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Error Analysis of Integrated Water Vapor Measured by CIMEL Photometer

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Abstract—Water vapor plays a key role in weather and climate forming, which leads to the need for continuous monitoring of its content in different parts of the Earth. Intercomparison and validation of different methods for integrated water vapor (IWV) measurements are essential for determining the real accuracies of these methods. CIMEL photometers measure IWV at hundreds of ground-based stations of the AERONET network. We analyze simultaneous IWV measurements performed by a CIMEL photometer, an RPG-HATPRO MW radiometer, and a FTIR Bruker 125-HR spectrometer at the Peterhof station of St. Petersburg State University. We show that the CIMEL photometer calibrated by the manufacturer significantly underestimates the IWV obtained by other devices. We may conclude from this intercomparison that it is necessary to perform an additional calibration of the CIMEL photometer, as well as a possible correction of the interpretation technique for CIMEL measurements at the Peterhof site.

Keywords: Integrated water vapor, AERONET, CIMEL, MW radiometer, FTIR spectrometer

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1. INTRODUCTION

The AERONET (Aerosol Robotic Network) International landline network comprises hundreds of observation stations on different continents of the globe in which measurements of the optical and microphysical parameters of atmospheric aerosol are carried out using a CIMEL photometer [1]. In Russia, there are at least eight such points [2]. In addition to the characteristics of aerosols, the CIMEL photometer in the AERONET network also measures the total water-vapor content (TWVC). Spectroscopic methods for determining the TWVC have been developed for a long time in Russia [3, 4]. The atmospheric TWVC data are obtained by the direct measurement of solar radiation in the 940-nm absorption band of water vapor. The application of TWVC data in a variety of tasks requires knowledge of the errors of these measurements. For example, it is stated in [5] that the measurement error of TWVC by the CIMEL photometer averages to ~10%. However, these errors are dependent on many factors and their analysis for a variety of measurement conditions and devices (for example, different values of TWVC, seasons, measurement altitudes, quality of calibration, etc.) is of considerable interest. Similar studies of the CIMEL photometer errors in different conditions have been described, for example, in [6–12] and monograph [13]. Since 2013, measurements with a CIMEL photometer, calibrated by the device manufacturer, are carried out in St. Petersburg University (SPU) in a suburb of St. Petersburg (Peterhof: 59.88° N, 29.82° E). This paper analyzes the simultaneous TWVC measurements by the CIMEL photometer, MW radiometer, infrared Fourier spectrometer, and radiosonde data (Voeikovo station) for the period of over a year. Joint analysis of nearly simultaneous measurements with different remote sensing methods allows evaluating the quality of measurement with the CIMEL photometer.

2. MEASUREMENT DETAILS

The automatic CIMEL CE 318N-EDPS9 photometer measures the direct solar radiation in the water-vapor absorption band in the spectral channel centered at a wavelength of 940 nm. On the basis of instrument calibration by the manufacturer (Cimel Electronique S.A.S, http://www.cimel.fr/) and standardized algorithms of the Goddard Center for Space Flight, TWVCs have been received for the period from March 13, 2013, to May 31, 2014 [14]. The duration of a single photometer measurement used to determine the TWVC was 1 min, and measurement processing algorithms excluded cases of cloud presence. In this paper, TWVC data of level 1.5 is analyzed. As was shown in [15], these data do not differ significantly from the data of level 2.0 by the TWVC determination quality.

Microwave TWVC measurements were carried out using a RPG-HATPRO radiometer (Radiometer Physics GmbH—Humidity and Temperature PROfiler) manufactured by the German company Radiometer Physics GmbH [16]. The radiometer has seven channels in the oxygen absorption band of 0.5 cm, and seven channels in the region of the 1.35-cm water-vapor absorption line and atmospheric windows. The radiometer makes it possible to determine the vertical temperature and humidity profiles in the troposphere, as well as the water content of clouds [17, 18]. The TWVC is measured by an instrument with an absolute accuracy of ±0.3 mm of deposited water and a random error of less than 0.005 mm [16]. Analysis of TWVC fluctuations, measured by the instrument at a constant TWVC for 5–15 min, fully confirmed the assessment of random errors mentioned above. For small TWVCs (below 4 mm), the relative random MW errors are ~2%, while the total error can reach ~10–15%.

The spectra of direct solar IR radiation with high spectral resolution were measured using a terrestrial spectral complex based on the Bruker IFS-125HR Fourier spectrometer [19]. Measurements were carried out in the case of a cloudless sky or in large enough cloud gaps. The determination of moisture content was carried out in six spectral intervals (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}. Interpretation of the IR measurements was conducted using the PROFFIT software package [20]. The details of these measurements and their processing are described in [21]. The error of TWVC measurement according to the error matrix calculations amounted to (3.6 ± 0.6)%, while its random component was (1.2 ± 0.2)% and the systematic component was (3.3 ± 0.6)%. Calculations have shown that the greater the TWVC is, the higher the random absolute error of IR measurements is, ranging from 0.05 mm (for TWVC < 4 mm) to 0.4 mm (for TWVC > 20 mm). In general, the relative random error of TWVC measurement changed little due to the random measurement noise, amounting to about 1% over the entire ensemble of measurements.

Regular AK2-02 radiosonde launches are carried out on the radiosonde stations of Roshydromet in the village of Voeikovo. They are used to measure altitude profiles of relative humidity, temperature, and wind conditions. The accuracy of radiosonde measurements of the water-vapor content in the troposphere does not exceed 5–10% on average [22]. It is important to mention that the distance between Peterhof and Voeikovo is about 50 km, and the mismatch with the radiosonde measurements in Peterhof may largely be due to spatial and temporal variations in water-vapor content [23, 24].

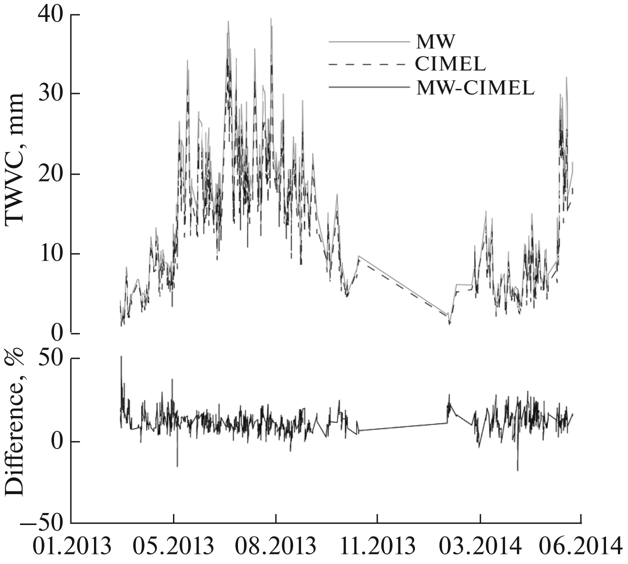

Fig. 1. Time dependence of TWVC values measured with MW RPG-HATPRO radiometer and CIMEL photometer and their relative difference.

3. RESULTS OF COMPARISON

An example of a comparison of TWVC measurements with a CIMEL photometer and MW radiometer is shown in Fig. 1. It can be seen that the photometer gives systematically lower TWVC values compared with measurements by the MW radiometer. The figure shows also the difference (in percentages given to the MW measurement) between the two ensembles. Note that 38% percent of all differences are less than 10%, and 93% of all differences are less than 20%. It should be noted that the RPG-HATPRO radiometer performs about 30000–50000 measurements per day (approximately every 2 s). Each CIMEL TWVC value was compared to the MW value averaged over 1 min, i.e., the two types of measurements were maximally time-aligned, and the instruments themselves were at a distance of about 3 m from each other. However, it should be taken into account that the MW radiometer measures TWVC in the vertical direction, while the CIMEL device is aimed at the solar disk. Thus, with an ideal time-correlation, these two measurements have spatial differences that are especially significant at a low sun. This feature can cause a disagreement in measurements due to the small-scale variability of the water-vapor content [23, 24].

The dependence of the absolute differences (MW minus CIMEL) on the TWVC value measured by a CIMEL photometer is shown in Fig. 2. It can be seen that the difference between the measurements with these two devices increases with the TWVC. It should also be noted that the difference between the two types of measurements grows quicker for TWVC larger than 20 mm. For the same TWVC values the general spread of the differences increases. At the same time, the vast

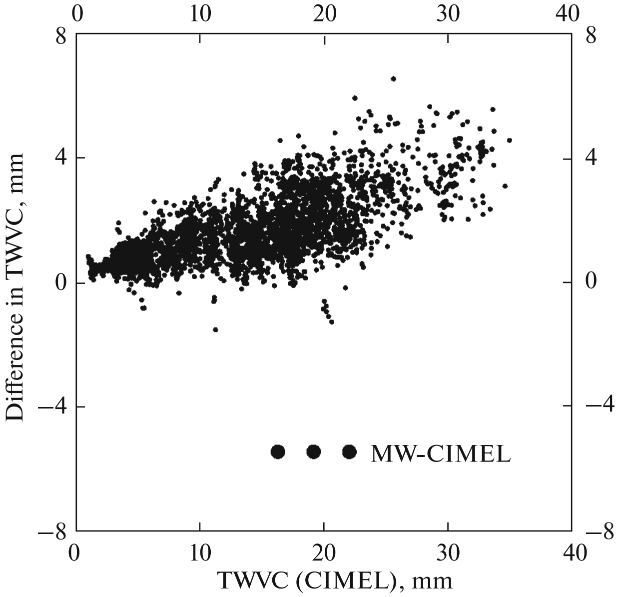

Fig. 2. Dependence of absolute difference (MW minus CIMEL) on the TWVC value measured with the CIMEL instrument.

majority of TWVC values are less than 20 mm. Thus, an increase in the difference between the measurements by the MW and CIMEL for large values of moisture content does not affect the overall statistics of comparisons.

For illustrative purposes, Fig. 3 shows a histogram of the distribution of relative difference between the MW radiometer and the CIMEL photometer for the entire range of the moisture-content variation. The main conclusion from this comparison is that, except for a few cases of measurements on May 8, 2013, and April 7, 2014, when some CIMEL measurements significantly exceeded MW measurements (up to ~20%), the CIMEL gives lower TWVC values compared to the MW radiometer for all TWVC subbands.

For a more detailed analysis of the comparison between the two methods of TWVC measurement, Table 1 shows the basic statistical characteristics of a mismatch in general for the entire ensemble, as well as separately for the subbands values of TWVC changes.

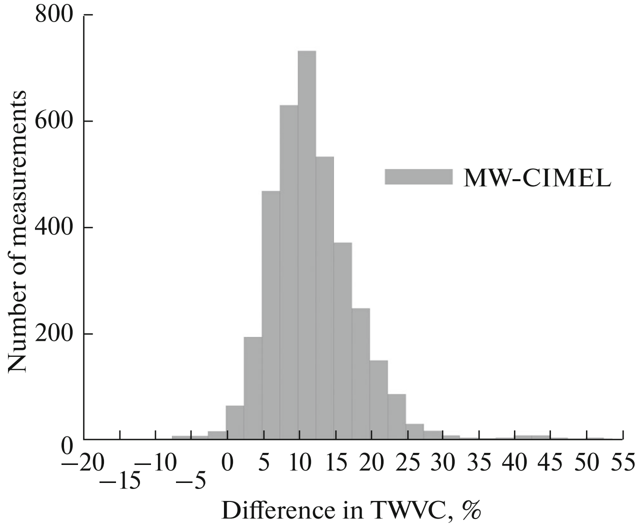

Fig. 3. Distribution of the relative TWVC differences (MW minus CIMEL).

As a criterion of divergence of ensembles, Table 1 shows the average error, standard deviation from the mean, and correlation coefficients. The mismatch characteristics are given both in absolute (millimeter of precipitated water) and relative (percentage) units.

It can be seen from the table that for all considered subbands there is a significant systematic mismatch in TWVC values measured with devices. The CIMEL device gives lower TWVC values compared to the MW measurements. In relative units, this underestimation is more pronounced for small TWVC values (less than 4 mm). With TWVC increasing, the relative disagreements usually decrease. The minimum average discrepancy is observed for TWVC values greater than 10 mm. At the same time, the absolute differences increase with the increase of the TWVC values.

The standard deviations from the average disagreements for all ensembles are small both in absolute and relative terms. Note that the very large correlation coefficient between the two types of measurements for the complete comparison ensemble is due to the large number of virtually reiterative measurements (the number of CIMEL measurements reaches 50 per day).

Table 1. Parameters of comparison of TWVC ensembles measured with MW HATPRO radiometer and a CIMEL photometer (average HATPRO–CIMEL values and standard deviations from the average values are taken as a disagreement)

TWVC ensembles	Number of comparisons	Absolute disagreement, mm	Relative disagreement, %	Correlation coefficient
All measurements	3563	1.56 ± 1.07	10.9 ± 7.4	0.9962 ± 0.0001
<4 mm	426	0.51 ± 0.17	18.4 ± 6.2	0.979 ± 0.002
4–10 mm	873	0.83 ± 0.45	12.7 ± 6.9	0.966 ± 0.002
10–20 mm	1311	1.54 ± 0.73	9.9 ± 4.7	0.968 ± 0.002
>20 mm	953	2.72 ± 1.01	10.9 ± 4.0	0.977 ± 0.001

Table 2. Parameters of comparison of TWVC ensembles measured with an IR Bruker spectrometer and CIMEL photometer (Bruker minus CIMEL)

Temporal alignment of ensembles	Number of comparisons	Absolute disagreement, mm	Relative disagreement, %	Correlation coefficient
5 min	262	1.06 ± 0.80	10.0 ± 7.6	0.9982 ± 0.0002
60 min	1094	1.11 ± 0.94	10.1 ± 8.6	0.9952 ± 0.0003

When considering selected intervals of TWVC change, it can be seen that correlations are minimal for TWVC values between 4 and 10 mm.

For comparisons of IR measurement with CIMEL measurements, two comparison ensembles were formed for different conditions of temporal matching for the two types of measurements, within 5 min and 1 h. The values of disagreement for the two ensembles are given in Table 2.

First and foremost, it should be noted that the use of different time intervals for the matching of the two types of measurements leads to a significant increase in the number of comparisons, but has relatively little effect on the magnitude of mismatch.

As can be seen from Table 2, the CIMEL measurements, as before, give lower TWVC values compared to the IR method. Comparing data in Table 2 with the data in Table 1 for the entire ensemble of comparisons of MW and CIMEL instruments, the proximity of characteristics of mismatches for the two types of comparisons should be noted. It is clear from this comparison that two different remote sensing methods (the method of IR transparency of the atmosphere and the method of MW thermal radiation) and two different instruments indicate a significant underestimation of the TWVC values measured by CIMEL, on average by 10–11%, or 1.1–1.6 mm. Note also that systematic differences between CIMEL and MW measurements are slightly larger than the differences between CIMEL and IR measurements. An independent comparison of MW and IR measurements at the St. Petersburg State University station in Peterhof have shown that the MW radiometer gives higher TWVC values than IR measurements, with the excess amounting to 1–8% for the different intervals of TWVC values.

When comparing the CIMEL measurement data with measurements of radiosondes, two ensembles were formed: CIMEL measurements differing from radiosondes measurements in time by no more than 15 min and a measurement with a time difference of no more than an hour. In the first case, there were 135 comparisons; in the second, there were 470. The relative difference between the two types of measurements varied from 0.08 to 124%. Moreover, 68% of all the differences were less than 20% (and 85% were below 40%). Differences in the temporal alignment of measurements had no significant impact on the statistical characteristics of ensemble discrepancies. One distinctive feature of TWVC measurement comparisons between radiosondes and the CIMEL photometer is the relatively small value of systematic differences (about –4% and –0.5 mm) and a large root-mean-square deviation (~19%, and 2.6 mm). These values were approximately the same as standard deviations. The correlation coefficient between the two types of measurements was 0.944 ± 0.005.

4. DISCUSSION OF RESULTS

Comparisons of TWVC measurements with CIMEL photometers were conducted with different methods of measurement and different instruments: radio-refractional GPS, MW radiometers, infrared high-resolution Fourier spectrometers, radiosondes, and other photometers (see, for example, [5–12] and the monograph [13]). Comparisons were made from polar latitudes to the tropics inclusively, at sea level and at an altitude of ~2300 m in different seasons. Systematic disagreements in the comparisons varied from zero to 3.73 mm, and standard deviation from 0.5 to 3.0 mm. In relative units, the spread in the differences between TWVC values measured with the CIMEL photometer and other instruments are much larger. Maximum differences were observed for the tropical station Izaña, Canary Islands (up to ~60%), located at an altitude of ~2300 m, because of the relative smallness of measured TWVC values.

Table 3 shows examples of the different comparisons of TWVC measurements in recent years. In these comparisons, various statistical characteristics of mismatches, depending on many factors (the measurement location, the season, the measurement altitude, TWVC values, temporal and spatial coherence, etc.), were obtained. For example, the complete absence of systematic differences is noted in [9] when comparing the data measured with CIMEL to the radio-refraction GPS method. On the other hand, comparison of CIMEL measurements with GPS measurements in Locarno, Switzerland, showed the presence of systematic differences of 1.9 mm [8]. Comparison of CIMEL data with the MFRSR photometer data at the Izaña observatory found systematic differences of 3.73 mm [10]. Various systematic measurement differences between the CIMEL and MW measurements (–3 to 5 mm) in a number of observation points have been reported in [11]. In [12], the presence of disagreements from 1.7 to 2.6 mm between MW measurements and CIMEL measurements at various observation points is

Table 3. Examples of comparison of TWVC measurements using solar photometers and other instruments

Instrument	*N*	Average deviations, mm (%)	Standard deviations, mm (%)	*R*	Notes
MW and 4 photometers	488	0.6–0.8 (6–14)	0.5–0.8	0.997	Great Plains, United States [6]
CIMEL, GPS	82	1.0	1.6	0.92	Ten stations, Canada [7]
CIMEL, model	271	−1.57	3.38	0.82	
PFR photometer, GPS		from −0.8 to 1.9	0.5–2.0		Switzerland, three stations [8]
CIMEL, GPS	1778	0.0	0.94 (6.8)	0.981	Haute-Provence, France [9]
CIMEL, FTIR	677	−1.13 (−25.4)	0.74 (12.7)	0.986	Izaña, Spain, 2370 m above the sea level [10]
CIMEL, MFRSR	17951	3.73 (62)	2.68 (17.5)	0.964	
CIMEL, GPS	1464	0.42 (9.5)	0.96 (34)	0.845	
CIMEL, R/S	875	1.23 (24)	1.34 (23)	0.953	
CIMEL, GPS	9452	−0.16	0.96	0.993	Belgium, 27 measuring points [11]
CIMEL, MW		−0.2			
MW, CIMEL	5424–41490	0.7–2.6 (6–9)	0.9–2.7 (6–10)	0.927–0.986	Three stations in the United States [12]
GPS, CIMEL	4404–19585	0.6–1.1 (2–8)	0.7–3.0 (7–15)	0.912–0.982	
R/S, CIMEL	161–3789	from −0.4 to 0.9 (from −0.8 to 4.8)	0.7–2.1 (4.5–7.5)	0.923–0.984	
CIMEL, GPS	890	0.0	0.93	0.98	Jülich, Germany [24]
CIMEL, MW	871	−0.32	0.91	0.99	
CIMEL, R/S	72	−0.42	1.0	0.98	
CIMEL, R/S		−2.62 (−19)	1.76 (12)		Barselona, Spain [25]
CIMEL, MW	3569	−1.5	1.1	0.996	This work
CIMEL, FTIR	1094	−1.1	0.94	0.99	
CIMEL, R/S	135	−0.52	2.6	0.94	

N is number of comparisons, *R* is correlation coefficient, R/S means radiosonde measurements, and FTIR is IR measurement.

noted. In most of the above comparisons, CIMEL gave lower TWVC values than other devices.

Various papers present different values for the root-mean-square mismatches and standard deviations. So, for comparison in Switzerland with GPS measurements, standard deviations were 0.5–2.0 mm for different observation points [8]. Relatively high standard deviations were found between CIMEL measurements and the MFRSR photometer at the Izaña observatory [10] and between GPS and CIMEL data in the Nauru tropical observation point [12].

From this brief overview, it is clear that mismatches obtained from the measurements in Peterhof are close to the results of a number of other observation points. For example, the CIMEL in Peterhof significantly underestimates the TWVC value, while the standard deviations for different types of comparison are relatively small. This suggests that the refinement of the instrument calibration (as is implied in the AERONET network) and correction in the method of interpretation of CIMEL measurement (to avoid the systematic component of the error) will make it possible to obtain the TWVC measurement error in Peterhof in the range of 5–10%.

Errors in the calibration of the CIMEL photometer, the temporal instability of its characteristics, an imperfect method for interpretation of measurements, etc., could be the reasons for the currently identified differences in TWVC measurements in Peterhof. We carried out a preliminary analysis of a number of possible reasons. Laboratory measurements of the spectral transmittance of interference filters of the instrument have shown that they agree with the passport data within 1%. Thus, no aging of the device filters was detected during the observation period. Also, no connection was found between differences in TWVC measurements and the value of the air mass in the direction to the Sun, which implies the absence of significant errors in instrument calibration. Furthermore, it is known that the silicon photodiode used in the instrument has a high temporal stability of its characteristics. Thus, we can draw a preliminary conclusion that the main cause of the observed systematic differences between TWVC measurements with the CIMEL instrument and independent data is an imperfect method of measurement interpretation. This can be both an error in setting the intensity of the water vapor absorption band and the approximate nature of parameterization of the transmission function in the 940-nm channel. Further analysis of the possible causes and correction of interpretation techniques will be addressed in future studies and publications.

5. MAIN RESULTS AND CONCLUSIONS

For the period of over a year (March 13, 2013—May 31, 2014) at St. Petersburg State University (Peterhof, 59.88° N, 29.82° E), simultaneous measurements of total water-vapor content were carried out using three remote methods and instruments: a CIMEL CE 318N-EDPS9 photometer, an RPG-HATPRO MW radiometer, and a Bruker IFS-125HR IR Fourier spectrometer. It should be emphasized that calibration by the instrument manufacturer was used for the interpretation of the CIMEL instrument data. The CIMEL photometer and Fourier spectrometer measured the absorption of direct solar radiation in the near- and mid-infrared respectively. The MW radiometer obtained the TWVC from measurements of descending thermal atmospheric MW radiation. A comparison of the three instruments, taking into account the mutual comparison of the RPG-HATPRO radiometer and Bruker IFS-125HR Fourier spectrometer and their high precision, made it possible to estimate the TWVC measurement uncertainty for the CIMEL CE 318N-EDPS9 photometer for St. Petersburg conditions.

(1) The CIMEL instrument underestimates TWVC values compared to MW measurements. This underestimation is particularly significant for small TWVC values (below 4 mm) and reaches ~18%. With the increase in TWVC, the relative disagreements usually decrease. The minimum average discrepancy is ~10% for TWVC values of 10—20 mm. The absolute values of disagreements are in the range from 0.51 to 2.72 mm, and increase with increasing TWVC values. For all the comparisons, the mean error is ~10.9% and 1.56 mm.

(2) CIMEL measurements also underestimate TWVC as compared to the IR method. In relative units this underestimation is ~10%, and in absolute units it is close to 1 mm. Differences between CIMEL measurements and the other two devices are very similar, which in view of the mutual calibration of these instruments indicates the need for additional calibration of the CIMEL instrument, and possibly for the correction of the methods and algorithms of interpretation of the CIMEL photometer measurements for St. Petersburg conditions.

(3) A comparison of TWVC measurement data by the CIMEL photometer with the results of radiosonding in the Voeikovo station showed once again (see. e.g. [21, 23, 24]) that there is often a significant horizontal inhomogenity of the moisture field at a distance of about 50 km, which may be due to the proximity of the observation station in Peterhof to the Gulf of Finland. Therefore, such comparisons often cannot be used as criteria of the quality of CIMEL instrument measurements.

(4) The small standard deviations between TWVC measurements using different instruments guarantee a CIMEL measurement error of 5—10% after additional instrument calibration and correction of the interpretation techniques.

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