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Evaluation of the atmospheric integral water vapor variability during strong convection

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ABSTRACT

This paper solves the problem of identifying the relationship between atmospheric parameters measured using GNSS receivers and the characteristics of convective processes according to monitoring data in Kazan for 2009-2021. It is shown that the statistical characteristics of the atmospheric integral water vapor significantly change depending on the indices depending on the potential available instability energy and vertical wind shear. This work was supported by the Russian Science Foundation (project no. 23-27-00222).

Keywords: water vapor, interannual variations, atmospheric circulation, troposphere, rain

1. INTRODUCTION

Due to climate change, the number of heavy showers, thunderstorms, squalls and other dangerous mesoscale weather events associated with convective processes is increasing. Monitoring and accurate prediction of mesoscale convective phenomena require experimental data with high temporal and spatial resolution. Satellite data does not always meet these requirements. In this regard, it is necessary to investigate the applicability of sub-satellite monitoring, for example, sounding of the troposphere using global navigation satellite systems (GNSS).

The main indicator of the influence of a neutral atmosphere on the propagation of satellite signals is the zenith tropospheric delay of GNSS signals ZTD[1]. The ZTD evaluates the integral water vapor of the atmosphere IWV - the content of water vapor in a vertical atmospheric column, usually measured in kg/m^2 or in millimeters of precipitated water.

Previously, the coherence and synchronism of variations in precipitation intensity and potential available energy of instability with variations in the zenith tropospheric delay of GNSS signals was shown[2].

In this work, We show the variability of the integral water vapor dependence on various indices of atmospheric instability, which characterized the high probability of dangerous mesoscale phenomena.

Kazan Federal University has developed its own TropoGNSS application, which allows estimating the ZTD and IWV tropospheric parameters. Verification of the IWV estimates obtained using TropoGNSS using independent data from solar photometers showed that the standard deviation in all seasons is 5–6% of the value of the integral water vapor content[3].

For 2009-2021 Kazan University received long series of GNSS data for monitoring the atmosphere in Kazan with a time resolution of 5 minutes. To estimate the intensity of convective processes, we are going to use various physical and statistical parameters of instability and compare them with the GNSS monitoring data from IWV.

For evaluation a convective processes, we using the physical and statistical parameters of instability calculated in the ECMWF model and presented as ERA5 reanalysis data. Based on data on wind speed and direction, humidity and air temperature at certain heights or isobaric surfaces, characteristics calculated that are often used to assess the probability of dangerous convective phenomena.

For comparison, we chose following indices[4], which characterize the probability of heavy showers, thunderstorms, and tornadoes.

Vertical Totals (VT) - temperature difference between 850 hPa and 500 hPa levels. This parameter characterizes the vertical temperature gradient and, accordingly, its stability.

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Total Totals TT - the final total TT increases with increasing humidity in the lower atmosphere and with increasing vertical temperature gradients

$$TT = T_{850} + Td_{850} - 2 \cdot T_{500} \tag{1}$$

Typically, the following three thresholds apply: TT. Thunderstorms possible at TT ≥ 44K; at TT ≥ 50K severe thunderstorms are possible, at TT ≥ 55K numerous severe thunderstorms are likely. he Whiting Index or K Index is calculated using the formula:

$$K\text{-}Index\ (K) = (T_{850} - T_{500}) + Td_{850} - (T_{700} - Td_{700}), \tag{2}$$

Typically, the following three thresholds apply: TT. Thunderstorms possible at TT ≥ 44K; at TT ≥ 50K severe thunderstorms are possible, at TT ≥ 55K numerous severe thunderstorms are likely.

The Whiting Index or K Index is calculated using the formula:

where T_{850}, T_{700}, and T_{500} are the air temperatures at the isobaric surfaces of 850, 700, and 500 hPa, respectively, °C; Td_{850} and Td_{700} - dew point temperature on the isobaric surface 850 hPa, and 700 hPa, °C. It is believed that with index values of 35 or more, the probability of developing thunderstorms exceeds 90%.

Iindices[5] are introduced that characterize the wind speed shift with height, calculated as the value of the difference in wind speed vectors at a height of 10 m from the Earth's surface and at a certain altitude level.

Wind shear in the 1 km layer or Low level Shear (LLS). At LLS values above 30 km/h (8.3 m/s), the probability of supercell tornadoes increases.

Wind shear in the 3 km layer - Mid-level Shear (MLS) is often used to provide a measure of convection longevity. The greater the shift, the longer the convection. Strong shear also contributes to high helicity values.

It is assumed[6] that classical supercell storms are associated with wind shear in the 6 km Deep Layer Shear (DLS). Deep shear is defined as the vertical wind shear between ground level (10 m altitude) and 6 km altitude. The threshold for a storm to occur is 40 knots (21 m/s).

Convection Inhibition Energy (CIN). Values CIN > 200 J/kg are sufficient to stop convection in the atmosphere.

Convective Available Potential Energy (CAPE) or the available potential energy of instability is the work that can be done by an air particle during adiabatic ascent. The index describes the stability of the atmosphere, with an increase in the probability of extreme precipitation increases. CAPE value of about 800 J/kg, the thunderstorm activity index strongly increases[8]. The probability of a tornado increases at CAPE values of 100–200 J/kg. Upward Vertical Velocity (UVV) is the maximum vertical wind speed[7] and is defined as

$$VGP = \sqrt{2 \cdot CAPE \cdot} MLS \tag{3}$$

The WMAXSHEAR complex index takes into account both vertical flow and wind shear[7]

$$WMAXSHEAR = \sqrt{2 \cdot CAPE \cdot} DLS \tag{4}$$

The result of intramass and frontal convective processes is the amount of precipitation (TP), which also serves as an indicator of the intensity of convection.

All of the above indices were calculated using ERA5 data for the coordinates of GNSS receiver antennas in Kazan. Since the original spatial resolution of ERA5 is 0.25 degrees, a two-dimensional non-linear interpolation was used to obtain these parameters at the coordinates of the GNSS receiver.

2. DATA AND ANALYSIS

For the period 2009-2021 (from April 15 to September 15) long series of all indices were calculated with a time step of 1 hour. For each of the parameters, according to their critical values, samples of the integral water vapor and its average hourly dispersion were formed, which characterized the conditions of weak and strong convection. We have chosen the critical value of total rainfall to be 1 mm, since a comparison of this parameter with weather station data showed that shower events are displayed in ERA5 grid nodes starting from this threshold. We compared the distributions of samples of the integral water vapor in pairs depending on each index. The following regularities have been obtained.

Using Pearson's test, it was shown that the distributions of IWV do not correspond to normal. Therefore, to pairwise check the differences in distributions for different indices corresponding to strong and weak convection, not only Student's and ANOVA tests were used, but also the Kruskal-Wallis test for checking distributions for compliance with their median values.

3. RESULTS AND DISCUSSION

Table 1 presents the boundary values of the convective indices used in the study to select GNSS monitoring samples and the corresponding values of the difference between the average and median values of the integral water vapor of the atmosphere with an increase in the convective index and with weak convection.

Table 1. Boundary values of convective indices and differences of IWV statistical characteristics

Convection parameter	**Boundary value**	**Difference in mean values IWV, mm**	**Difference median values IWV, mm**
LLS	17 m/c	Statistically insignificant	Statistically insignificant
MLS	16m/c	5,1	8,5
DLS	25m/c	2,2	3,1
VT	30K	2,8	5,6
TT	55K	7.6	10,1
К-индекс	40К	2,8	5,8
CAPE	800	11,4	11,6
UVV	40m/c	10,6	11,6
VGP	400 J.	11,4	11,8
WMAXSHEAR	800	8,9	9,3
CIN	-100	Statistically insignificant	Statistically insignificant
TP	1 mm	6,9	7,9

It was found that selection by wind shear in 1 km layer and by magnitude of energy of counteraction to convection does not give reliable differences of statistical parameters of integral moisture content. Selection by MLS, DLS, K, VT, TP, TT showed statistically reliable differences of distributions, but the value of difference of average IWV values corresponding to strong and weak convection is less than 7 mm of deposited water. Big differences of 10 mm gave such indices as TT, CAPE, VGP, WMAXSHEAR.

Examples of empirical IWV distributions for different convective conditions are presented on Fig.1., Fig.2. and Fig.3.

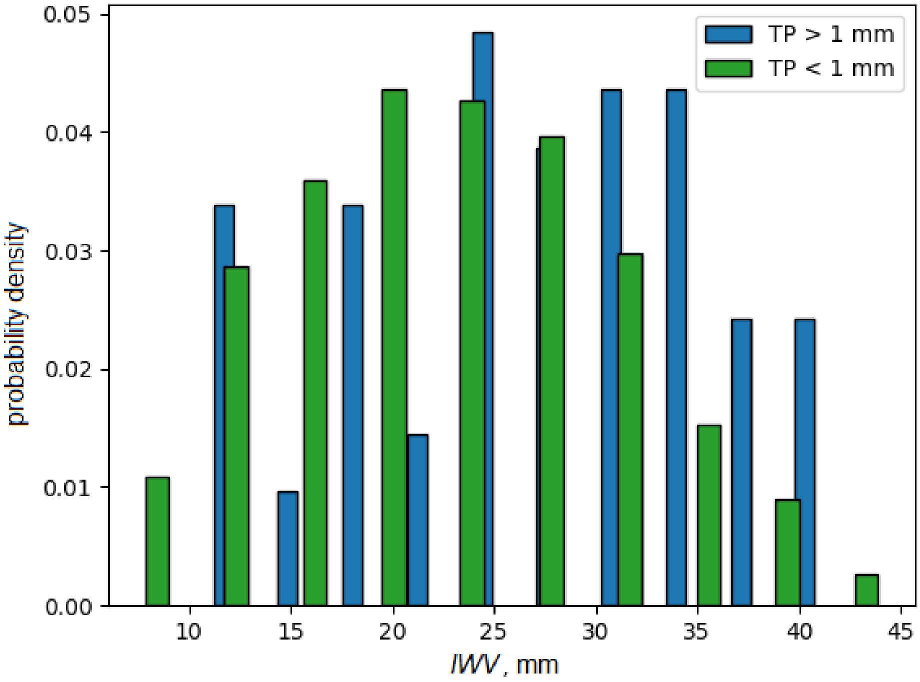

Figure 1. IWV distributions for different total precipitation

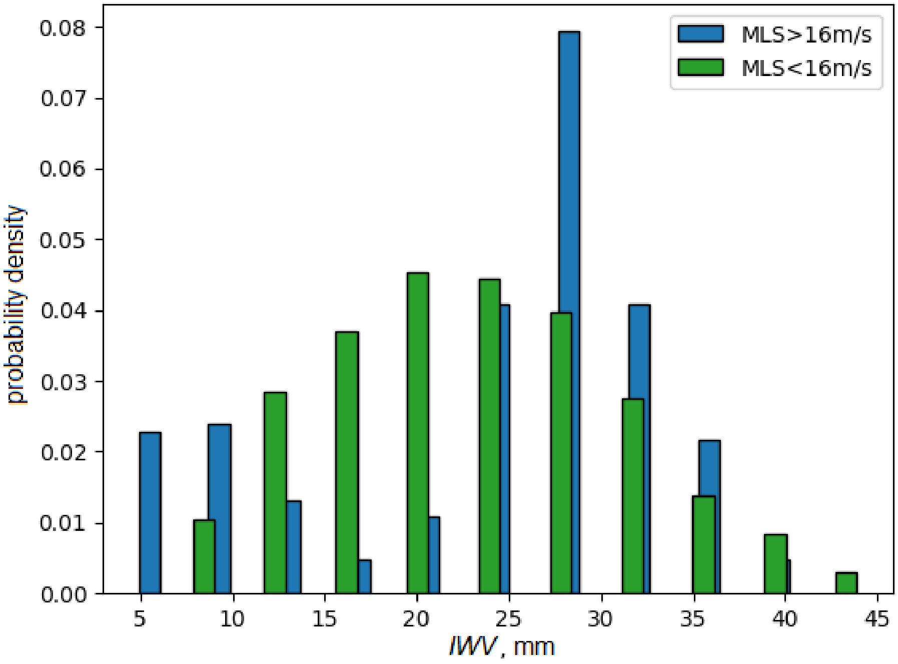

Figure 2. IWV distributions for different Mid-level Shear

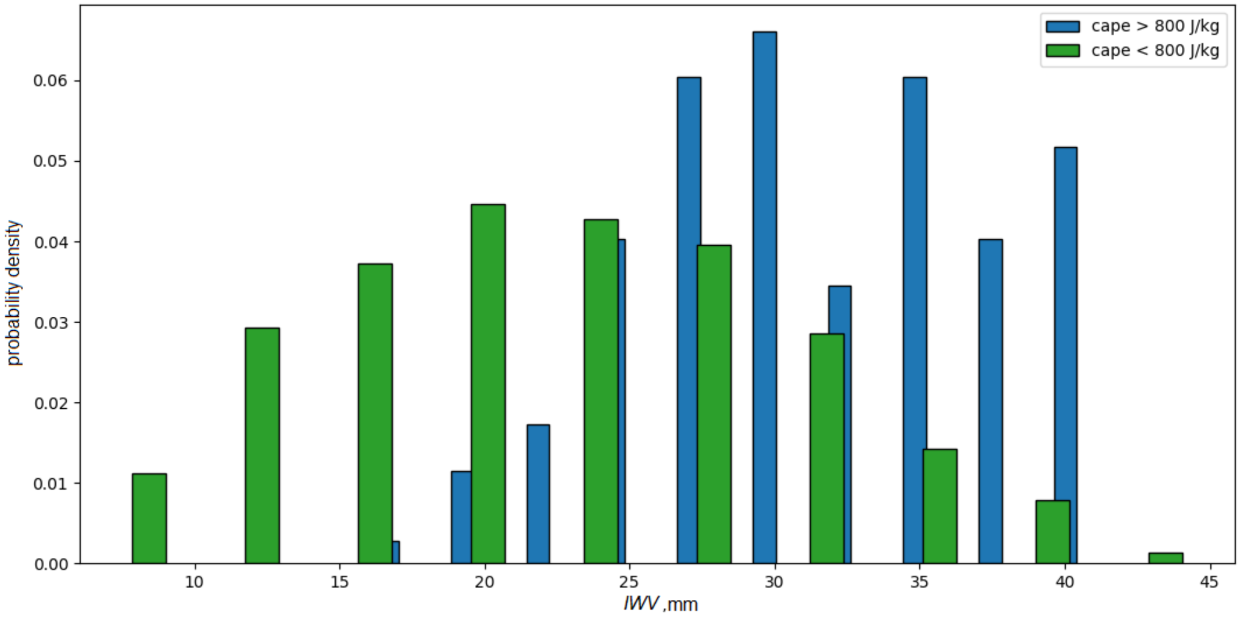

Figure 3. IWV distributions for different Convective Available Potential Energy

A wavelet correlation of the IWV time series with the time series of total precipitation, CIN, CAPE, and other convective parameters was calculated for 2010-2020.Fig. 4 shows of wavelet correlation with IWV variations. It can be seen that in most cases the correlation level is greater than 0.8. Fig. 5 shows the histograms of the distributions of the identified coherent variations scales. The coherence of variations in precipitation intensity and potential available instability energy with variations in zenith tropospheric delay is most often found on time scales smaller than 4 hours, as would be expected.

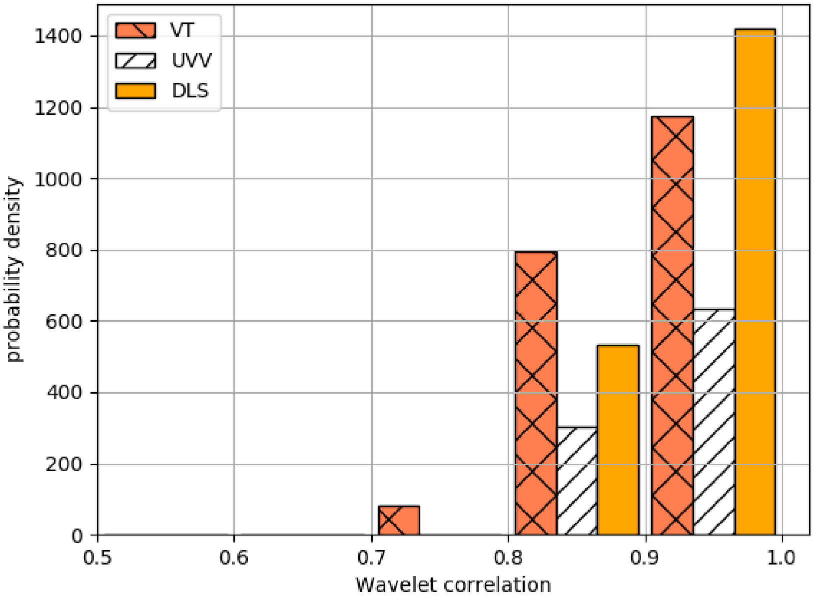

Figure 4. Wavelet correlation for IWV with Vertical total (VT), Upward Vertical Velocity (UVV) and Deep Layer Shear (DLS) coherent variations

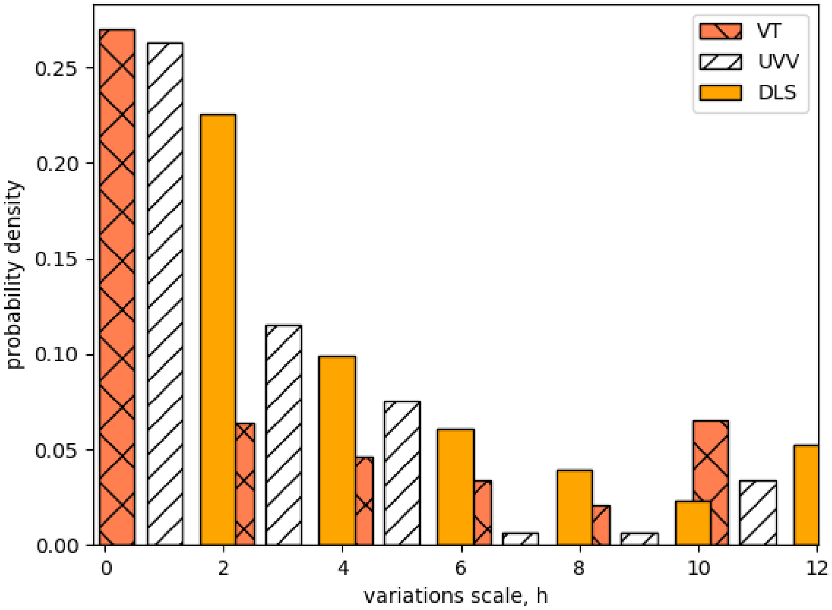

Figure 5. Coherent cariations scales for IWV with Vertical total (VT), Upward Vertical Velocity (UVV) and Deep Layer Shear (DLS)

The same results obtained for other convective indices, which shows the variability of the integral moisture content with increasing convection.

4. CONCLUSION

The results of our work, have shown that remote sensing of the troposphere with the help of global navigation satellite systems should definitely be used as a tool for monitoring convective processes. Statistical characteristics of the atmospheric integral water vapor significantly change depending on the indices depending on the potential available instability energy and vertical wind shear. Rapidly developing atmospheric inhomogeneities, which can be harbingers of dangerous weather events, such as heavy precipitation, thunderstorms and tornadoes, are reflected in coherent variations of the integral water vapor of the atmosphere, which can be estimated by existing networks of GNSS receivers with high time resolution.

5. ACKNOWLEDGMENTS

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