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The Comparison of IR and MW Ground-Based Measurements of Total Precipitable Water

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Abstract—Water vapor is one of the basic climate gases playing a key role in various processes at different altitudes of the Earth's atmosphere. An intercomparison and validation of different total precipitable water (TPW) measurement methods are important for determining the true accuracy of these methods, the shared use of data from multiple sources, the creation of data archives of different measurements, etc. In this paper, the TPW values obtained from solar IR spectral ~~measurements~~ (~8–9 μm absorption band) and ~~intrinsic~~ MW radiation of the atmosphere (1.35 cm absorption line) for 138 days of observation are compared. Measurements have been carried out from March 2013 at Peterhof station of the St. Petersburg State University in (59.88° N, 29.82° E). It is shown that MW measurements usually give higher TPW values than IR measurements. The bias between the two methods varies from 1 to 8% for small and large TPW values, respectively. With increasing TPW values, the bias reduces and for TPW > 1 cm it is ~1%. Standard deviation (SD) between the two methods reaches 7% for TPW < 0.4 cm and 3–5% for TPW > 1 cm. These data show the high quality of both remote sensing methods. Moreover, the IR measurements have a higher accuracy than MW measurements for small TPW values.

Keywords: total precipitable water, MW method, intrinsic radiation, IR method, solar radiation, radiosounding
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1. INTRODUCTION

Water vapor in the Earth's atmosphere plays a unique role in weather and climate. It is the most important natural greenhouse gas. It is involved in the transfer of latent heat by evaporation and condensation, in a variety of chemical and photochemical processes, and in the formation and transformation of clouds and aerosols. The spatial and temporal variations of water vapor content are monitored both by direct measurements and remote sensing methods. In connection with this, it is important to intercompare and validate different total precipitable water (TPW) measurement methods. In [1], an overview of projects aimed at comparing different TPW measurement methods conducted for the last two decades in different geographical regions was given. In 2009–2012, the ESA DUE Global Vapour project was carried out for the validation of different satellite measurements and the creation of a single database [2]. Different ground-based measurements of water vapor were reviewed in [3]. In [4] and [5], remote and radiosonde/IR spectral TPW measurement methods were compared, respectively.

2. EQUIPMENT AND METHODS OF TPW MEASUREMENTS

This paper analyzes the results of a comparison of TPW ground-based measurements by the IR spectral method using the direct solar radiation and by the MW method using the ~~intrinsic~~ thermal radiation of the atmosphere. Total precipitable water measurements were carried out at the Physical Faculty of St. Petersburg State University (Peterhof, 59.88° N, 29.82° E). Radiosonde data, which were also used in the comparison of the results of TPW IR measurements, were obtained at the station in the village of Voeikovo (59.95° N, 30.70° E).

The spectra of direct solar IR radiation with high spectral resolution were measured using the ground-based spectral complex based on the Fourier spectrometer Bruker IFS-125HR [6]. Measurements were carried out under cloudless atmospheric conditions or in sufficiently large cloud breaks. The water content was determined in six spectral ranges (1110.00–1113.00) cm^{-1}, (1117.30–1117.90) cm^{-1}, (1120.10–1122.00) cm^{-1}, (1196.00–1200.40) cm^{-1}, (1220.50–1221.50) cm^{-1}, and (1251.75–1253.00) cm^{-1}. IR measurements were interpreted using the PROFFIT software package [7]. Measurement details were given in [5]. During the considered period (March 2013 to June 2014), TPW values for 138 days were obtained by us using all available spectral solar radiation measurements in the 8–12 μm spectral window. For the entire ensemble of 936 individual measurements, the TPW total measurement error by matrix computation was (3.6 ± 0.6)%. Its random component was (1.2 ± 0.2)%

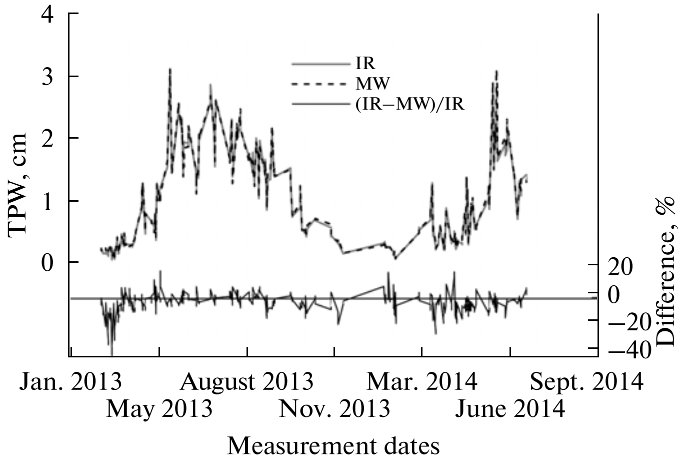

Fig. 1. The time variation of measurement results of the total precipitable water by MW and IR methods and their relative differences.

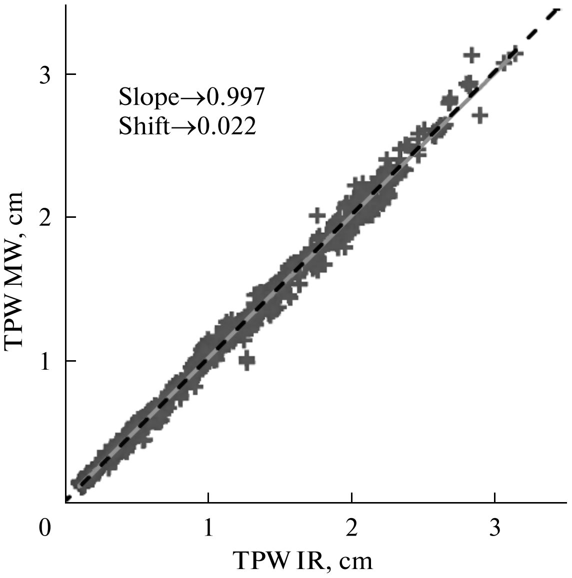

Fig. 2. Scatterplot of TPW values obtained by IR and MW methods.

and systematic was (3.3 ± 0.6)%. Calculations showed that the larger the TPW value is, the higher the random absolute IR measurement errors are, ranging from 0.005 mm for TPW < 0.4 cm to 0.4 mm for TPW > 2 cm. In general, the relative random TPW measurement error changed little because of the random measurement noise and amounted to about 1% over the whole ensemble.

Total precipitable water microwave measurements were carried out using the RPG–HATPRO (Radiometer Physics GmbH–Humidity And Temperature PROfiler) of the German company Radiometer Physics GmbH [8]. The radiometer has seven channels in the oxygen absorption band and seven channels in the 1.35-cm water-vapor absorption band. Total precipitable water is determined by the instrument with an absolute accuracy of ±0.3 mm and with a random error of less than 0.05 mm [8]. Our estimates of TPW fluctuations measured by the instrument at constant TPW values for 5–15 min fully confirmed the estimates of random errors given above. For small TPW values (less than 0.4 cm), relative random MW errors are ~2%; total error can reach ~10–15%. This is because of the fact that the atmospheric absorption is small in the used water vapor absorption band. In the case of medium and large TPW values, the random error of the MW method is less than 1%. Based on these figures, the MW method should have some advantages over the IR method at TPW > 1 cm. For small TPW values, the IR method has undoubted advantages.

Radiosondes AK2-02, which measure altitude profiles of relative humidity, temperature, and wind conditions, are regularly launched at the Roshydromet radiosounding station in the village of Voeikovo. The accuracy error of radiosonde measurements of the total precipitable water in the troposphere is on average 5–10% [9, 10]. Errors of TPW measurements using the radiosonde depend on the correlation degree between humidity measurement errors at different levels and cannot exceed the specified error for the humidity profile in the troposphere. It is important to mention that the distance between Peterhof and Voeikovo is about 50 km, and the discrepancies between the radiosonde measurements and measurements in Peterhof can be to a great extent caused by spatial and temporal variations in total precipitable water [5].

3. COMPARISON RESULTS

The ensemble of comparisons of IR and MW measurement was synchronized as much as possible taking into account continuous MW measurements at intervals of 2 s. The MW measurement results were averaged over the time of IR measurements (about 12 min). Figure 1 shows the time course of TPW IR and MW measurements for the considered period and their relative difference. The time variation of TPW values themselves is almost indiscernible in the plot. However, as is evident from the given difference, on average, the discrepancy between the two methods is usually in the range of 5–10%. Figure 2 presents the same data but in the form of a scatterplot of simultaneous TPW measurements by IR and MW methods. Figure 2 also provides the value of the slope of IR measurements to MW measurements. It is close to unity, which indicates that the absolute discrepancy between the two TPW measurement methods does not depend on the TPW value itself. The magnitude of the shift of TPW MW measurements to IR measurements (0.022 cm) indicates that MW measurements are generally higher than TPW IR measurements. Figure 2 also shows that

Features of biases for four subensembles of TPW values (mean values and standard deviations from the mean values were used as biases)

Ensemble	Number of comparisons	Absolute bias, cm	Relative bias, %	Correlation coefficient
TPW < 0.4 cm	266	−0.021 ± 0.020	−8 ± 7	0.971 ± 0.004
1 cm < TPW < 0.4 cm	280	−0.025 ± 0.039	−4 ± 6	0.981 ± 0.002
1 cm < TPW < 2 cm	236	−0.012 ± 0.067	−1 ± 5	0.971 ± 0.004
TPW > 2 cm	132	−0.019 ± 0.077	−0.8 ± 3.0	0.960 ± 0.007

the higher the absolute TPW values are, the greater the variation between IR and MW measurements is.

Subensembles for four TPW bands were formed for a more detailed analysis: less than 0.4 cm, 0.4–1.0 cm, 1.0–2.0 cm, and more than 2 cm. The basic statistical characteristics of discrepancies between IR and MW measurements for different TPW ensembles are given in the table.

Features noted in the figure quantitatively manifest themselves in mean discrepancies. For TPW ensembles of less than 0.4 cm, the MW method gives values that are 8% greater than the values given by the IR method, for ensembles of 0.4–1.0 cm it gives values 4% greater, and for ensembles of 1.0–2.0 cm and for TPW values greater than 2 cm, they are ~1% greater. When considering absolute discrepancies, it can be seen that for almost all subensembles (except for the ensemble with TPW values within 1–2 cm), the MW method overestimates the obtained TPW values compared to the IR method by about 0.02 cm, which is within the estimated MW method absolute error of 0.03 [8]. This bias can be caused by errors in setting of spectral information in the 1.35 cm water absorption band. Thus, according to the estimates in the HITRAN2008 database [11], this bias for the band intensity is ~1% and, for the halfwidth, ~20%. In relative units, standard deviations (SDs) from the mean discrepancies decrease with increasing TPW values from 7 and 3%. The correlation coefficients between the two remote measurements for different TPW subensembles are from 0.960 ± 0.007 to 0.981 ± 0.002.

Comparisons of the TPW IR measurement results in Peterhof with the radiosonde measurements in the village of Voeikovo confirmed the conclusions of [5] that the spatial variations in total precipitable water contribute significantly to these differences. The correlation coefficient between IR and radiosonde measurements was 0.945 ± 0.004 and mean discrepancy was 0.005 cm, but, in this case, SD was ~0.24 cm (about 25%). Note that, in addition to spatial differences, there are also temporal ones, i.e., in order to obtain a sufficiently representative ensemble, we compared individual TPW IR measurements obtained within 3 h from the radiosonde launch. Thus, the 582 TPW IR measurements were compared with data from 105 radiosondes (105 days in 2013–2014).

Different remote TPW measurements were compared in many papers. The radio refractive (GPS) measurement method, direct solar radiation absorption measurement in the NIR band by different photometers, solar radiation absorption measurement in the IR spectral bands by Fourier spectrometers, measurements of intrinsic MW atmospheric radiation, lidar method, different radiosondes, and various satellite techniques and tools were compared [3]. There were relatively few actual IR and MW measurements. Thus, in [1, 12] TPW measurements obtained using IR and MW methods were compared. However, MW measurements were carried out using instruments that were designed to measure not the total precipitable water, but the content of other gases, such as ozone. In these experiments, TPW values were found in order to eliminate the influence of the tropospheric water vapor on the atmospheric radiation in the ozone emission band. In this regard, TPW MW measurement accuracies were not optimal. The mean discrepancy between TPW MW and IR measurements were from –1.9% (0.02 cm) to 8.22% (0.09 cm) and for SD from 12.8% (0.092 cm) to 29.3% (0.108 cm).

4. CONCLUSIONS

The method of the TPW IR spectral measurement by the direct Sun and MW measurement method of the ~~intrinsic~~ atmospheric radiation were compared for 138 days of observations during the period from March 2013 to June 2014 in Peterhof (59.88° N, 29.82° E). Both measurement methods were synchronized in time as much as possible. It was shown that MW measurements give higher TPW values than IR measurements, and this bias reaches 8% for small TPW values. With increasing TPW values, this bias decreases, and for TPW > 1 cm it is ~1%. The standard deviation between the two methods reaches 7% for TPW < 0.4 cm. With increasing TPW values, it reduces, and for TPW > 1 cm it is 3–5%. These data confirm the high quality of remote sensing methods. Moreover, the IR measurements have advantages compared with MW measurements (the 1.35 cm absorption band) for small TPW values. Differences in TPW measurement results in Peterhof from the radiosonde data from the village of Voeikovo (59.95° N, 30.70° E) are much greater (SD is ~25%), which confirms the conclusions of [5] on the significant influence of spatial and temporal variations of water vapor on values of discrepancies.

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