Results of Year-Round Remotely Sensed Integrated Water Vapor by Ground-Based Microwave Radiometry

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ABSTRACT

Based on two years of measurements with a time resolution of 1 min, some climatological findings on precipitable water vapor (PWV) and cloud liquid water (CLW) in central Europe are given. A weak diurnal cycle is apparent. The mean overall diurnal variation was about 0.15 cm in summer and 0.05 cm in winter, equivalent to 8% and 5%, respectively. The PWV increase starts in summer at about 0800 local time and has a maximum of about 0.02 cm h^{-1} between 1000 and 1500 local time, equivalent to about 1% PWV h^{-1}. There was, on average, no PWV variation during the night in winter. PWV decreased in winter during the morning with a maximum of 0.01 cm h^{-1} and increased in the afternoon with a maximum of 0.01 cm h^{-1}. Thus, the accuracy of the monthly means of PWV based on monitoring systems with low-time resolution (satellites, radiosondes) is only slightly affected by the diurnal course of PWV in central Europe.

On average an increase in PWV and CLW was found in the 30-min interval before precipitation in summer. The PWV increase was, however, only about 0.1 cm or 5% of PWV within the last 2 h before rain. The corresponding CLW increase was 0.1 mm, which is considerable as precipitation was observed when CLW reached 0.3–0.4 mm.

1. Introduction

Atmospheric water vapor is one of the most variable atmospheric parameters. It plays a vital role in the hydrological cycle and dominates the atmospheric radiative properties. Despite the importance for the understanding and prediction of many atmospheric processes, the present observing system, based mainly on radiosonde data, is inadequate to monitor the atmospheric moisture variability, which needs measurements of high resolution in space and time. Quoting Rogers and Schwartz (1991) ''the water-vapor content of the atmosphere is a noisy quantity, and many applications require an understanding of the character of the noise.'' Although the requirements for atmospheric water vapor monitoring are far from being met, microwave radiometry is feasible to monitor at least one moisture parameter, namely the integrated water vapor or equivalently, precipitable water vapor (PWV), above a site with the required resolution. The continuously operating geodetic Global Positioning System (GPS) offers complete coverage of PWV over land with a resolution of about 10 min and an accuracy of better than about ±5%

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(Bevis et al. 1992). The rms error of PWV from GPS data is estimated by Bevis et al. (1994) as less than 2 kg m^{-2} of the PWV, equivalent to the height of a corresponding column of water of 0.2 cm. The long-term bias was estimated to be less than 0.2 cm.

Ground-based, upward-looking microwave radiometers that measure the background microwave radiation in the vicinity of water vapor lines are able to monitor PWV at a site with a time resolution less than about 1 min and an accuracy better than conventional radiosondes (Guiraud et al. 1979). Intercomparisons of different techniques for PWV estimates, including satellite near infrared (IR) reflectance and IR emittance techniques, radiosondes, and ground-based microwave radiometers, agreed to within 0.1 cm PWV (Gao et al. 1992).

Microwave radiometry has the advantage of a near-all-weather capability as the signal is affected only in case of precipitating clouds. Ground-based microwave radiometers have the additional advantage of providing the integrated cloud liquid water (CLW).

At the Meteorological Observatory Potsdam of the German Weather Service (52°23′N, 13°04′E, 81 m ASL) a dual-channel microwave radiometer has been in operation for two years as part of a remote sensing facility that includes a Fourier transform infrared (FTIR) emission spectrometer (Spänkuch et al. 1996) and a laser ceilometer. Reasonable estimates of the vertical water vapor structure are expected when relevant information

TABLE 1. Instrument specification.

Frequencies (GHz)	23.8	31.4
Bandwidth (double side) (GHz)	0.4	0.4
Beamwidth (degrees)	5.5	4.6
Absolute accuracy	0.5 K	0.5 K
Pointing slew rate	$3°\ s^{-1}$ azimuth	
	$>90°\ s^{-1}$ elevation	
Sample time	1 s	1 s
Cycle time	<1 min	
Dimensions	$45 \times 28 \times 74$ cm	
Weight	21 kg	

from such different data sources are combined. Analogous efforts are made by several groups such as Han and Westwater (1995), Stankov et al. (1995), Feltz et al. (1996), and others.

A short description of the estimation of PWV and CLW from ground-based microwave radiometer measurements is given in section 2. Section 3a presents a statistical analysis of the PWV measurements. PWV and CLW tendencies before summer precipitation events are analyzed in section 3b.

2. Basic principles of water vapor and cloud liquid water estimation

Ground-based microwave radiometry for PWV and CLW retrievals have some tradition beginning in the 1970s (see, e.g., Ulaby et al. 1986), and appropriate radiometers are commercially available. Therefore only a short outline of the technique is given for completeness and better understanding.

Since February 1996 the dual-channel microwave radiometer WVR-1100 from Radiometrics Corporation has been operating at the tower of the Potsdam Observatory. The radiometer is described in detail by Solheim (1993). Basic characteristics are compiled in Table 1. It operates at 23.8 and 31.4 GHz. The 23.8-GHz channel was selected instead of the otherwise equally suitable 20.6-GHz channel (Westwater 1978; Hogg et al. 1983) because it is in a reserved frequency band and therefore free from satellite downlink transmissions that could cause erroneous results in sky observations. The use of a common antenna and wave guide system with individual Gunn Diode oscillators for each channel implies that simultaneous measurements at the two frequencies are not possible and that the fields of view of each channel are not identical (see Table 1). The accuracy of the estimation of PWV and CLW is, however, not severely reduced due to different time- and space scales of both parameters and the differences in the sensitivity of the channels to PWV and CLW (Liljegren 1994). Absolute calibration is achieved by the "tipping curve" procedure (see, e.g., Decker and Schröder 1991) that uses measurements at different zenith angles. The radiometer is portable, needs a minimum of power, operates in an unattended mode, and is therefore well suited for field campaigns.

The 23.8-GHz channel in the vicinity of the 22.235-GHz water vapor spectral line is more sensitive to PWV than to CLW, and the 31.4-GHz channel in the atmospheric transmission window is more sensitive to CLW than to PWV.

Measurements of the sky radiance at the two frequencies, converted to sky brightness temperatures, $T_{b\nu}$ allow the simultaneous determination of PWV and CLW from the linear equations

$$PWV = c_0 + c_1\tau_{23.8} + c_2\tau_{31.4}$$

and (1)

$$CLW = d_0 + d_1\tau_{23.8} + d_2\tau_{31.4},$$

where τ_ν is the frequency-dependent total atmospheric optical depth as the sum of the optical depths of water vapor, liquid water and dry air. Here, τ_ν is determined from Eq. (2),

$$\tau_\nu = \ln[(T_{mr,\nu} - T_{b0})/(T_{mr,\nu} - T_{b\nu})], \quad (2)$$

where $T_{b\nu}$ is the measured sky brightness temperature at frequencies ν, $T_{mr,\nu}$ is the mean radiating temperature of the atmosphere estimated on a seasonal basis for a given observation site

$$T_{mr,\nu} = \frac{1}{1 - \exp[-\tau_\nu]} \int_0^{\tau_\nu} T(z) \exp[-\tau_\nu(z)]\, d\tau_\nu(z), \quad (3)$$

and T_{b0} is the cosmic background brightness temperature taken to be 2.7 K.

The quantity τ_ν is dependent on the zenith angle Θ of the measurement as is the sky brightness temperature $T_{b\nu}$. Nonzenith measurements are related to zenith measurements by a so-called mapping function [for details see, e.g., Bevis et al. (1992)]. The regression coefficients of Eq. (1) were estimated for each month from radiative transfer simulations using more than 2000 representative radiosonde data from Lindenberg, about 75 km east of Potsdam.

The accuracy of the retrievals was checked in the field campaign LINEX 96/1 from 15 April 1996 through 13 May 1996 (Steinhagen et al. 1998). The mean value of the absolute difference of PWV between the microwave measurement and the radiosonde was 0.1 cm, which agrees with the findings of previous investigators (e.g., Guiraud et al. 1979; Gao et al 1992; Lesht and Liljegren 1996). Additionally, microwave radiometer and GPS PWV estimates at the same site agreed within 0.1 cm confirming the results of Rocken et al. (1993). Westwater (1978) assessed the theoretical accuracy of PWV retrievals by ground-based microwave radiometry to better than 15%.

3. Results

a. Precipitable water vapor (PWV)

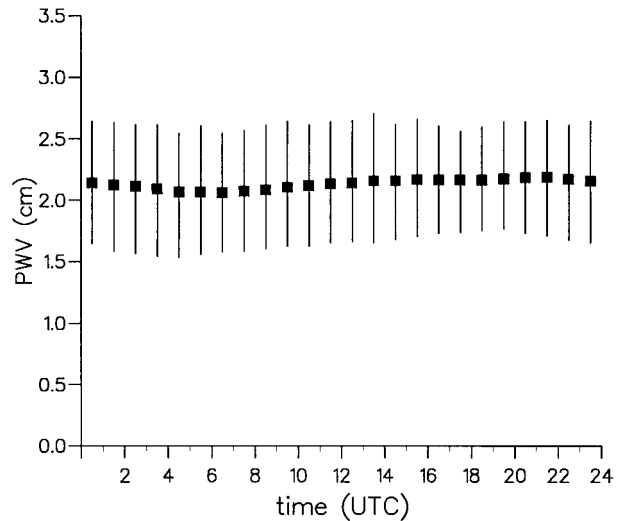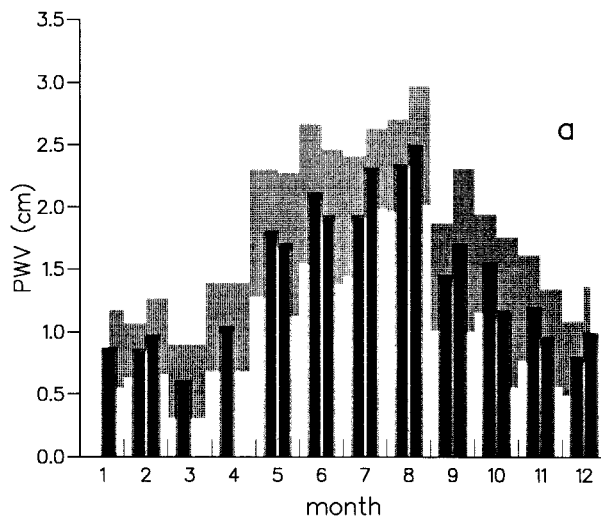The following results are based on 1-min values from 1 February 1996 to 31 December 1997 measured at

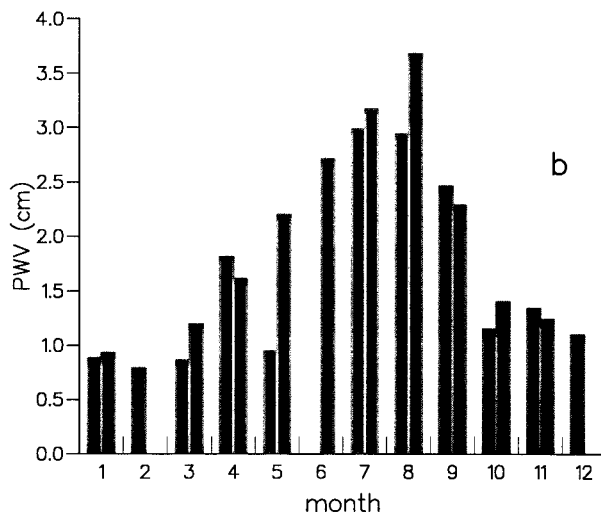FIG. 2. Hourly means (solid box) plus/minus standard deviations (line bar) of PWV at Potsdam in summer.

FIG. 1. Monthly means (dark bar graph) plus/minus standard deviation (gray area) of PWV at (a) Potsdam, and (b) at the Southern Great Plains Testbed Site 1994/95 (Lesht and Liljegren 1996). The left bar graph at each month in (a) denotes the monthly means in 1996 and the right graph the monthly means in 1997.

Potsdam and during two campaigns (15 April–13 May 1996, 13–30 September 1996) at Lindenberg. The 23.8-GHz measurements were disturbed in March and April 1997 due to radio link interference and are thus not included in the investigation. This interference was eliminated by appropriate shielding of the radiometer and a slight change in location.

Figure 1a shows the monthly means of PWV at Potsdam together with corresponding standard deviation. The left bar graph at each month denotes the monthly means in 1996 and the right the monthly means in 1997.

The PWV and its standard deviation in winter are about 1 cm and 0.3 cm, and in summer about 2.5 cm and 0.5 cm, respectively. The minimum PWV was observed in March 1997 at 0.6 cm. In March 1997 anticyclonal synoptic patterns were predominant with advection of arctic air masses.

Figure 1b gives equivalent results of the contigous United States in north-central Oklahoma (36°36′N, 97°29′W, 320 m ASL) from 1994 and 1995 at the Southern Great Plains Testbed Site of the Atmospheric Radiation Measurement Program (Lesht and Liljegren 1996). Similar amounts are found at both sites in winter, whereas in summer, PWV is up to 1 cm higher in the contigous United States than in central Europe. Note, however, the considerable interannual variability as indicated in the United States amounts in May 1994 and 1995. The results in Fig. 1 confirm, by and large, corresponding climatologies from radiosonde data, despite their poor time resolution compared to the radiometer measurements. This agreement is not surprising because there is only a slight diurnal cycle in PWV, as shown in Fig. 2, where the hourly means of the summer months are given. The diurnal cycle is extremely weak compared to the overall value of about 2 cm PWV. The result of the winter months (not shown) is similar. Note that the difference between local time and UTC is about +1 h.

The diurnal PWV cycle can more distinctly be shown by the interhourly differences of the means from hour to hour as done in Figs. 3a,b for summer and winter. Negative differences mean decrease of PWV with time and positive differences mean PWV increase. The increase starts in summer (1 May–31 July 1997) around 0700 UTC and is about 0.02 cm h^{-1} between 0900 and 1400 UTC, equivalent to about 1% PWV increase h^{-1}. In winter, (1 November 96–26 February 1997) there is
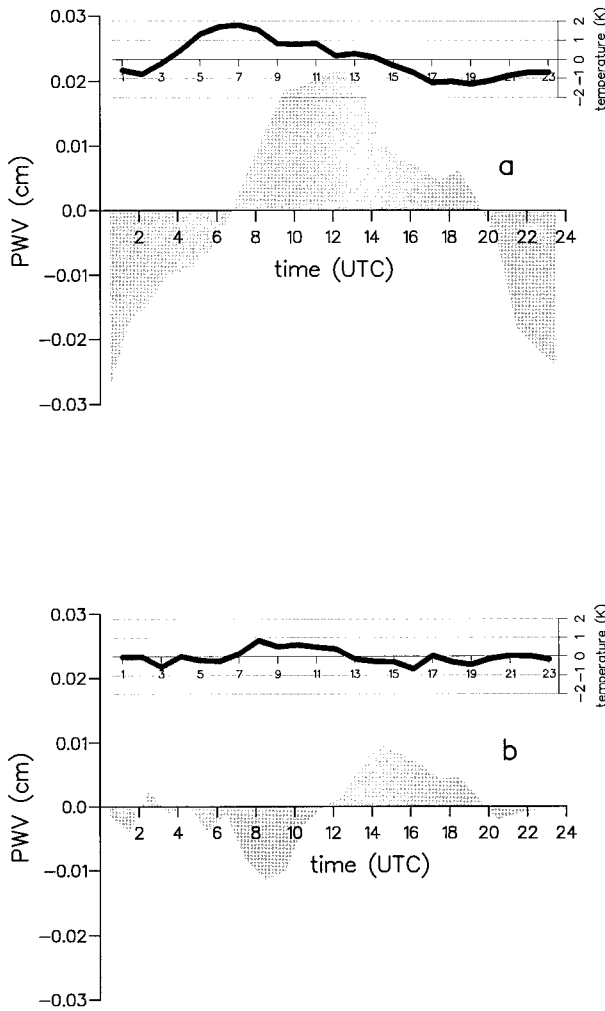
FIG. 3. Mean deviations (gray area) of two consecutive hourly values of PWV in (a) summer from 1 May to 31 Aug 1997 and (b) winter from 1 Nov 1996 to 26 Feb 1997 (lower panel), and the corresponding ambient temperature deviations from hour to hour (upper panel).

on average nearly no PWV variation during night. During the morning hours, from 0800 to 1200 local time, a decrease in PWV of 0.01 cm h^{-1} in maximum was observed and an increase from 1300 to 2100 local time with a maximum of 0.01 cm h^{-1} at 1500 local time. The overall diurnal variation is about 8% in summer and 4% in winter. As the average procedure suppresses advectively induced PWV changes to some extent, the mean interhourly variations reflect dew formation and evapotranspiration around the site. This evapotranspiration starts in summer some time after sunrise when the sun radiation has attained some power level, and ceases at sunset. The nearly constant PWV during night in winter indicates insignificant dew or rime formation at the site.

Any ground-based microwave radiometer generates some virtual diurnal course due to the dependence of the radiometric measurements on the ambient temperature. There are two causes for such a virtual diurnal course, the algorithm error and the instrumental error. The algorithm error is due to using nonrepresentative mean radiating temperatures T_{mr} for the two channels. The T_{mr} are a function of the physical temperature of the water vapor and oxygen in the atmosphere and vary diurnally, especially in the boundary layer. The average difference of T_{mr} and their rms, calculated from the morning (0500) and midday radiosonde ascent (1100) throughout one year, were found to +0.58°C and 1.8°C for the 23.8-GHz channel, and 0.31° and 2.4°C for the 31.4-GHz channel, respectively. Their effect on the retrieval accuracy of PWV and CLW is about 0.5% for a typical brightness temperature of 30 K, and thus negligible.

The instrument error is due to temperature effects on the hardware configuration. The WVR-1100 takes into account this hardware dependence with the temperature coefficients determined from tip curves. The temperature coefficients of the gain are determined by performing many tipping curves through a range of ambient temperatures followed by a linear regression fit. However, actual tipping curves are not always available. A thorough analysis of the data used revealed a dependence of noise diode injection temperature of +0.02 K change in noise diode temperature per 1 K change in ambient temperature for the 23.8-GHz channel, and −0.038 K for the 31.4-GHz channel, respectively. The resulting maximum error in PWV is estimated to +0.038 cm PWV (10 K)$^{-1}$ increase in ambient temperature as shown in the appendix. The interhourly change in ambient temperature drawn in the upper panels of Figs. 3a,b is less than 1 K during the time of maximum PWV increase in summer between 1000 and 1400 UTC. The resulting maximum error in the PWV estimate is thus 0.0038 cm PWV or about 20% of the PWV change of Fig. 3.

A more detailed study of the impact of different temperature coefficients and retrieved coefficients of Eq. (1) was performed by numerical experiments. For a single day (20 April 1996) with a distinct diurnal course of the ambient temperature from 9.0° to 27.4°C and with PWV values from 1.04 to 1.41 cm, the results of retrievals with different input data were compared. Using inappropriate temperature coefficients cause almost systematic deviations of 0.23 cm ($\pm$0.01 cm). In the other simulation the less appropriate retrieval coefficients of Eq. (1) for January are used to estimate the PWV content in April. With a bias of 0.22 cm the impact of the diurnal course ($\pm$0.01 cm) is marginal too.

The reliability of the diurnal variations in PWV is supported by collocated simultaneous GPS measurements at the GeoForschungZentrum Potsdam, one of the present International GPS Service Analysis Centres.

Taking into account the extended averaging interval of 2 h and the diurnal components of the GPS values, that is, the ''mapping function,'' the diurnal course in PWV is traceable with reduced amplitude in the 2-h

FIG. 5. Mean hourly deviations of PWV from the daily mean for the two intervals of Figs. 4a (solid box) and 4b (cross).
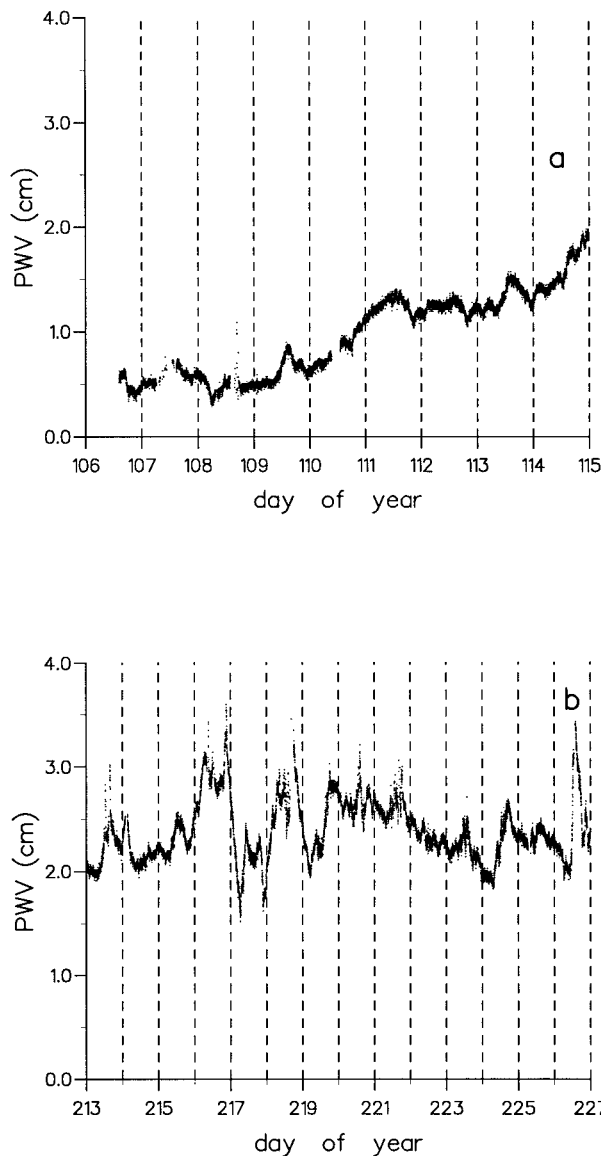

FIG. 4. PWV values during the two special periods from (a) 15 to 23 April 1996 at Lindenberg and (b) 1 to 14 August 1997 at Potsdam.

averages of the available GPS data with a minimum of PWV at 0600 UTC and about 0.1 cm higher averages at 1800 UTC. A more detailed error estimate seems only feasible by extended intercomparison campaigns of radiometers.

Figure 3 is based on all measurements, except those values influenced by rain. To exclude the condensation impact the same exercise was done for two periods with low cloudiness. During the first period within LINEX 96/1 (Fig. 4a) there was a nearly steady increase of PWV from about 0.5 to 2 cm. PWV was rather constant at about 2.5 cm during the second period from 1–14 August (Fig. 4b). The mean difference of the hourly means of each day from the daily mean of PWV, drawn in Fig. 5, shows the maximum PWV at about 1600 UTC in
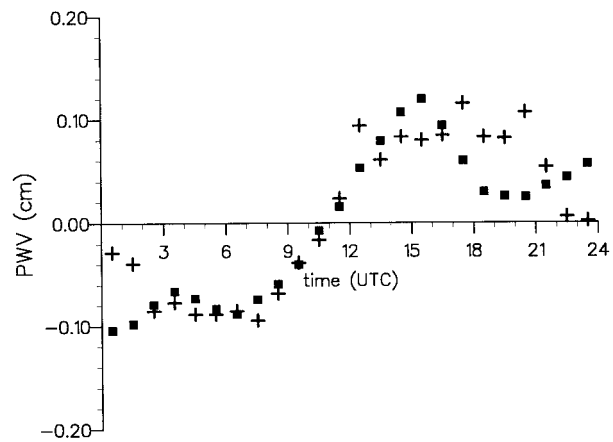
April and a broad maximum in August from 1300 to 2200 UTC. The hourly mean at 1100 UTC corresponds to the daily mean at both periods. The interdiurnal variance of PWV was 0.2 cm or about 10%. The autocorrelation function of PWV calculated from the deviation to the specific daily mean is shown for both periods in Fig. 6. The course of the autocorrelation function confirms the existence of a daily period.

The weak diurnal variation of PWV is not surprising in extratropical latitudes where its variations are caused mainly advectively by synoptic-scale events and weather front passages with periods of several days and hours, respectively (Hogg 1981; Ciotti et al. 1987). Higher frequency fluctuations with frequencies between 0.2 and 2 h^{-1}, corresponding to periods between 30 min and 5 h, observed occasionally by Rogers and Schwartz (1991) and probably caused by convection-induced waves in the boundary layer, are of considerably lesser influence on the mean daily course. The high-frequency
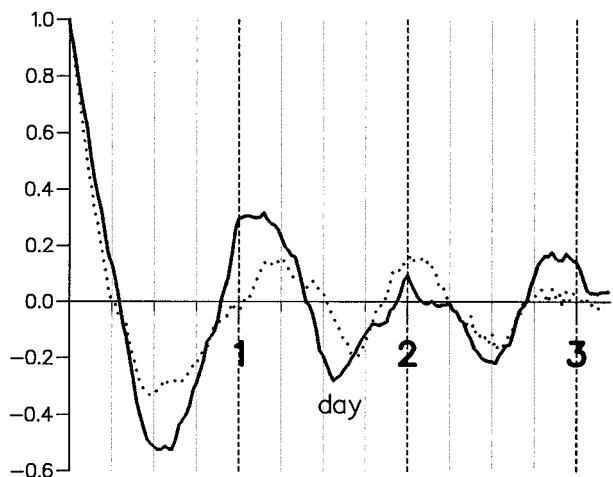

FIG. 6. Autocorrelation function of PWV for the two intervals of Figs. 4a (solid line) and 4b (dashed line).

PWV fluctuations due to the patchy nature of the water vapor distribution are of even lower magnitude and are too irregular to be of relevance in this context. The results of a weak diurnal PWV variation confirm tele-communication attenuation measurements of Szuppa et al. (1995). Pronounced daily amplitudes of as much as 1.5 cm were occassionally observed at Potsdam too (Sierk et al. 1997) as well as by other investigators (Snider et al. 1995).

b. Cloud liquid water (CLW)

CLW monitoring from ground-based microwave ra-diometry is of particular interest as there is presently no alternative approach to measure this parameter rou-tinely. A climatological description of CLW analogous to that of PWV needs some care, however, when related to cloud classes because additional information on the cloud amount within the radiometer's field of view is needed. The appropriate equipment consisting of ceil-ometer and digital camera to gain this additional infor-mation is under preparation.

In the following section, PWV and CLW measure-ments before precipitation events are discussed. Thirty-two cases from June and July 1997 were selected that simultaneously showed beginning of rain in the micro-wave data by strongly increased brightness temperatures in both channels as well as in the ceilometer output. For each such event all PWV and CLW measurements were gathered 2 h before the event and normalized by their differences to the specific mean value of the 2-h interval. The normalized differences are shown in the scatter di-agrams 7a for PWV and 7b for CLW. The diagrams also contain the regression lines for the 30-min subintervals. Despite considerable scatter, particularly in PWV, an increase in both parameters was found in general, es-pecially during the last half hour before raining. About half of the overall enhancement, 42% for PWV and 57% for CLW, took place within the last 30 min. The PWV increase within the 2-h interval was about 0.1 cm, or only about 5% of the mean value in summer. The CLW increase of 0.1 mm is considerable, however, as amounts of 0.3–0.4 mm, depending on season, correspond to precipitation. The corresponding increases in winter (not shown) are only 0.045 cm for PWV and 0.15 mm for CLW. While the CLW increase is only marginal in win-ter, the percentage enhancement of PWV is of the same order of magnitude as in summer. The different seasonal CLW enhancement before precipitation is explained by the fact that summer precipitation is mostly of convec-tive nature with a rather fast buildup of precipitating clouds, while winter precipitation is bounded to frontal passages with a slower buildup rate.

To test the hypothesis that local increases in PWV and CLW are indeed associated with precipitation, the single events of Fig. 7 were analyzed with extended periods of the same summertime that are not associated with precipitation. The nonprecipitating cases were ran-
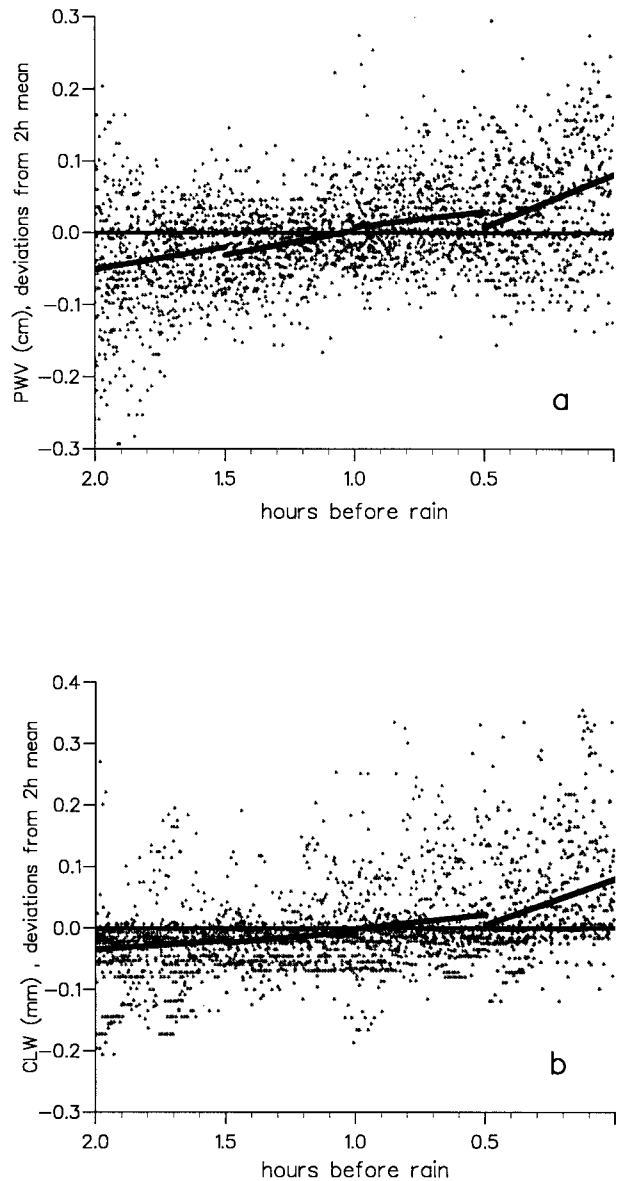
FIG. 7. Deviation of (a) PWV and (b) CLW from corresponding 2-h mean before precipitation in summer from 1 Jun to 31 Jul 1997. Solid lines are linear regressions for 30-min intervals. Note the dif-ferent scale for PWV (in cm) and CLW (in mm).

domly selected with regard to day within the time period and time of day. For each of these, about 60 cases the regression coefficients in PWV and CLW during 1-h periods before precipitation or nonprecipitation were calculated and drawn in Fig. 8. Symbols in the upper-right quarter mean increase in CLW and PWV simul-taneously, symbols in the lower-right quarter mean in-crease in CLW and decrease in PWV, and so forth. Fig-ure 8 gives an increase in CLW of more than 0.02 mm h^{-1} before precipitation in about 70% of cases but only in 7% of cases without precipitation. The corresponding figures for PWV were 82% and 47%, respectively. There
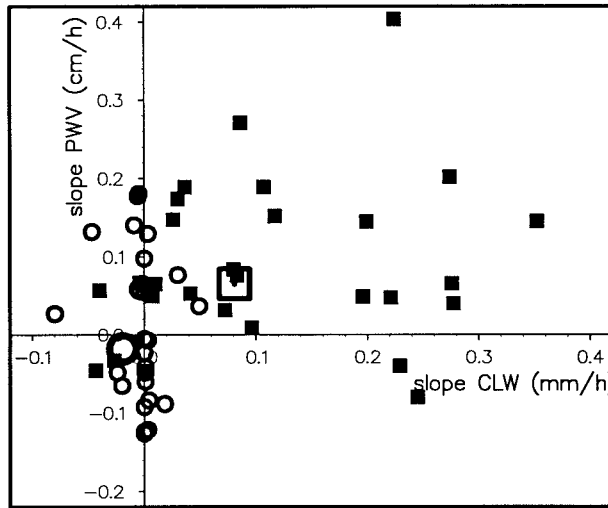
FIG. 8. Scatterplots of trends in PWV (ordinate) and CLW (abscissa) in 1-h intervals before precipitation (solid box) and without precipitation (circles). The corresponding enhanced symbols indicate the position of the average of the ensemble used.

were only two cases where an increase in both parameters, CLW and PWV, was not followed by precipitation, but evaporating precipitation between cloud base and surface cannot be ruled out. Two cases, too, were observed, however, when there was precipitation after decrease of both parameters. Similar figures were obtained for the 2-h interval. Even better results are obtained in case of half-hour intervals as expected from Fig. 7. In summary, the figures are encouraging that the skill of short-term local precipitation forecasts can be enhanced by appropiate ground-based MWR equipment.

4. Summary

Some climatological findings on PWV and CLW in central Europe are given on 2 yr of measurements with a time resolution of 1 min. The diurnal cycle of PWV is only weakly pronounced. The mean overall diurnal variation was about 0.15 cm in summer and 0.05 cm in winter, equivalent to 8% and 5%, respectively. The PWV increase starts in summer at about 0800 local time and has a maximum of about 0.02 cm h^{-1} between 1000 and 1500 local time, equivalent to about 1% PWV h^{-1}. There was, on average, no PWV variation during night in winter. PWV decreased in winter during morning with a maximum of -0.01 cm h^{-1} and increased in the afternoon with a maximum of 0.01 cm h^{-1}. Thus, monthly means of PWV based on monitoring systems with low-time resolution are reliable due to the only slight diurnal course of PWV in central Europe.

On average, an increase in PWV and CLW was found in the last 30 min before precipitation in summer indicating this criterion useful for short-term local precipitation forecast. The PWV increase was, however, only about 0.1 cm or 5% of PWV within the last 2 h

before rain. The corresponding CLW increase was 0.1 mm, which is considerable as precipitation was observed when CLW reached 0.3–0.4 mm.

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APPENDIX

Estimation of the Maximum Uncertainty in PWV by the Instrumental Error

The radiometer has a residual gain dependence upon ambient temperature. An appropriate correction is modeled by temperature coefficients determined by linear regression. The error in PWV as a function of error in the measured sky brightness temperatures T_b due to incorrect temperature coefficients is given by differentiating Eq. (1),

$$\frac{d(\text{PWV})}{dT_b} = c_1 \frac{d\tau_{23}}{dT_b} \epsilon_{23} \Delta T_{b23} + c_2 \frac{d\tau_{31}}{dT_b} \epsilon_{31} \Delta T_{b31}, \quad \text{(A1)}$$

where ϵ_{23} and ϵ_{31} are the estimated errors of the temperature coefficients in the two channels. The dependence of opacity τ_ν upon T_b follows from Eq. (2) to

$$\frac{d\tau_\nu}{dT_{b\nu}} = \frac{1}{(T_{\text{mr},\nu} - T_{b\nu})} \approx \frac{1}{(270 - 30)} \approx 0.004 \quad \text{(A2)}$$

for both channels. With $c_1 \approx 22$, $c_2 \approx -12$ and $\epsilon_{23} \approx 0.02$ and $\epsilon_{31} \approx -0.038$ per 1 K change in ambient temperature the deviation PWV is about $+0.0038$ cm for a 1 K increase in ambient temperature.

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