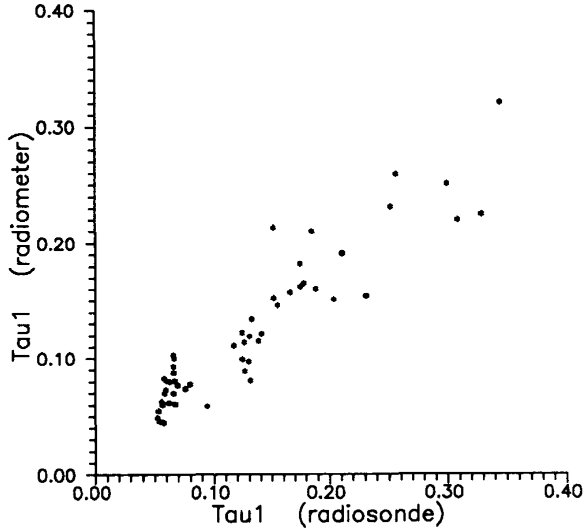

Fig. 1. Comparison of tipping curve and radiosonde predicted opacities.

The CSSL portable radiometer will be used in many different geographic locations as part of the Network for Detection of Stratospheric Change. Some of these locations will not have weather balloon soundings continuously available, but will only have surface measurements of temperature and humidity. As a check on the sufficiency of reduced tropospheric measurement, we have also performed forward model calculations with an assumed temperature lapse rate and humidity scale height. Fig. 2 shows the zenith opacity if climatological altitude variations are assumed for the temperature lapse rate and the pressure and water vapor scale heights.

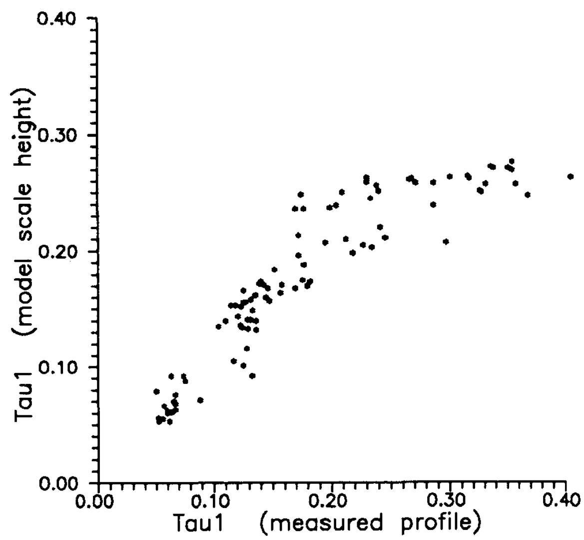

Fig. 2. Comparison of predicted tropospheric attenuation using observed temperatures and humidity profiles versus using assumed simple model distributions.

The simple model opacities of Fig. 2 were calculated using the method of Liebe (4). A simple temperature lapse rate of -6.2 K/km, a pressure scale height of 8.25 km, and a water vapor scale height of 1.8 km were used. Examination of the radiosonde profiles shows that these model values are reasonable. If latitudinal variations of these model parameters were utilized, we would expect the results of the simplified model approach to be in even better agreement with the data derived from the radiosonde data. Thus it is possible to roughly estimate the amount of tropospheric attenuation based upon surface measurements of temperature and humidity without requiring radiosonde measurements.

From the tipping curve data from the radiometer we obtain the zenith opacity, Tau1. We can then adjust the water vapor scale height parameter in the simple model to produce a predicted Tau1 that matches the value observed from the tipping curve. Integration of the water vapor distribution of the simple model, then produces an estimate of the total precipitable water. Even without consideration of the relative contribution of cloud liquid water, reasonably good agreements between tipping curve-generated values of total precipitable water vapor and the values that were obtained directly from the radiosonde measurements (Fig. 3).

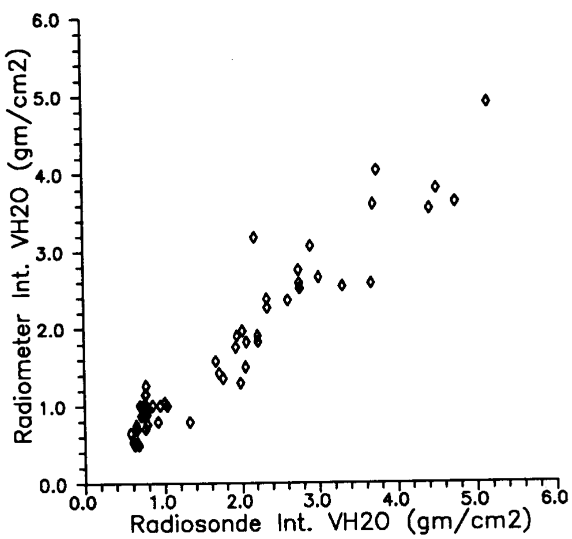

Fig. 3. Total precipitable water vapor obtained by radiometer tipping curves compared to that measured by radiosondes.

Microwave Radiometer-Lidar Intercomparisons

Another powerful technique uses Raman scattering of a high-power laser beam to determine the relative concentrations of water vapor and nitrogen in the troposphere (2,7). A scaler calibration coefficient of the technique is determined periodically by comparing weather balloon soundings and the derived lidar-based profiles. Fig. 4 shows a comparison of the total integrated water vapor as determined by the Raman lidar technique with the values obtained from radiosonde measurements. Heavy cloud cover can limit the altitude range of the lidar technique, so the correlation between the techniques is best under clear sky conditions.

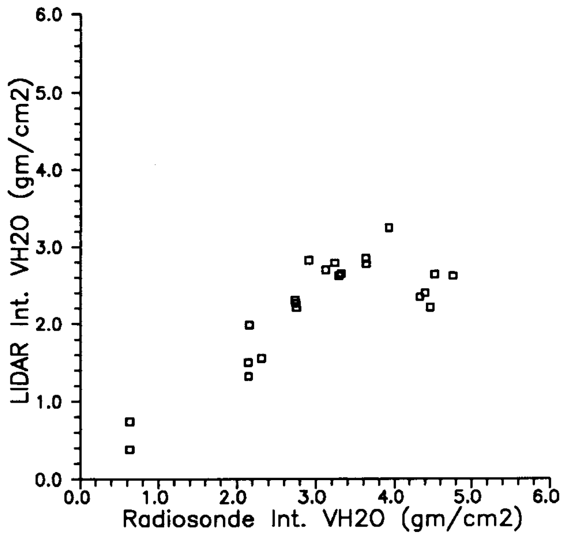

Fig. 4. Comparison of total integrated water vapor obtained by Raman lidar and radiosonde techniques.

Experimental difficulties limited the lowest range of the lidar measurements to about 0.5 km. Since the contribution of the first few kilometers to the total column content can be quite significant, the lidar data was augmented by using a linear straight line fit between surface relative humidity measurements and the bottom edge of the lidar profile. Even though the radiosonde data is periodically used to determine a calibration scale factor for the lidar experiment (2), the data of Fig. 4 suggests that the lidar technique may underestimate the total precipitable water. Some of the scatter in Fig. 4 resulted from in-the-field adjustments of the experiment configuration. Recent equipment modifications have lowered the measurement range to about 100 m. We should also note that while radiosonde measurements are often considered to be a "ground truth," there can in fact be significant variations in radiosonde measurements when intercomparisons of data from sondes of various manufacturers are compared (7).

Conclusion

The LADIMAS campaign during the voyage of the *Polarstern* in the fall of 1991 provided the opportunity to compare three different techniques that can be used to determine the total integrated water vapor content of the atmosphere. The tropospheric attenuation expected from a full radiosonde profile does not differ significantly from that obtained from surface measurements and simple climatological models. Tipping curve estimates of the zenith opacity agree well with the estimates made from the radiosonde data. If a simple exponential model is adjusted to produce a tropospheric attenuation that matches the tipping curve observation, the corresponding total precipitable water vapor correlates well with that obtained from radiosondes. Raman lidar estimates of the total precipitable water vapor also agree reasonably well with radiosonde measurements.

Acknowledgements

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