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Comparison of Ground-Based FTIR and Radio Sounding Measurements of Water Vapor Total Content

A. O. Semenov, Ya. A. Virolainen, Yu. M. Timofeyev, and A. V. Poberovskii

Saint Petersburg State University, ul. Ul'yanovaskaya 1, Petrodvorets, St.-Petersburg, 198504 Russia
e-mail: aleksem@mail.ru, Yana.Virolainen@spbu.ru, tim@JT14934.spb.edu, avpob@troll.phys.spbu.ru

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Abstract—We compared two datasets of the total content of atmospheric water vapor received near St. Petersburg in 2009–2012 from ground-based Fourier transform spectroscopy measurements at the Peterhof station and from radio sounding at Voyeykovo station. Despite a good correlation of daily measurements in Peterhof and Voyeykovo, the standard mismatch is significant, 20% or more, for most subsets taken for the comparison. The high mismatch is mainly due to the natural spatial variability of the total content of water vapor, accounting for the 50-km distance between Peterhof and Voyeykovo. This variability needs to be considered when validating the satellite measurements of water vapor content by ground-based measurements.

Keywords: water vapor, Fourier spectrometry, radio sounding

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INTRODUCTION

Water vapor is one of the most important natural greenhouse gases; it plays a great role in different physical and chemical processes in the Earth's atmosphere [1]. There are many various local and remote methods for studying its spatial and temporal variations; however, there are cases when it is difficult to estimate accurately water vapor measurement errors.

Techniques for measuring the water vapor content (ground-based, airborne, satellite, local, and remote) were compared many times (see, e.g., [2]). In this work, we compare radio sounding (Voyeykovo station) and ground-based Fourier-transform IR (FTIR) spectroscopy (StPSU, Peterhof) data on the water vapor total content (TC). Depending on the state of the atmosphere, the comparison data provide for information either about the spatiotemporal inhomogeneity of the water vapor TC at a measuring site (the sites are spaced apart by about 50 km) or about agreement between two types of observations.

GROUND-BASED FTIR SPECTROSCOPY

Spectra of direct solar radiation are measured with a ground-based spectral complex based on a high-resolution Bruker IFS-125HR spectrometer at the Department of the Physics of Atmosphere, Physical Faculty, St. Petersburg State University (in Peterhof, 35 km to the south-west of the center of St. Petersburg, 59°53′ N, 29°50′ E, 36 m above sea level) [3]. The measurements are carried out under clear sky or quite large cloud breaks. The FTIR measurement data were interpreted using the PROFFIT software complex [4] developed at Karlsruhe University (Germany) and used at stations of the Network for the Detection of Atmospheric Composition Change (NDACC). Meteorological data (pressure and temperature profiles) received via automated electronic mail from NASA GODDARD SPACE CENTER [5] and a priori data on atmospheric parameter profiles on the basis of the Whole Atmosphere Community Climate Model (WACCM) data [6] were specified for each day of FTIR measurement at Peterhof station. The HITRAN-2008 database [7] was used as a source of data on parameters of the fine structure of absorption lines. The water vapor TC was calculated using the solar radiation spectra measurements (with a resolution of ~0.005 cm^{-1}) in six spectral ranges: 1110.00–1113.00, 1117.30–1117.90, 1120.10–1122.00, 1196.00–1200.40, 1220.50–1221.50, and 1251.75–1253.00 cm^{-1}. In addition to water vapor absorption lines, absorption in N_2O, CO_2, CH_4, and O_3 lines was considered and refined. Random errors of FTIR measurements of the water vapor TC are estimated to be 1–2%, and systematic errors, 3–5% [8]. The total error is estimated to be about 5%.

RADIO SOUNDING MEASUREMENTS

Radio sounders are regularly (twice a day) launched at the Roshydromet radio sounding station in Voyeykovo vil. (20 km to the east of the center of St. Petersburg, 59°57′ N, 30°42′ E, 78 m above the sea level); they measure altitude profiles of relative humidity, temperature, and wind parameters. Data received from a radio sounder are published in the central radio sounding archive on the site [9]. The

Comparison parameters of different data subsets for two types of measurements

Comparison type, limitations	Number of comparisons	Absolute mismatch ($M \pm S$), kg/m^2	Relative mismatch ($M \pm S$), %	Correlation coefficient
Daily average FTIR and daytime radio sounding measurements				
All comparisons	182	–0.27 ± 2.62	–2.34 ± 21.2	0.956 ± 0.006
Wind:				
north	27	–0.19 ± 1.85	–3.97 ± 18.4	0.973 ± 0.010
east	46	0.30 ± 3.02	3.03 ± 21.8	0.954 ± 0.013
south	47	–0.32 ± 2.93	–2.21 ± 26.5	0.953 ± 0.013
west	62	–0.69 ± 2.33	–4.72 ± 17.1	0.955 ± 0.011
strong	107	–0.31 ± 2.89	–1.91 ± 23.5	0.939 ± 0.011
weak	75	–0.21 ± 1.17	–2.95 ± 17.53	0.974 ± 0.006
Winter	30	–0.38 ± 0.69	–10.9 ± 21.0	0.860 ± 0.048
Spring	65	0.27 ± 2.59	2.38 ± 27.2	0.903 ± 0.023
Summer	67	–0.47 ± 3.26	–1.18 ± 15.9	0.871 ± 0.030
Autumn	20	–1.17 ± 2.18	–8.79 ± 13.4	0.963 ± 0.016
Stable conditions	154	–0.50 ± 2.17	–3.74 ± 16.2	0.971 ± 0.004
Single daytime FTIR and radio sounding measurements with a time lag specified				
Time lag				
no longer than 1 h	111	–0.06 ± 2.34	–1.66 ± 22.1	0.961 ± 0.007
no longer than 30 min	75	0.16 ± 2.37	0.35 ± 23.8	0.961 ± 0.009
Monthly average FTIR and radio sounding measurements				
All comparisons	28	–0.39 ± 0.98	–5.30 ± 11.1	0.993 ± 0.003

water vapor TC radio sounding errors are 5–10% and higher on the average [10]. The altitude profiles of the relative humidity found from daytime radio sounding data in Voyeykovo (launch at 12:00 UTC) were integrated over altitude with the aim of calculating the water vapor TC for the days of FTIR measurements in Peterhof. As a result, we have 182 days when both radio sounding and FTIR measurements were carried out.

ANALYSIS OF COMPARISONS RESULTS FOR TWO TYPES OF MEASUREMENTS

The mismatch δ between two types of measurements can be represented as the sum

$$\delta \approx \delta_{rs} + \delta_{IR} + \delta_1 + \delta_2, \qquad (1)$$

where the components δ_{rs} and δ_{IR} are caused by errors of two types of measurements, and δ_1 and δ_2, by spatial and temporal variations in the water vapor TC. The radio sounding errors in the water vapor TC depend on the ratios of random and systematic errors and are within the ~5–8-% range. The total FTIR measurement error of water vapor TC is about 5% on the average. In general, δ_1 and δ_2 can be quite high, accounting for possible significant spatial and temporal variations in H_2O, a significant distance between Peterhof and Voyeykovo, and time differences between radio sounding and FTIR measurements. Thus, the mismatch between the two types of measurements is characterized by their total errors under conditions of horizontally homogeneous and stationary humidity fields near St. Petersburg; if these conditions are not satisfied, the mismatch is characterized by spatiotemporal inhomogeneity of the integral humidity field. One can try to estimate both components of the mismatch using different subsets for comparison. The two types of measurements have been compared for different subsets (Table).

Figure 1 compares FTIR measurements of water vapor TC in Peterhof averaged over a day of measurements and radio sounding measurements in Voyeykovo (50 km away from Peterhof) for the whole period of comparison. The water vapor TC varied by more than an order of magnitude during the period under study. Average TCs for Peterhof and Voyeykovo are very close, 13.31 and 13.58 kg/m^2, respectively. TC minima and maxima were 1.66 and 38.7 kg/m^2 in Peterhof and 2.07 and 36.4 kg/m^2 in Voyeykovo.

A relative difference between FTIR (Peterhof) and radio sounding (Voyeykovo) data on the water vapor TC can attain 30–40% in modulus and even more (Fig. 2a). However, 86% of all relative differences do not exceed 25% in modulus, and 57% of these differ-

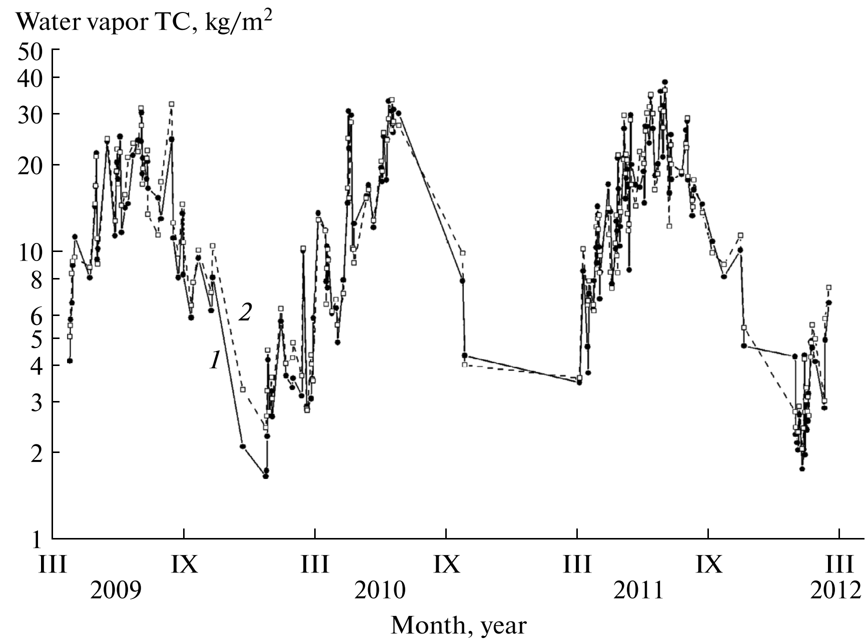

Fig. 1. Seasonal variations in the water vapor TC found from ground-based FTIR measurements in Peterhof (*1*) and from radio sounding in Voyeykovo (*2*). The relative difference between these measurements is shown in Fig. 2.

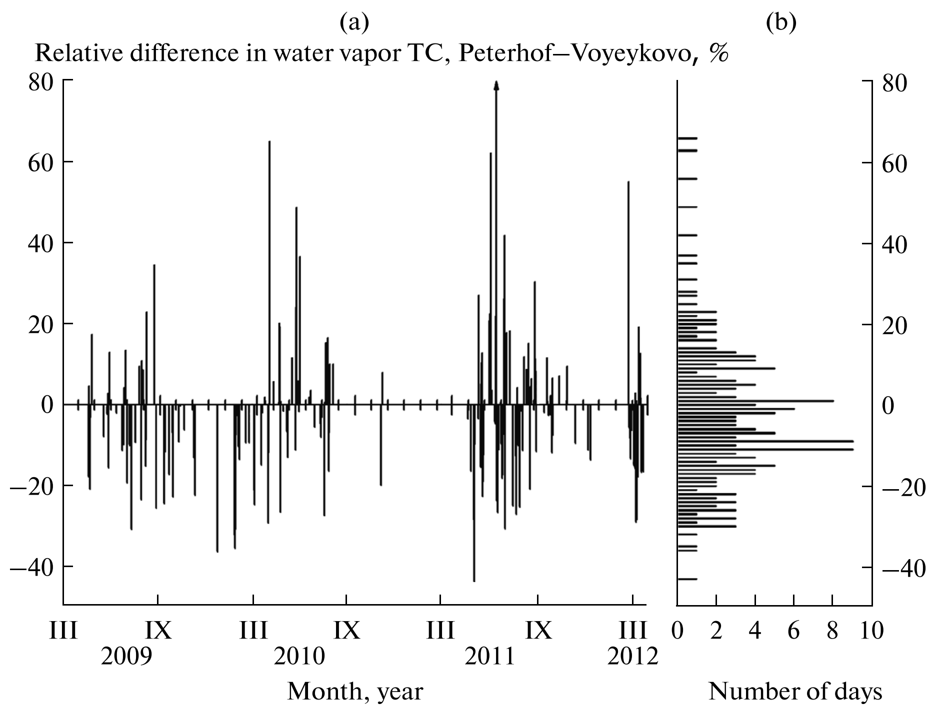

Fig. 2. (a) Relative difference between FTIR and radio sounding measurements of water vapor TC and (b) histogram of this difference.

ences are within the –15 to +10% range (see histogram in Fig. 2b, which shows the number of days for which relative differences fell in the range specified with a step of 1%).

The total range of mismatches between the two types of measurements is from 2–3% to more than 100%. The mismatch between FTIR measurements of water vapor TC in Peterhof and radio sounding measurements in Voyeykovo was maximal on May 23, 2011, and equal to 149% (shown by the arrow that points beyond the plot range in Fig. 2a). The water vapor TC measured in Peterhof was 21.1 kg/m^2 on this day, and

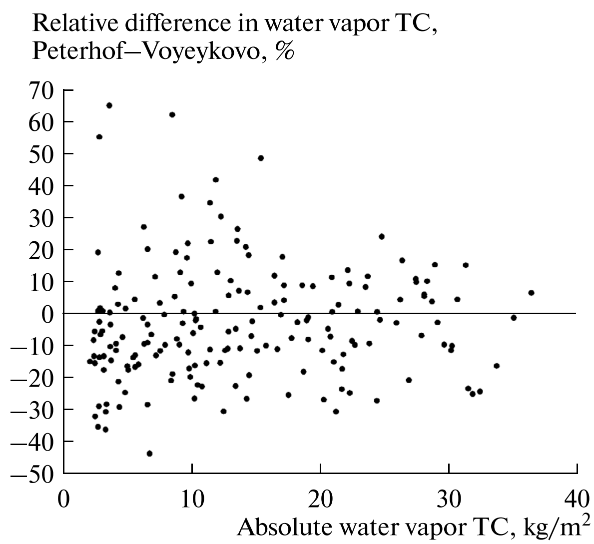

Fig. 3. Relative difference between daily average water vapor TC measured in Peterhof and Voyeykovo versus the absolute TC.

only 8.46 kg/m^2 in Voyeykovo. However, the water vapor TC on the next day attained 21.6 kg/m^2 in Voyeykovo and 16.5 kg/m^2 in Peterhof, that is, the columnar humidity in Voyeykovo was the same as in Peterhof the day before; however, measurements on one day showed significantly different humidity values. These two days of sequential measurements show the clearest strong spatiotemporal variations in the water vapor TC, which can attain ~13 kg/m^2 and are caused by air mass transport. High mismatches of about 40–60% are apparently reasonable and follow from significant spatial inhomogeneity of the humidity field near St. Petersburg.

To analyze the comparison of the two data series (FTIR and radio sounding), the mean M and standard S mismatches were used, and the linear correlation coefficient.

FTIR data on water vapor TC measured in Peterhof and averaged over a day of measurements and radio sounding data in Voyeykovo are compared in the table. The correlation coefficients turned out to be quite high (0.956) when comparing all 182 days of measurements; however, the standard mismatch was high (about 21%). Subsets for different wind directions should be compared accurately, since they include different numbers of comparisons and measurements in different seasons. Nevertheless, relatively small values of S (~17–18%) under north, west, and weak winds are noticeable. Vice versa, maximal relative mismatches were observed under south wind.

Comparison of these two types of measurements in different seasons has shown minimal relative mismatches in summer and autumn and minimal absolute mismatches in winter. This is caused by the seasonal variations in TC, which were maximal in summer and minimal in winter. (Negative M means that the water vapor TC in Peterhof was lower than in Voyeykovo on the average.) The mean M and standard S mismatches strongly vary depending on the subset under analysis; for the whole set of comparisons, $M = -0.27$ (–2.34%) and $S = 2.62$ kg/m^2 (21.2%).

A minimal $M = -0.06$ (–1.66%) was observed for a set with a 1-h time step of comparison; a maximal $M = -1.17$ (–8.79%) was noted in autumn; minimal $S = 0.69$ (21%) were in winter and maximal $S = 3.26$ (15.9%), in simmer. This dependence is caused by seasonal variations in TC by more than an order of magnitude.

Comparison of measurements at 0.5- and 1-h differences did not result in a noticeable decrease in the mismatches, which points to spatial inhomogeneity of the humidity field as the main cause of high mismatches. Typical absolute standard mismatches [2], found between different types of water vapor TC measurements (radio sounders, IR, GPS, and mkV radiometers, etc.) in Northern Sweden with a time lag of no longer than 1 h but for shorter distances between measurement sites, are in the 0.66–2.66 kg/m^2 range. Thus, the absolute standard mismatch from the table (2.34 kg/m^2) is in the upper end of the range (see [2]).

The mean mismatches also agree well with data from [11], but standard mismatches are higher by 1.5–2 times. The comparison of monthly average water vapor TC shows a very high correlation coefficient (0.993 ± 0.003) and an approximate 2-fold decrease in the mismatch between two types of measurements.

Figure 3 shows that the relative difference between the daily average values of the water vapor TC in Peterhof and Voyeykovo tends to decrease with an increase in the absolute value of the water vapor TC. It is natural that relative differences strongly increase at small TC values (e.g., in winter).

CONCLUSIONS

The analysis of the comparison between water vapor TC measurements with two techniques, FTIR in Peterhof and radio sounding in Voyeykovo, has shown the following.

1. Despite a good correlation (0.96 and higher) between measurements in Peterhof and Voyeykovo, the standard mismatches are significant and attain ~20% and more for most subsets of comparison. Tighter time matching between these two types of measurements, with a time lag of no more than 0.5 or 1 h, does not provide for a better agreement. A strong mismatch is mainly caused by natural spatial variability of water vapor TC accounting for a distance of 50 km between Peterhof and Voyeykovo. This variability can attain ~ 13 kg/m^2 (1.35 mm precipitable water) per 1 day at a distance of 50 km. Let us note that close spatial gradients of TC were recorded by

V. V. Kalinnikov with the help of global satellite positioning systems [12].

2. Comparison of monthly average values of the water vapor TC shows a very high correlation coefficient (0.993 ± 0.003) and about 2-fold decrease in the relative and absolute mismatches, to 11% and 0.98 kg/m^2, between the two types of measurements.

3. The comparison results and variations in the mismatches caused by spatiotemporal variations in the water vapor TC pose severe requirements on agreement between these two types of measurements during validation of satellite data on TC by different ground-based measurements.

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REFERENCES

1. *SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour*, *SPARC Report no. 2,* Ed. by D. Kley, J. M. Russell, III, and C. Philips (2000).
2. S. A. Buehler, S. Ostman, C. Melsheimer, G. Holl, S. Eliasson, V. O. John, T. Blumenstock, F. Hase, G. Elgered, U. Raffalski, T. Nasuno, M. Satoh, M. Milz, and J. Mendrok, "A multi-instrument comparison of integrated water vapour measurements at a high latitude site," Atmos. Chem. Phys. **12** (22), 10925–10943 (2012).
3. A. V. Poberovskii, "High-resolution ground measurements of the IR spectra of solar radiation," Atmos. Ocean. Opt. **23** (2), 161–164 (2010).
4. F. Hase, J. W. Hannigan, M. T. Coffey, A. Goldman, M. Hopfner, N. B. Jones, C. P. Rinsland, and S. W. Wood, "Intercomparison of retrieval codes used for the analysis of high-resolution, ground-based FTIR measurements," J. Quant. Spectrosc. Radiat. Transfer **87** (1), 25–52 (2004).
5. http://www.nasa.gov/centers/goddard/missions/index.html
6. http://www.cesm.ucar.edu/working_groups/WACCM/ The Whole Atmosphere Community Climate Model
7. L. S. Rothman, I. E. Gordon, A. Barbe, D. C. Benner, P. F. Bernath, M. Birk, V. Boudon, L. R. Brown, A. Campargue, J.-P. Champion, K. Chance, L. H. Coudert, V. Dana, V. M. Devi, S. Fally, J.-M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, I. Kleiner, N. Lacome, W. J. Lafferty, J.-Y. Mandin, S. T. Massie, S. N. Mikhailenko, C. E. Miller, N. Moazzen-Ahmadi, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. I. Perevalov, A. Perrin, A. Predoi-Cross, C. P. Rinsland, M. Rotger, M. Simeckova, M. A. H. Smith, K. Sung, S. A. Tashkun, J. Tennyson, R. A. Toth, A. C. Vandaele, and J. V. Auwera, "The HITRAN 2008 molecular spectroscopic database," J. Quant. Spectrosc. Radiat. Transfer **110** (9), 533–572 (2009).
8. M. Schneider, F. Hase, and T. Blumenstock, "Water vapour profiles by ground-based FTIR spectroscopy: Study for an optimised retrieval and its validation," Atmos. Chem. Phys. **6** (3), 811–830 (2006).
9. http://weather.uwyo.edu/upperair/sounding.html
10. M. B. Fridzon and Yu. M. Ermoshenko, http://ria-stk.ru/mi/adetail.php?ID=30717
11. R. Van Malderen, H. Brenot, E. Pottiaux, K. Mies, S. Beirle, T. Wagner, C. Hermans, M. De Maziere, H. De Backer, C. Bruyninx, "Inter-technique comparison of integrated water vapour measurements for climate change analysis," in *European Geoscience Union General Assembly, 2012, Vienna, April 22–27, 2012.*
12. V. V. Kalinnikov, Extended Abstract of Candidate's Dissertation in Mathematics and Physics (Kazan Federal University, Kazan, 2013).

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