Some regularities of atmospheric mesoscale variations obtained from satellite navigation system remote sensing

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Abstract. The paper analyses the long series of measurements of atmospheric variations according to the observations of GPS-GLONASS receivers for an 11-year period. The main contribution to the variance of variations in the integral moisture content is made by seasonal variations, it is 63 percent. Mesoscale processes yield about 7 percent of the dispersion of moisture content. The network of stations in Russia near Kazan city and the troposphere remote sensing technique made it possible to obtain the seasonal variability in the intensity of mesoscale variations. The daily dynamics of mesoscale inhomogeneity estimation are made, horizontal structure functions of zenith tropospheric delay is calculated. A relationship with the fields of humidity and pressure fields of wind speed is found.

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1. Introduction

Water vapour has a huge impact on climate and atmospheric radiation, is closely associated with clouds and precipitation. Therefore, taking into account its fine spatial structure, especially mesoscale spatio-temporal variations, will help improve the quality of operational weather forecasts. To improve the forecast quality of the fine structure of meteorological parameters, it is necessary to rely on a dense network of atmospheric monitoring tools with a high temporal resolution. Recently, works have appeared that show the relevance of identifying patterns of occurrence and development of mesoscale processes in the atmosphere. For example, at work [1] it is shown that the use in calculations of underestimated or overestimated values of the H_2O content in the atmosphere leads to errors in the calculation of downward radiation fluxes, which can reach tens of percent. In work [2] an algorithm for modeling the propagation of laser beams on atmospheric paths is presented, taking into account the refraction and focusing of the beam on mesoscale inhomogeneities. It was previously shown that mesoscale processes in the surface layer make a significant contribution to the dispersion of atmospheric impurities [3]. In [4] is shown that mesoscale processes, including their manifestation in the mass concentration of aerosol, are modulated by seasonal and synoptic processes.

In this paper, the task is to study the mesoscale variability of the troposphere using a network of receivers of global satellite navigation systems (GNSS). The method of remote sensing of the troposphere with GLONASS and GPS signals is currently used to determine the integral moisture content and other atmospheric parameters [5, 6], due to such advantages of this technology as the presence of a dense network of ground stations, round-the-clock recording of measurements with high temporal resolution, and independence from weather conditions. Studies are underway to assimilate GPS data into non-hydrostatic mesoscale weather fields to improve the quality of weather forecasts [7]. The paper uses phase measurements of the network of Kazan Federal University [8].

The phase of the signal emitted by the navigation satellite, measured by the ground receiver, carries information that characterizes the state of the atmosphere. This information is determined by the refractive index, which, in turn, is associated with meteorological parameters - the partial pressure of gases, temperature, partial pressure of water vapor [10]:

$$N = A1\frac{P}{T} + A2\frac{e}{T} + A3\frac{e}{T^2}. \qquad (1)$$

The first term is proportional to the density of the atmosphere, and the second and third are determined by humidity. In the experiment on measuring the receiver, a parameter characterizing the state of the troposphere is estimated — the zenith tropospheric (total) delay, which can be determined through the integral of the refraction index [5]:

$$\mathrm{ZTD} = 10^{-6}\int_{h_r}^{h_s} N(h)\,\mathrm{d}h, \qquad (2)$$

The integral is taken from the height of the receiver antenna to the height of the satellite antenna in the zenith direction. This parameter is traditionally measured in units of length [10]. Due to the fact that the refractive index decreases exponentially with height, the main contribution to the ZTD is made by the troposphere. Substituting (1) into (2), we can see that ZTD is the sum of the delays caused by dry ZHD gases and water vapor ZWD. The first term is determined by integration over the height of the air density, it can be determined by the surface values of temperature and pressure, and from the ZWD to obtain the integral water vapor (IWV) content of the atmosphere [6].

2. Analysis and results

In this paper, we will operate with the total delay of GNSS radio signals in order to take into account both humidity variations and possible density variations. Additionally, Roshydromet weather station data was used to calculate ZHD and ZWD [9]. All parameters are obtain on Kazan stations. The integral moisture content of the atmosphere can be obtained from ZWD. An example of the obtained IWV series is shown in figure 1.

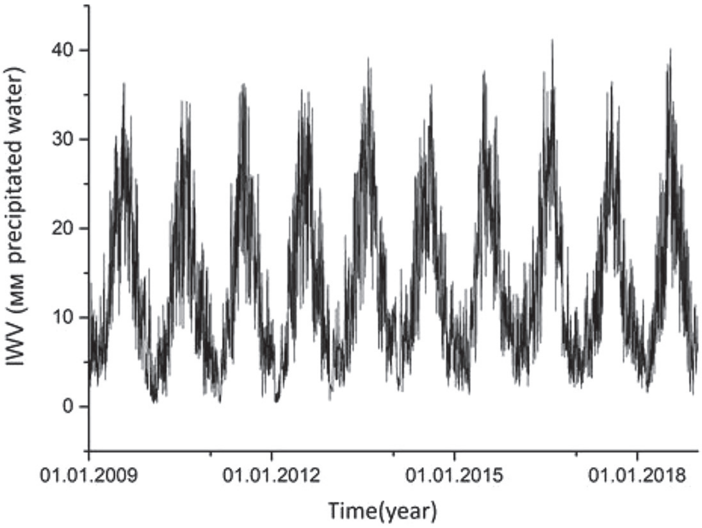

Figure 1. Time series of GNSS-derived integral water vapor in Kazan 2009–2018.

On long rows from 2009 to 2019 estimates of the contribution of trend, seasonal and synoptic variations to the total variance of IWV were made. The results and average values of the studied values are given in the table 1.

At the same points, the partial pressure of water vapor and the measurements of relative humidity and temperature were evaluated simultaneously with the integral moisture content. All investigated series are reduced to a temporary resolution of 5 minutes.

Table 1. Characteristics of the series of integral (IWV) and surface (partial pressure e) moisture content. Average amplitudes and variance of variations of various processes in their variance.

Parameter, mm	IWV		*e*	
	Mean, mm	Dispersion, mm^2	Mean, mbar	Dispersion, mbar^2
Statistical Characteristics	13.3	82.2	8.2	23.6
Linear increase (in year)	0.4	0.5	0.1	0.1
Seasonal processes (annual harmonics)	10.2	52.0	5.6	13.5
Synoptic processes	17.9	18.0	2.3	4.6

We estimated the contributions to the total dispersion of variations in the integral and surface moisture content of processes of various scales. For this, several groups of processes were identified by digital filtering: the average and linear trend, seasonal variations, synoptic processes, mesoscale processes.

The coefficients of determination of the linear trend showed that the trend is not more than 0.7 % of the total variance.

Since seasonal variations are due to the meteorological parameters due to the rotation of the Earth around the Sun, they can be described by the sum of the annual and semi-annual harmonics. Harmonic analysis was used to filter them.

The coefficients of determination of the linear trend showed that in 11-year series the trend is not more than 0.3 % of the total variance. Harmonic analysis made it possible to single out the sum of annual and semi-annual harmonics. The determination coefficient showed that their contribution to the total dispersion of moisture content was from 62 %. Filtration of interannual and seasonal variations in the series of daily average values allowed us to estimate the share of synoptic variations in the total variance — 22 %. The proportion of mesoscale variations with periods from 10 minutes to 10 hours was estimated by filtering using a moving average and reaches 7 %. Patterns were similar for integral and surface moisture content. Interannual variations are also present in the variability of the intensity of synoptic processes

The results of the ZTD analysis are as follows. The seasonal variations in the observed ZTD are almost completely determined by seasonal variations in the integral atmospheric moisture content. The second most intense are synoptic variations, and they give the greatest variability of ZTD and the integral moisture content of the atmosphere. The intensity of the variations in density and humidity is close in magnitude and, accordingly, their contribution to the synoptic variations of ZTD can be considered comparable. However, in winter, at a negative temperature in the troposphere, water vapor "freezes" and the synoptic variations in refraction in the troposphere are mainly determined by the density variability.

In works [3, 4] it is shown that a wavelet analysis with the Morlet maternal function is a successful method for estimating the intensity of unsteady atmospheric fluctuations, especially mesoscale ones. Applying the wavelet transform, we obtained from the ZTD series the series of intensity of variations with time scales from 15 minutes to 24 hours. Estimates of the seasonal variability of the intensity of mesoscale variations (periods from 15 minutes to 16 hours) and diurnal variation (period of 24 hours) were obtained from these series. For convenient comparison, table 2 shows the intensity level of mesoscale Am and diurnal variations of A24 for each season relative to the average level of these variations for the entire study period. Table 2 also shows the maximum and average values of the ratio of the mesoscale intensity to the diurnal value.

Table 2. Relative intensities of mesoscale variations in ZTD to their average level and level of diurnal variation.

Parameter, mm	Am	A24	Mean Am/A24	Max Am/A24
Winter	0.87	0.61	0.471	23.0
Spring	0.92	0.93	0.328	9.8
Summer	1.21	1.38	0.291	16.9
Autumn	0.98	1.088	0.301	23.7

It can be seen that the highest intensity of both mesoscale and diurnal variations of the zenith tropospheric delay of GNSS radio signals is achieved in summer, and the minimum in winter. In spring and autumn, the level of variations of all scales almost corresponds to the annual average. It is interesting that, on average, the intensity of mesoscale processes relative to the diurnal variation is 30–50 %, however, the maximum intensity ratios of mesoscale processes can be several times higher than the diurnal variation at certain points in time. That is, the forced oscillations of atmospheric refraction (the daily course of meteorological parameters) and the mesoscale dynamics, as one would expect, are due to various reasons.

We compared the intensity variability of separately mesoscale processes of the γ-mesoscale (time scale up to 2 hours) and β-mesoscale (time scale from 2 to 20 hours) depending on surface meteorological parameters. Over the three years studied, the following patterns were obtained.

As a rule, in any season, a decrease in atmospheric pressure exerts a clear influence on the intensity of all intraday variations in ZTD, for example, when an anticyclone passes, an increase in the intensity of both γ and β-mesoscale variations by an average of 15 %, and the diurnal amplitude increases by 50 %. An example is shown in figure 2, it can be seen that with decreasing pressure, the average level of mesoscale fluctuations (total) increases, well noticeable even taking into account its strong diurnal variability.

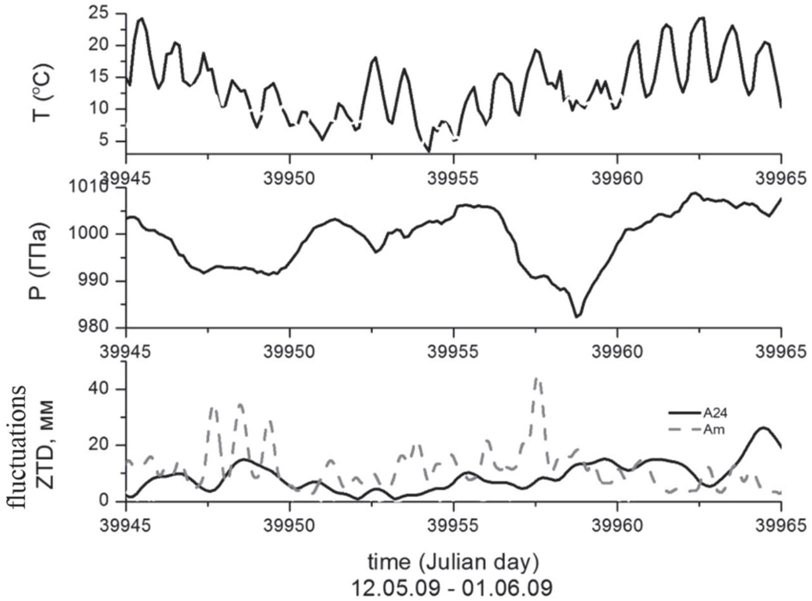

Figure 2. The series of surface temperature (*T*), pressure (*P*), diurnal amplitude (A24) and intensity of mesoscale fluctuations of the zenith tropospheric delay of GNSS signals (meso).

In winter, there is an increase in the intensity of the γ-mesoscale processes by an average of 20 % and a decrease in the intensity of the β-mesoscale by 15 % with positive values of surface daytime temperatures. Moreover, an increase in the amplitude of the diurnal variation of ZTD is also observed, which can be explained by an increase in the concentration of water vapor. A significant increase in the surface partial pressure of water vapor (up to 18 mb) coincides with a significant (up to 40 %) increase in the amplitude of variations of the γ-mesoscale, the daily course and amplitude of variations of the β-mesoscale increase by only 15 %.

Sometimes in winter, the increase in the meridional wind speed coincides with an increase in the intensity of mesoscale fluctuations by 15–20 %. Moreover, the north wind coincides with an increase in the amplitude of variations of the γ-mesoscale, and the south wind with an increase in the intensity of variations of the β-mesoscale.

The amplification from May to September of the southwest wind sometimes coincides with an increase in the amplitude of variations of the γ-mesoscale by 20–30 % and beta by 40 %. In summer, an increase in temperature often coincides with an increase in the intensity of both γ and β-mesoscale processes by 20 %.

In figure 3, one can see strong diurnal variations in the intensity of mesoscale processes, synchronous with the diurnal course of temperature. Perhaps this diurnal course is due to increased convection. To estimate the diurnal dynamics of mesoscale inhomogeneities from the experimental data of a network of receivers spaced at distances from 1 to 35 km, the horizontal structural functions ZTD were calculated and their diurnal behavior was constructed.

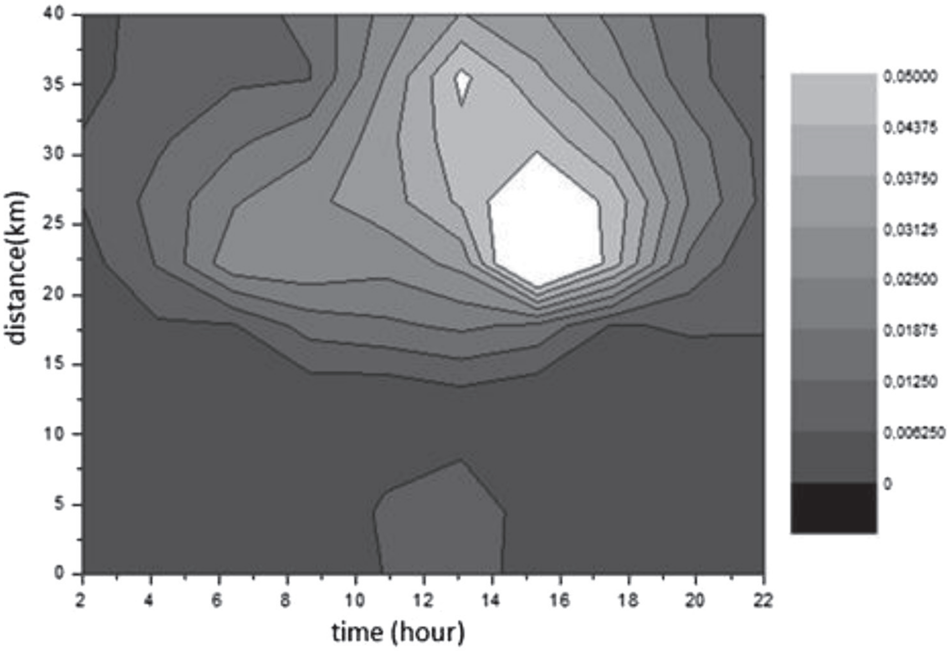

Figure 3. Daily variations in the structural function of the zenith tropospheric delay of GNSS signals in the region of spatial scales from 0.8 to 40 km August 23, 2009.

The physical meaning of the structural function is the mean of the square of the fluctuations of the investigated quantity in the region of the corresponding spatial or temporal scales in processes with a stationary increment [12].

$$D_{\mathrm{ZTD}}(r)=\left\langle\left(\mathrm{ZTD}(r+\mathrm{d}r)-\mathrm{ZTD}(r)\right)^{2}\right\rangle. \tag{3}$$

Here, the estimated value, presented as a function, r is the argument of this function, the distance.

3. Conclusion

The summertime period is selected because in summer the amplification of mesoscale eddies due to convection should manifest itself more strongly [11]. Observation periods for which there are no fronts are selected, the diurnal course of meteorological parameters is clearly manifested. An example of the variability of the structural function of the zenith tropospheric delay of GNSS signals during the day is presented in figure 3. The color scale is the value of the structural function in m^2.

It is seen that the maximum values are structural functions in the daytime, while the minimum values are observed in the morning and evening. The uneven growth of the structural function with increasing scale indicates the presence of coherent structures. This behaviour of the structural function means that in the daytime the dispersion of the refractive index in the horizontal direction increases in the range of scales of the order of tens of km. We suggest that this is due to an increase in convective instability in the daytime [11]. An analysis of the weather station data showed that in the daytime the average wind speed increased to 4 m/s, while in the morning and at night it was about 1 m/s. This indirectly confirms our assumptions about an increase in the hydrodynamic instability of the atmosphere in the daytime and, accordingly, an increase in mesoscale fluctuations of atmospheric density and tropospheric delay of radio waves.

Summarizing the patterns obtained, it can be assumed that the emergence and development of mesoscale processes in the troposphere is associated with several reasons.

In the warm season, as a rule, in the daytime, mesoscale dynamics is due to convection caused by heating of the underlying surface [11]. The flows of air masses created in this way form tropospheric inhomogeneities, which manifest themselves in the spatial-temporal structure of atmospheric density and are fixed.

In addition, at positive surface air temperatures, the amount of water vapor in the troposphere increases, and its field is substantially inhomogeneous [6]. Consequently, the contribution of water vapor inhomogeneities to the variation of the refractive index increases, which can also enhance the seasonal variation of fluctuations in the tropospheric delay of radio waves.

The influence of the pressure field on the intensity of the mesoscale dynamics of the troposphere is most likely also due to the complex effect of convection and increasing concentration of water vapor in the troposphere.

The revealed ambiguous relationship between the amplification of mesoscale ZTD fluctuations and the wind velocity field requires further research. We can assume the influence of orography on the occurrence of wave mesoscale processes, as, for example, in [3].

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4. References

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