ISSN 1024-8560, Atmospheric and Oceanic Optics, 2018, Vol. 31, No. 5, pp. 486–491. © Pleiades Publishing, Ltd., 2018.
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Interannual Variability of Surface and Integrated Water Vapor and Atmospheric Circulation in Europe

O. G. Khutorova[a, *], V. E. Khutorov[a], and G. M. Teptin[a]
[a]*Kazan Federal University, Kazan, 420008 Russia*
**e-mail: Olga.Khutorova@kpfu.ru*
Received February 22, 2018

Abstract—The variability of time series of the integrated water vapor of the atmosphere and the surface partial pressure of water vapor for the territory of Europe over a long period have been studied. The main contribution to the variance of both integrated and surface water vapor is made by seasonal variations of 60–70%; mesoscale processes, 7–17%; and synoptic processes, 17–27%. The linear trend contributes less than 1% to the overall variance of the variability of the atmospheric water vapor in Europe. It has been shown that the interannual variability of the atmospheric water vapor manifests itself both in quasi-periodic variations in the annual average values and in variations in the intensity of synoptic processes. The irregular coherence of variations in the circulation indices and surface partial water vapor pressure in Europe with periods of 2–3, 5–6, 8–11, and 10–13 years has been established.

Keywords: atmospheric integrated water vapor, water vapor partial pressure, interannual processes, remote sensing by satellite navigation systems

DOI: 10.1134/S1024856018050081

INTRODUCTION

Water vapor is one of main greenhouse gases; its spatiotemporal structure is closely related to the radiation balance of the atmosphere and Earth's surface and atmospheric circulation. The formation of spatiotemporal characteristics of humidity fields is influenced by atmospheric processes of different scales interacting with each other.

In recent times, GPS meteorology using global navigation satellite systems (GNSSs) for estimating the integrated water vapor (IWV) with a high spatiotemporal resolution have been developed [1]. Most atmospheric monitoring programs developed by the international scientific community use GPS signals, which demonstrates the relevance of this technology. Many studies were devoted to comparison between the IWV from aerologic and GNSS-measurements for different geographic regions: Australia and Antarctica [2], Sweden [3], Italy [4], the Unites States [5], China [6, 7], and India [8]; standard deviations are from 1 to 4 mm of precipitated water. Similar estimates of accuracy are obtained when GPS estimates are compared with radiometric data [9, 10], which indicates the reliability of GNSS monitoring data.

The GNSS data series accumulated during the last one and half decades allow one to investigate trends in the IWV. In [11], long-term IWV trends (1996–2010) over the western coast of Sweden were considered using data from four technologies: microwave radiometers, very-long-baseline radio interferometry, GNSS, and radiosondes. In all the series, IWV trends from 0.3 to 0.5 mm of precipitated water per decade were revealed. There are shifts between synchronized IWV data obtained by independent methods: radiointerferometer—GNSS, 0.39 mm; radiometer—GNSS, 0.4 mm; and radiosonde—GNSS, 0.01 mm of precipitated water.

In [12], the IWV was studied using a microwave radiometer (near Bern, Switzerland, 1994–2007). The GPS and radiosonde data were used for homogenization of the IWV series. It was shown that the diurnal cycle was weak, had amplitude of 0.32 mm with a maximum at 2100 and minimum at 1100 UTC. The linear IWV trend according to radiometer data is positive and is 0.39 mm/yr. The trend according to data of the nearest radiosonde station was 0.45 mm/yr; according to reanalysis data, 0.25 mm/yr, which exceeds values obtained in [11]. At the same time, it was mentioned that seasonal trends were ten times stronger. Positive trends in summer are partially compensated by negative trends in winter. It was stated that predicting climatic changes needs longer series of measurements. In [5], according to data of GNSS networks in the United States, IWV trends for 2002–2009 were found. It was established that revealing a trend of about 0.05 mm/yr needs 25–30 years of observations.

Unfortunately, in most works on studying moisture content, attempts were made to represent its variability by average or stationary processes: interannual processes, in the form of a linear trend; diurnal ones, in

Table 1. Characteristics of series of integral and surface water vapor and contribution of different processes to their variance

Point	Average	RMSD	Determination coefficient of the linear trend	Determination coefficient of seasonal variations	Fraction of synoptic processes in the total variance	Fraction of mesoscale processes in the total variance
			IWV			
Potsdam (Germany)	15.3 mm	8.2 mm	0.001	0.60	0.21	0.17
Zvenigorod (Russia)	14	8.6	0.003	0.61	0.23	0.11
Olsztyn (Poland)	15.1	8.4	0.004	0.57	0.26	0.12
			e			
Potsdam (Germany)	9.4 mbar	4.0 mbar	0.001	0.61	0.20	0.12
Zvenigorod (Russia)	8.2	4.9	0.003	0.70	0.20	0.07
Olsztyn (Poland)	10.7	5.9	0.001	0.62	0.17	0.12

the form of average diurnal variations; and seasonal ones, in the form of monthly average quantities. We propose to segregate water vapor variations by filtration with respect to processes of different scales and to consider interannual variations in connection with macrocirculation processes which are believed to be among main factors of the climate formation across the planet and in certain regions [13–16].

In this work, we have constructed long IWV series calculated from every second observation of a GNSS detector in Kazan [17] and measurements of the world GNSS service in 2000–2016 in Europe [18]. In step with the IWV, the surface moisture content (water vapor partial pressure *e*) is estimated at the same points by measurements of relative humidity and temperature. All series under study have been reduced to a temporal resolution of 5 min.

CONTRIBUTIONS OF DIFFERENT PROCESSES TO THE VARIANCE OF THE INTEGRAL AND SURFACE WATER VAPOR

We have estimated the contribution of different scale processes to the total variance of the integral and surface water vapor. For this purpose, several groups of processes were distinguished using digital filtration: average with the linear trend, seasonal variations, synoptic processes, and mesoscale processes.

Determination coefficients of the linear trend demonstrated that the trend in 16-year series did not exceed 0.4% of the total variance. The absolute values are within the range from 0.04 to 0.3 mm per year for the IWV, which agrees with [11, 12].

Since seasonal variations in the IWV are caused by the variation in meteorological parameters due to the rotation of the Earth around the Sun, they can be described by a sum of annual and semiannual harmonics. They were filtered using the harmonic analysis [19]. The determination coefficient showed that their contribution to the total variance of the moisture content ranged from 57 to 70% depending on the point. Filtration of interannual and seasonal variations in series of daily average values made it possible to estimate the fraction of synoptic variations in the total variance (20–25%). The fraction of mesoscale variations with periods from 10 min to 10 h was estimated by filtration with the use of the moving average (10–17%). The regularities turned out to be common for the integral and surface water vapor.

Table 1 presents results of simultaneous measurements of the integral and surface water vapor with a time step of 5 min.

The estimates we have obtained also confirm that linear trends, as the characteristic of interannual variability of the atmospheric water vapor, do not yield an adequate picture. In addition, in contrast to other works, we studied the spectrum of variations in the region of smaller time scales (synoptic and mesoscale ones).

The practical importance of this result is that mesoscale water vapor fields can cause a discrepancy between the model and experimental radiation calculations or the accuracy in problems of admixture transport at least by 7–10%. For example, in [20–22], the

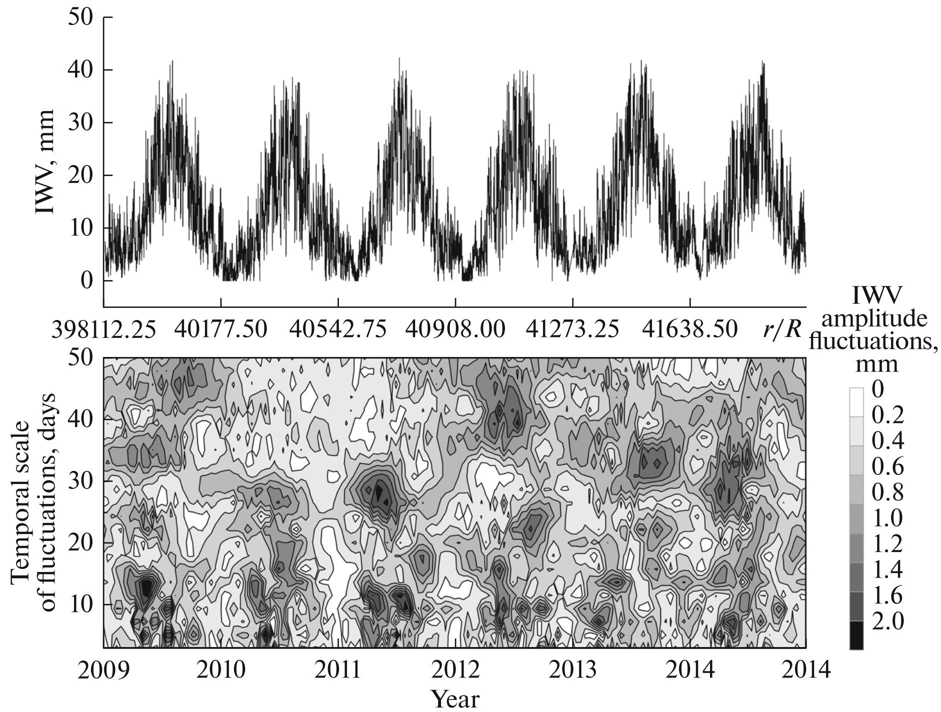

Fig. 1. Series of the atmospheric IWV and its wavelet spectrum by measurements of GNSS detectors in Kazan over 2009–2015; the *y* axis is the axis of wavelet transform scales corresponding to variation periods from 1 to 50 days.

topicality of revealing regularities in the appearance and development of mesoscale processes in the atmosphere was considered. In [20, 21], it was shown that using underestimated or overestimated values of the H_2O content in the atmosphere leads to errors in calculations of downward radiation fluxes; the errors can reach tens of percent. In [22], the relation between mesoscale variations in the concentration of atmospheric admixtures and variations in meteorological parameters (in particular, in humidity) was analyzed.

LONGTERM VARIABILITY OF IWV

Synoptic processes take a large part in variations in the atmospheric water vapor, and these variations cannot be treated as stationary. In connection with this, an appropriate tool for tracking the spectrum variability in time is the wavelet analysis with the Morlet mother function [22].

Figure 1 shows a fragment of the series of the IWV and its wavelet-spectrum for Kazan over 2009–2015. The gray gradations show absolute values of wavelet coefficients, the maximum values of which are associated with amplitudes of especially considerable IWV variations (the white color means the minimal value of the coefficients; the black color, the maximal value).

Synoptic fluctuations of the IWV field amount to 2–5 mm of precipitated water on the average. They sometimes reach 12 mm. The spectra of synoptic variations contain significant modes of 3–4, 7–10, 11–14, 20–30, and 40–45 days. It is seen that the intensity of synoptic variations is modulated by harmonics of annual variations for all parameters under study. It has been found that wave variations with periods from 3 to 10 days, which is typical for Rossby waves, prevail in the time series under study. However, variations with periods from 15 to 45 days, although less frequent, are more powerful. Amplitudes of IWV variations grow from 1 to 4 mm of precipitated water. The intensity of synoptic processes in IWV series varies from year to year. Since synoptic processes are surely determined by the atmospheric circulation [14], one can suppose that interannual variations in the atmospheric water vapor are related to the predominance of particular circulation mechanisms in different years.

However, 15-year series are not long enough for revealing long-period variations in the IWV. For this reason, we decided to take longer series of the surface water vapor which was estimated by meteorological parameters [23]. According to results of eight-term measurements of relative humidity and temperature, a series of water vapor partial pressure for 1966–2015 has been obtained.

We have studied variations in the IWV and compared them with variations in the surface water vapor partial pressure. The variations were measured at the same points with the same temporal discreteness. It has been found that seasonal, synoptic, and even mesoscale variations in the integral and surface water vapor are synchronous (Fig. 2). It is seen that the vari-

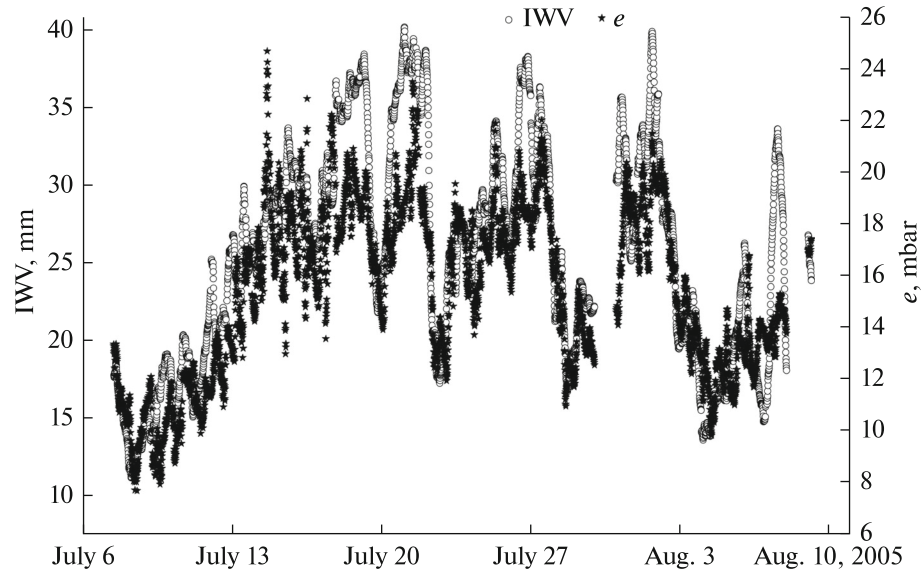

Fig. 2. Synchronicity of variations in the integral and surface water vapor (Zvenigorod, Russia).

ations are coherent during the month of observations. The correlation coefficient of these series is 0.86. The correlation coefficient of 16-year series of monthly average IWV values and surface water vapor partial pressure for the same point is 0.94. This fact suggests that main regularities of variations in the integral and surface water vapor also will be similar. For this reason, we analyzed interannual processes using series of the surface water vapor partial pressure with a duration of at least 50 years.

Long-time average annual values of the surface water vapor in Europe vary from 2 to 8 mbar depending on the latitude, which is related both to the solar radiation inflow and influence of humid air masses. Amplitudes of annual variations in the surface water vapor partial pressure amount to 2.5–10 mbar; amplitudes of the IWV, 3–7 mm of precipitated water.

The interannual variability of the most powerful seasonal variations was analyzed using an estimate of the annual harmonic amplitude inside a moving annual time window with a half-year step.

Figure 3 shows interannual variations in amplitudes of the annual variations for several points in European Russia and their linear trends. It is seen that the annual harmonic amplitudes increase with time on the average; however, the slope angle of the trend varies depending on the location of the points and continentality of their climate. The interannual variations in the atmospheric water vapor can be described as locally quasi-periodic.

The detailed analysis shows that no trends toward an increase in the amplitude have been observed since 2000. Comparison between interannual variations in the IWV and water vapor partial pressure in the surface air layer during 2000–2016 revealed that they were synchronous.

In [23–28], the correlation between the global circulation and climate was shown. In our investigation, the coherence between interannual variations in the water vapor partial pressure and macroscale circulation processes has been considered. The state of the atmospheric circulation was characterized using teleconnection indices obtained by expansion of the geopotential field with the use of the empirical orthogonal function analysis [29]. It has been shown that the North Atlantic Oscillation (NAO) index is related to

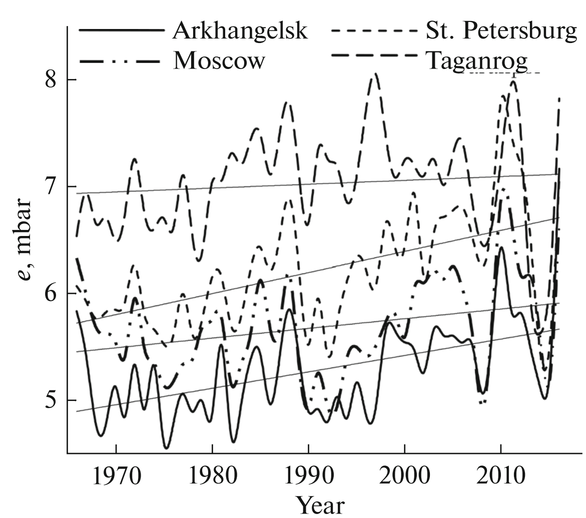

Fig. 3. Interannual variations in the amplitude of the annual harmonic of the surface water vapor partial pressure for different points.

the precipitation transfer in Europe [23] and intensity of cyclonic activity [25, 26]. The EA/WR index (the East Atlantic/West Russia oscillation) is related to the intensity and trajectories of cyclones in Europe [27]. The Arctic oscillation (AO) index reflects anomalies of the global circulation in the Northern Hemisphere [28, 29]. We complemented the analysis with the sea surface temperature anomaly index related to El Niño processes because it was noted [30] that this phenomenon has an effect on the dynamics of the whole climate system of the planet on scales of a decade and larger.

We sought for coherent events on similar time scales in series of IWV and circulation indices by analyzing their wavelet spectra. The last obtained by the Morlet mother function distinguishes a quasi-periodic signal on a required time scale and localizes its amplitude and phase in time (the method was developed in [22] for seeking for coherent variations in series of atmospheric parameters and admixtures).

In the obtained wavelet spectra referenced to a single period of time, disturbances significant with a probability of at least 90% and revealed simultaneously in series of IWV and circulation indices were chosen. The main criterion of selecting coherent variations, namely, the distribution of the difference of phase spectra for a given time scale, has a narrow maximum during the time when their amplitude spectra exceed the 90% significance level. The constancy of phase characteristics indicates that coherent processes and the wavelet transform localize these processes in time. Therefore, the periods of variations, their amplitudes, and time reference were established.

Synchronous variations with a period of 8–11 years were found at almost all points under study in Europe. They were coherent with similar variations in the AO index (1967–2000) which were in phase with them. This is well explained by the fact that the AO reflects the transport of air masses between the polar regions and middle latitudes. It is believed that positive values of the AO index are associated with the predominant west winds carrying warm and humid air to Eurasia. During periods of negative values, a drop in temperature and decrease in precipitation are observed. The AO influence is especially strong in winter [28].

The coherence of variations in circulation indices (AO, NAO, and EA/WR) and surface water vapor partial pressure in Europe with periods of 2–3 and 5–6 years has been established. Similar synchronous variations have been revealed in the index of anomalies in the ocean surface temperature due to the El Niño phenomenon. It has been found that the amplitude of these variations changes with a period of approximately 10–12 years. The coherence is irregular; it arises, exists during several periods, and then disappears. The oscillation scale of 2–3 years is close to the period of the quasi-two-year oscillation observed in the stratosphere and, as it is supposed, is related to the solar activity [31]. It is believed that quasi-two-year oscillations are formed owing to internal waves propagating from the equatorial region of the troposphere. The quasi-two-year periodicity is a global phenomenon covering the troposphere, stratosphere, and thermosphere not only of equatorial but also of polar regions [32].

A short-time (1990–2016) coherence of variations with a period of 10–13 years has been found for the surface water vapor partial pressure at some points in Europe, NAO indices, and anomalies in the ocean surface temperature due to the El Niño phenomenon. Oscillations of the surface water vapor partial pressure are opposite in phase both with oscillations in the NAO index and with anomalous variations in the ocean surface temperature.

The results demonstrate a clear connection between variations in the atmospheric circulation and interannual variability of the atmospheric water vapor in Europe, as well as the correlation between equatorial and midlatitude processes.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 17-05-00863).

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Translated by A. Nikol'skii