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REMOTE SENSING OF ATMOSPHERE, HYDROSPHERE, AND UNDERLYING SURFACE

Comparison of Ground-Based Microwave Measurements of Precipitable Water Vapor with Radiosounding Data

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Abstract—Microwave (MW) radiometers are widely used for monitoring the precipitable water vapor (PWV), which is a key greenhouse gas in the Earth's atmosphere. Different measurement campaigns are carried out to estimate the accuracy of MW measurements of PWV. In this work, we compare the results of PWV measurements performed with a ground-based MW radiometer RPG-HATPRO at the Peterhof station of Saint Petersburg State University with radiosounding data from the Voyeykovo station. More than 850 measurements (at the day and nighttime) in the period from March 13, 2013, to May 31, 2014, are included in the comparison. It is shown that the discrepancy of PWV values measured with both methods is caused by the errors of the methods and by the spatial inhomogeneity of the PWV field. The discrepancy can attain tens of percent, which is to be taken into account in the intercomparison and validation of different methods for PWV retrieval. Exclusion of the cases with strong spatial inhomogeneity allowed reducing the mean deviations between MW and radiosounding measurements to 3–4% and the standard deviations between two sets of measurements to 12–14%.

Keywords: precipitable water vapor, MW radiometer, radiosounding

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INTRODUCTION

Ground-based microwave (MW) atmospheric sounding techniques are widely used today for acquisition of data on the air temperature and humidity, content of ozone and other climatically important gases, water content of clouds, and precipitation intensity [1–7]. Limited-edition instruments for tropospheric studies (PM-5 MW profilers for measurements of temperature profiles in the boundary air layer; RPG-HATPRO, MP-3000A, and Microradkom radiometers) are produced in Russia [7, 8], Germany (Radiometer Physics GmbH), and the United States (Radiometrics Corporation). The International MW atmospheric sounding network MWRnet (An International Network of Ground-based Microwave Radiometers) currently operates [9]. Some scientific institutions use their own instruments; for example, relatively simple dual-channel MW radiometers have been designed and are produced for estimation of the integral water vapor and water vapor of clouds [10].

Estimation of remote MW measurement errors under different operating conditions is an important problem. The errors of remote measurements of precipitable water vapor (PWV) are of special importance, since this gas is a key greenhouse gas in the Earth's atmosphere. Works [11–23] are devoted to comparison of MW and radiosonde measured PWV. Results of comparison of MW and spectroscopic IR measurements of PWV are analyzed in [24].

In this work, we compare PWV MW measured near St. Petersburg (Peterhof) with the radiosounding data from Voyeykovo station. This comparison allows estimation of MW-measured PWV under conditions of the spatially homogeneous humidity field, and the value of the inhomogeneities under spatial variations in PWV, which is the aim of this work.

1. PWV MEASUREMENTS

1.1. MW Measurements

RPG-HATPRO MW radiometer (Radiometer Physics GmbH—Humidity And Temperature PROfiler) produced by Radiometer Physics GmbH (Germany) [25] has seven channels in the region of oxygen absorption band at 0.5 cm and seven channels in the region of water vapor absorption band at 1.35 cm. The radiometer measures the temperature and humidity profiles in the troposphere and liquid water in clouds. It is mounted on a mast on the roof of the Institute of Physics, St. Petersburg State University (59°53′ N, 29°50′ E). The radiometer operates permanently; the measurements are carried out in the zenith direction

Table 1. Parameters of daytime (12:00 UTC) and nighttime (00:00 UTC) ensembles of PWV measured in Voyeykovo and Peterhof

Measurements	Mean PWV, mm	Standard deviation		Value, mm	
		absolute, mm	relative, %	maximum	minimum
Daytime (Voyeykovo)	13.27	7.32	55.2	1.74	46.53
Nighttime (Voyeykovo)	14.96	8.44	56.4	2.11	41.58
Daytime (Peterhof)	14.51	8.67	59.8	1.43	41.38
Nighttime (Peterhof)	14.35	8.84	61.6	1.01	56.90

(main mode) and in the angular scanning mode (additional mode).

The radiometer is regularly calibrated by an operator using liquid nitrogen according to the operational requirements. PWV is measured by the radiometer with an absolute error of ± 0.3 mm and a random error of less than 0.05 mm [25]. The analysis of PWV fluctuations retrieved from measurements at St. Petersburg State University during 5–15 min (at fixed PWV values) allowed upper estimation of the random measurement error [24]. This error was within the limits of 0.050–0.057 mm for different PWV values, which is very close to the above-mentioned random error.

1.2. Radiosonde Measurements

Radiosondes are regularly launched (twice a day) at the Roshydromet radiosounding station in Voyeykovo (20 km to the east of St. Petersburg, 59°57′ N, 30°42′ E); they are used for measurements of the altitude profiles of the relative humidity, temperature, and wind parameters. The radiosonde data are published on website [26]. The mean radiosonde measurement error of the tropospheric water vapor is 5–10% and higher [27]. Altitude profiles of the relative humidity received from the radiosounding measurements at Voyeykovo st. (launches at 00:00 and 12:00 UTC) were integrated over altitude to retrieve PWV for days when PWV MW measurements were carried out in Peterhof.

The radiosounding PWV errors depend on the degree of correlation of the humidity measurement errors at different altitudes and cannot exceed the mentioned errors for the humidity profile in the troposphere. It is important that the distance between Peterhof and Voyeykovo is ~50 km; hence, the discrepancy between the radiosonde and MW measurements in Peterhof can be sometimes caused by spatiotemporal variations in the water vapor content [28].

2. PWV MEASUREMENTS IN PETERHOF AND VOYEYKOVO

The number of measurements differs significantly for different instruments. A radiosonde measures twice a day, at 00:00 and 12:00 UTC. The MW radiometer performs about 30–50 thousand measurements a day (every 2 s). Every radiosonde value was matched with a PWV value averaged over 15 min of MW measurements beginning from the radiosonde launch. To characterize the water content in Voyeykovo and Peterhof, the mean PWV and the standard deviations were calculated for day and nighttime measurements, and the minima and maxima were chosen. The comparisons were carried out only for events without precipitation, but in different states of the cloudy atmosphere. Radiosounding and MW measurement data are characterized in Table 1.

The nighttime mean PWV are higher than the daytime mean in Voyeykovo; the daily variation in the mean values is 1.69 mm. Vice versa, the daytime means PWV are higher than the nighttime means in Peterhof, and the daily variation of the mean is an-order-of magnitude lower than in Voyeykovo (0.16 mm). The daytime mean PWV in Voyeykovo is noticeably lower (13.27 mm) than in Peterhof (14.51 mm); the difference is 1.24 mm. The nighttime mean PWV are close at two sites (14.35 and 14.96 mm), and the difference between them is two times lower (0.61 mm). The standard deviation of PWV from the mean is higher in Peterhof than in Voyeykovo. The standard deviation in Voyeykovo in daytime is lower than in nighttime (the difference is 1.12 mm), and they are close in Peterhof (the difference is 0.17 mm). The amplitude of variations (the difference between the minimum and maximum) in PWV is maximal in nighttime in Peterhof (55.89 mm) and minimal in nighttime in Voyeykovo (39.47 mm). The above differences are caused by closeness of Peterhof to the Gulf of Finland.

Figure 1 shows the histograms of PWV distributions at two measurement sites. The above brief analysis and Fig. 1 show that radiosonde and MW radiometer measurements are carried out in close though different states of the atmosphere.

3. RESULTS OF COMPARISON

PWV values measured with the RPG-HATPRO MW radiometer (Peterhof) and radiosondes (Voyeykovo) have been compared for the period from March 13, 2013, to May 31, 2014 (427 daytime and 437 nighttime comparisons in total). Figure 2 compares PWV measured by two methods in day and nighttime, as well as the differences between them in

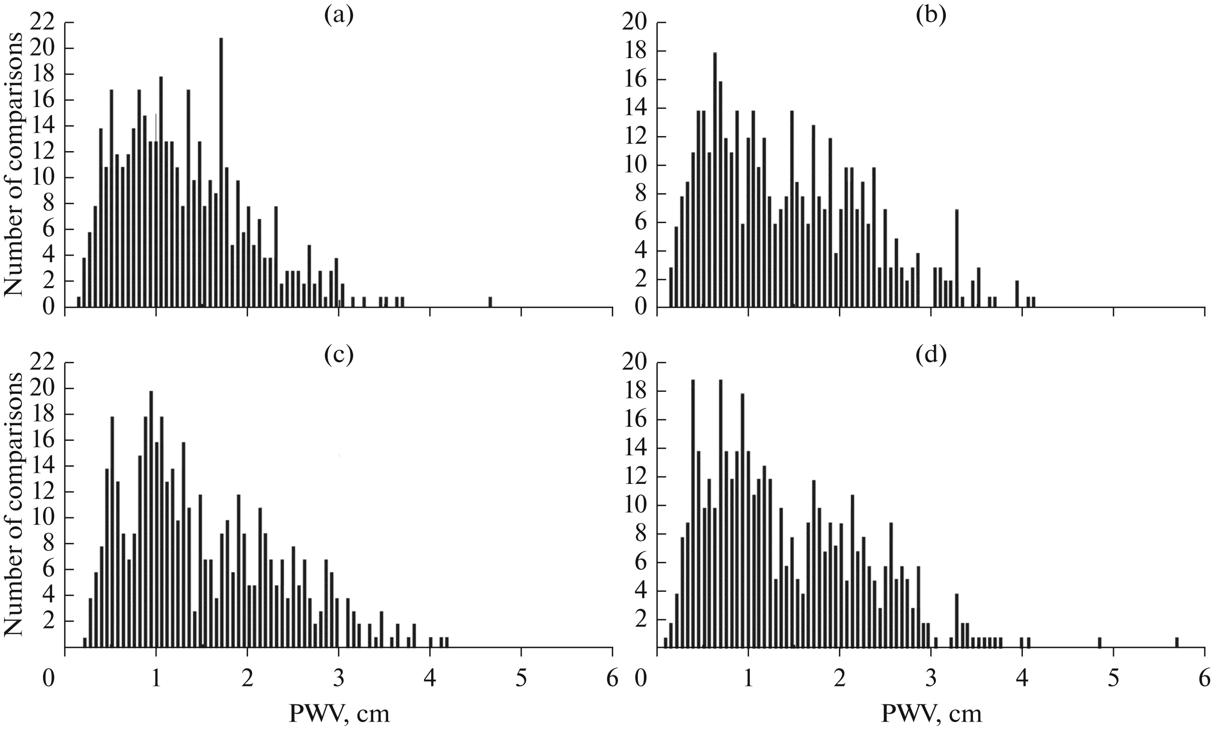

Fig. 1. Histograms for PWV measured with a radiosonde in (a) daytime (12:00 UTC) and (c) nighttime (00:00 UTC) and with the MW radiometer in (b) daytime (12:00 UTC) and (d) nighttime (00:00 UTC).

percentage (right scale). The relative difference in nighttime changes from –103 to 47%. The difference in nighttime is lower; it changes from –76 to 48%.

For daytime measurements, 24% of absolute values of all relative differences do not exceed 5% (23% for nighttime measurements), and 68% of absolute values of all relative differences do not exceed 20% (75% for nighttime measurements). Figure 3 shows the histograms of differences between the two measurement types.

The differences between two measurements are equal to radiosonde measurements minus MW measurements. Therefore, the histograms show that the MW method provides for higher PWV values in daytime (the histogram is shifted toward negative values) and lower PWV values in nighttime (the histogram is shifted toward positive values). Statistical characteristics of the comparisons between these two methods are given in Table 2.

Table 2 shows that the rms differences are 2.93 mm (19.6%) in daytime and 3.34 mm (25.2%) in nighttime. It also shows numerically that the daytime MW measurements are higher than radiosonde values by 1.24 mm (9.3%) on the average, and nighttime MW measurements are lower by 0.608 mm (4.1%). The standard deviations (due to small mean deviations) are close to rms differences. The correlation coefficients between both measurement types are high; the highest coefficient is observed for nighttime measurements (0.946).

Based on Table 2, one may conclude that nighttime MW measurements are more accurate, since they differ weakly from those from the radiosonde. However, this can also show that atmospheric conditions in Peterhof and Voyeykovo are closer in nighttime (see

Table 2. Parameters of discrepancies between radiosonde and MW measurements

Measurements	Number of comparisons	Rms difference		Mean deviation		Standard deviation from the mean deviation		Correlation coefficient
		mm	%	mm	%	mm	%	
Nighttime	437	2.93	19.6	0.61	4.1	2.87	19.2	0.946 ± 0.005
Daytime	427	3.34	25.2	–1.24	–9.3	3.10	23.4	0.939 ± 0.006
Diurnal	864	3.14	22.2	0.31	–2.2	3.13	22.1	0.934 ± 0.004

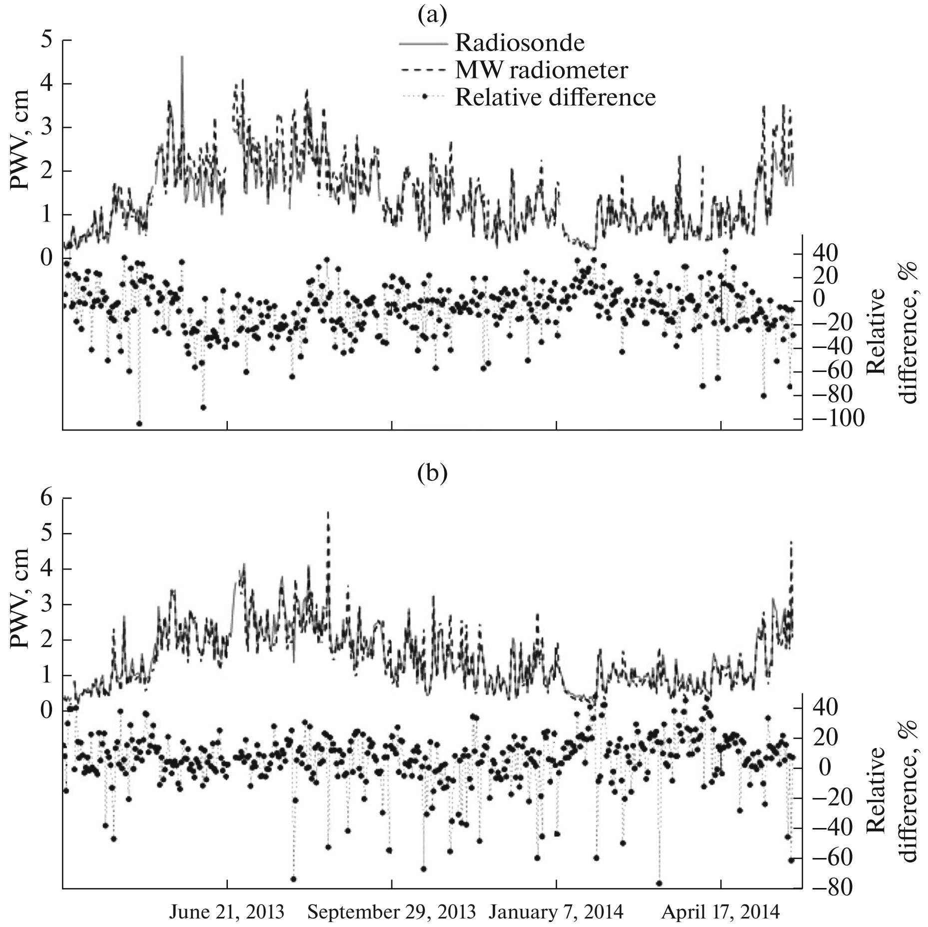

Fig. 2. PWV measured with a radiosonde and the MW radiometer and their relative difference (%): (a) daytime and (b) nighttime.

Table 1). Radiosonde data are mostly higher than MW measurements in nighttime and vice versa in daytime.

Figure 4 shows the dependencies of relative differences between the two measurement types (in percentage) on nighttime and daytime PWV. The relative differences increase as the PWV decrease on the average, as could be expected.

The discrepancy of PWV values measured with the two methods is caused by the errors of the methods and by the spatial inhomogeneity of the PWV field. It is known that spatial variations in PWV are mesoscale (see, e.g., [29]). The distance between the two sites (~50 km) results in differences in PWV in Peterhof and Voyeykovo of more than 100% due to the horizontal inhomogeneity of the atmosphere [28].

4. ANALYSIS OF THE EFFECT OF SPATIAL INHOMOGENEITY OF THE HUMIDITY FIELD

As already mentioned, the spatial inhomogeneity of the air humidity field definitely contributes to the discrepancy between the two measurement types. In

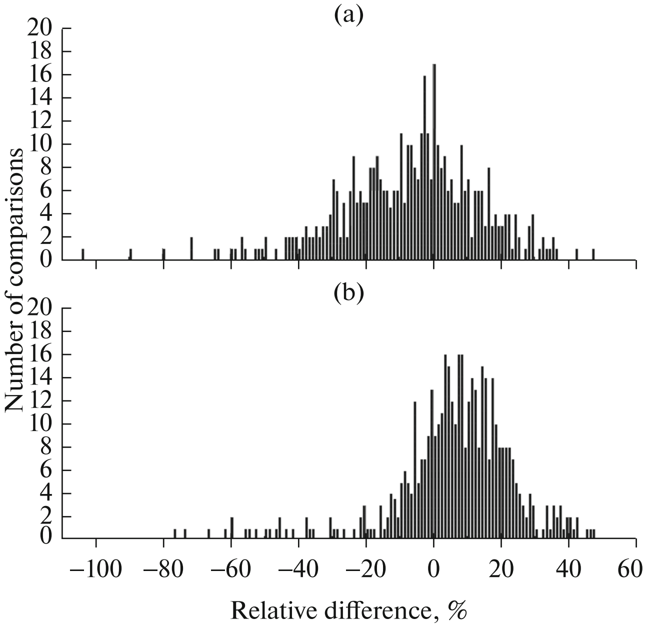

Fig. 3. Histograms for the relative difference in radiosonde and MW measurements: (a) daytime and (b) nighttime.

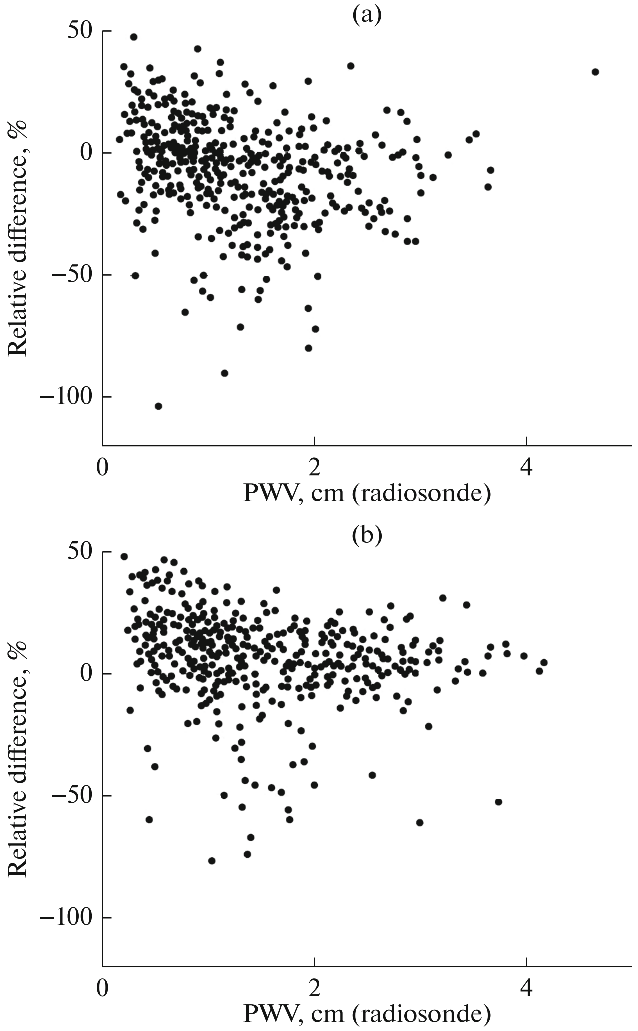

Fig. 4. Relative difference between radiosonde and MW measurements on the radiosonde PWV: (a) daytime and (b) nighttime.

many comparisons (in particular, ground-based and satellite), time variations in the air humidity significantly contribute into the discrepancy. In our comparison, this source of discrepancy is excluded because of time matching of the two measurement types.

To decrease the effect of spatial inhomogeneity of the humidity field in the comparison of radiosonde measurements in Voyeykovo and MW measurements in Peterhof, the time dependencies of these measurements have been analyzed. This analysis allows formation of a new ensemble of comparisons on the basis of exclusion of the events of sharp variations in PWV (by more than 40–50% a day) at one or both measurement sites or of oppositely directed variations in PWV at the stations. Table 3 presents the statistical parameters of PWV comparisons for this subensemble 1.

These data shows that the daytime mean and standard deviations are noticeably lower and the correlation coefficients are higher for subensemble 1. This witnesses that the effect of spatial inhomogeneity of the humidity field is weaker for this subensemble. Further, the relative difference between the ground-based measurements of the absolute humidity in Voyeykovo and Lomonosov (3 km from Peterhof) has been selected as the criterion of humidity field inhomogeneity. Each ensemble of comparisons (day and nighttime) was divided into four subensembles according to the humidity field inhomogeneity criterion: the relative difference between the absolute humidity in Voyeykovo and Lomonosov is from 0 to 3, from 3 to 6, from 6 to 15% and is higher than 15%.

New computations for daytime conditions have shown that consideration of the ground-based measurements of the absolute humidity allowed a reduction of the discrepancy in the standard deviation between MW and radiosonde measurements down to 12% for the absolute humidity difference from 0 to 15% and a sharp increase in the discrepancy between measurements in Voyeykovo and Peterhof up to 21% for the absolute humidity difference higher than 15%.

5. DISCUSSION OF THE RESULTS

Results of the comparison of PWV measured with MW radiometers (in the water vapor absorption line at 22 GHz) and radiosondes are presented in Table 4. The mean and standard deviations and the correlation coefficients are tabulated.

The measurements with different types of radiosondes in comparison with MW PWV measurements were analyzed in [12]. The dual-channel MW radiometer used in the comparison measured the downward radiation of the atmosphere in and out of the water vapor absorption line (22.6 and 31.6 GHz). The comparison was carried out in summer of 1987 in Denver (United States). The discrepancies in Table 4 are quite high; they are 0.75–3.21 mm for the standard devia-

Table 3. Parameters of discrepancies between radiosonde and MW measurements for subensemble 1

Measurements	Number of comparisons	Mean deviation		Standard deviation from the mean deviation		Correlation coefficient
		mm	%	mm	%	
Nighttime	254	−0.44	−3.4	1.87	14.4	0.974 ± 0.003
Daytime	295	0.72	4.5	1.84	11.6	0.978 ± 0.003

Table 4. Examples of comparison of MW and radiosonde PWV measurements

Example	Deviation, mm		Correlation coefficient	Number of comparisons	Site, period	Ref.
	mean	standard				
1	1.11–2.7	1.04–2.62		28–89	Denver, USA, June–August, 1987	[12]
	1.62–3.21—day	0.70–1.22		16–19		
	0.75–2.03—night	0.75–2.03		12–28		
2	–1.18	3.02	0.950	1573	Central Italy, August, 2002–December, 2003	[18]
3*	0.11—A	~2			Switzerland,	[19]
	–0.12—B		0.970	183	2003–2004	
	0.14—C		0.970	169		
	–0.35—D		0.996	3072		[20]
	0.40—D^1				1994–2007	[21]
4	Payerne—0.20	2.00		2723	Switzerland, 1994–2007	[22]
	Thun—0.37	2.50		164		
5	0.61—night	2.90	0.946	437	Peterhof–Voyeykovo, 2013–2014	This work
	1.24—day	3.10	0.939	428		
6	0.71—night	1.87	0.978	295	Peterhof–Voyeykovo, 2013–2014	This work
	0.44—day	1.84	0.974	254		

* Example 3: comparison with the TP/WVP-3000 MW (A) and ASMUWARA (B) radiometers, comparison between two radiometers TP/WVP-3000 and ASMUWARA (C), TROWARA radiometer (D) and after correction (D^1).

tions. It could be also noted that they are higher in the daytime, which, in the opinion of the authors of the work, is connected with the temperature effect on the MW radiometer operation and, mainly, with the solar radiation effect on the radiosonde readings. Later, these comparisons allowed one to reveal and exclude many causes of low-quality measurements for both MW radiometers and different radiosonde types.

PWV measurements with dual-channel MW radiometers and radiosondes in Central Italy are compared in [18]. The mean deviations were –1.18 mm, and standard deviations, 3.02 mm (despite geographic proximity of sites where these two measurement types were carried out ~2 km). The long-term study of MW PWV measurements were carried out at the Institute of Applied Physics (Bern, Switzerland) [19–22]. Table 4 presents the results of comparison of different MW radiometers (TP/WVP-3000, ASMUWARA, and TROWARA) with radiosondes, and of intercomparison of the TP/WVP-3000 and ASMUWARA radiometers. Absolute values of the systematic differences between the two measurement types are 0.11–0.35 mm for different radiometers, and rms differences are ~2 mm. Comparison 4 is given for two radiosondes located at a distance of 40 km (Payerne) and 25 km (Thun) from the TROWARA MW radiometer. It is noted that the differences are mainly caused by different atmospheric state at three measurement sites. It is of interest that rms differences are minimal (0.37 mm) for the comparison between two MW radiometers TP/WVP-3000 and ASMUWARA.

Comparison of MW and radiosounding data at St. Petersburg State University (example 5, Table 4) shows high mean and standard deviations, which is caused by a large distance between the two sites (50 km). Close standard deviations were observed during the comparison of TROWARA radiometer data (~2 mm) with radiosounding data at a distance of ~40 km [20]. Thus, horizontal inhomogeneity of the water vapor field should be accurately considered in some problems, e.g., during validation of satellite measurements. Exclusion of the strongest effect of the spatial inhomogeneity (example 6, Table 4) noticeably decreased the standard deviations between MW and radiosounding data. The mean (3–4%) and standard deviations (12–14%) (example 6, Table 4) upper estimate the difference between MW and radiosonde PWV caused by the errors of the two measurement types.

Spectroscopic IR method for PWV measurements was compared with the MW method for 138 days of measurements in Peterhof in the same period of observations in [24]. It was shown that MW measurements provide for higher PWV than IR measurements, and the difference attains 8% at small PWV. This difference decreases with an increase in PWV and is ~ 1% at

PWV above 10 mm. The standard deviations between the two methods attain 7% at PWV below 4 mm; it decreases with an increase in PWV and makes 3–5% at PWV above 10 mm. If rms errors of MW measurements are assumed to be ~5–7%, and of radiosonde measurements, ~5%, then the differences in PWV measurements (example 6, Table 4) are close to the total contribution of the measurement errors of these two measurement methods.

CONCLUSIONS

We have compared ground-based RPG-HATPRO MW radiometer measured PWV (Peterhof) with radiosounding data from Voyeykovo. The stations are spaced 50 km apart. More than 850 measurements (at the day and nighttime) in the period from March 13, 2013, to May 31, 2014, have been included into the comparison. Every radiosonde value (measurements start at 12:00 and 00:00 UTC) was matched with a PWV value found from averaging over MW measurements during 15 min after the radiosonde launch. The both methods were maximally matched in time. The analysis of MW and radiosonde measurements showed that they were carried out in close though different states of the atmosphere. This allows a conclusion that spatial inhomogeneity of water vapor is a key factor that affects that quality of validation of different measurement types.

For daytime measurements, 24% of absolute values of all relative differences do not exceed 5% (23% for nighttime measurements), and 68% of absolute values of all relative differences do not exceed 20% (75% for nighttime measurements).

The daytime MW measurements are higher than radiosonde values by 1.24 mm (9.3%) on the average, and nighttime, by 0.608 mm (4.1%). The rms differences are 2.93 mm (19.6%) in nighttime and 3.34 mm (25.2%) in daytime. The correlation coefficient between both measurement types are the highest for nighttime measurements (0.946). The discrepancy between PWV values measured with the two methods is caused by both the errors of the methods and the spatial inhomogeneity of the PWV field in the atmosphere.

To minimize the effect of spatial inhomogeneity of the humidity field, a new ensemble of comparisons has been formed by means of exclusion of the events of sharp variations in PWV (by more than 40–50% a day) at one or both measurement stations or of oppositely directed variations in PWV at the stations. The daytime mean and standard deviations are noticeably lower for the new subensemble, and the correlation coefficients are higher. The mean (3–4%) and standard deviations (12–14%) provide for the upper estimate of the discrepancy between the MW and radiosonde PWV measurements caused by the errors of the two measurement types. If the rms errors of MW measurements are assumed to be ~5–7% (from the analysis of results of work [24]), and of radiosonde measurements, ~5%, then one can see that the differences in PWV measurements are close to the total contribution of the measurement errors of these two measurement methods.

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