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FEATURES OF THE VERTICAL DISTRIBUTION OF THE WET COMPONENT OF ZENITH TROPOSPHERIC DELAY IN MIDDLE AND TROPICAL LATITUDES

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Introduction

Atmospheric air shows a natural mixture of gases, that can be divided into dry and moist air (that is, the one containing the water vapor). It depends on the amount of solid and liquid impurities and the content of water vapor in the air that depends on the absorption and diffusion of radiation. Therefore, the distribution of radio signals from navigational satellites to ground receivers through a neutral atmosphere is accompanied by a decrease in its speed. This process is called tropospheric delay. It is accepted to divide it into hydrostatic and wet components. The hydrostatic component, which basically depends on the composition of dry air, is rather accurately determined by the indicators of the surface meteorological values, in particular atmospheric pressure. Wet component, which depends directly on the concentration of water vapor in the atmosphere, is precisely impossible to simulate precisely because of the chaotic motion of water vapor in space. However, today a number of approaches and technologies have been developed that allow somehow to determine the content and distribution of water vapor in the atmosphere, in particular, atmospheric radio sounding, water vapor radiometers, hydrological systems, etc. However, the above-mentioned technologies have certain disadvantages associated with costly, long-term measurements and weather conditions, and therefore their use is not always advantageous. Recently, the content of water vapor in the atmosphere began to be determined by the signals of global navigation satellite systems. Since GNSS observations are continuous and not weather-dependent, and the GNSS station network is well developed, this approach is very convenient and cost-effective. As already noted, water vapor is the main factor affecting the accuracy of GNSS measurements, since the value of the wet component of the zenith tropospheric delay (ZTD) depends directly on its concentration in a neutral atmosphere. Actually, it is precisely the inverse problem of GNSS-measurements, and they determine the wet component of the ZTD.

The tropospheric delay has been studied for several decades by different scholars. The features of the zenith tropospheric delay in the tropical zone, determined by the data of the radio sounding and analytical models, are covered in articles [2, 3, 13, 14]. Analysis of the ZTD in the middle latitudes is given in the works [4, 5, 7, 10, 11, 15]. However, no comparisons have yet been made between the values of the ZTD obtained from the aerological and GNSS stations located in the middle and tropical latitudes.

Aim

The main objective of the work is to investigate the vertical distribution of the wet component of the zenith tropospheric delay, based on the materials of the radio sounding in the middle latitudes and to compare the obtained results with the corresponding values obtained in the tropical zone. Also, a comparison of these values with the corresponding values of the wet component of the ZTD, derived from the GNSS-measurements.

Methodology and results of work

According to the initial data in the study, vertical profiles of the main meteorological values (atmospheric pressure P, air temperature t, relative humidity U) were obtained from radio sounding during ten-day periods (mostly from 11 to 20) in January and July 2013 at six aerological stations [8]. In general, the stations were selected in the central-eastern region of Europe, located about 50th parallel. The exception is the Voaykovo station (St. Petersburg, Russia), which is shifted 10 ° to the north. Similar data was also selected for three stations located in the equatorial zone. The coordinates of stations are shown in Table 1.

Table 1

Coordinates of stations

Aerological stations			GNSS stations			Country	Distance, km
Latitude 0° 00′	*Longitude 0° 00′*	*Height, m*	*Latitude 0° 00′*	*Longitude 0° 00′*	*Height, m*		
1	2	3	4	5	6	7	8
Middle latitudes							
Praha, 11520			GOPE			Czech Republic	28,0
50 00	14 27	303,0	49 54	14 47	592,6		

Kyiv, 33345			GLSV			Ukraine	4,0
50 23	30 33	167,0	50 22	30 30	226,8		
Legionowo, 12374			BOGI			Poland	10,9
52 23	20 57	96,0	52 28	21 02	139,9		
Budapest, 12843			BUTE			Hungary	10,6
47 25	19 10	139,0	47 29	19 04	180,1		
Poprad, 11952			GANP			Slovakia	1,2
49 02	20 18	706,0	49 02	20 19	745,2		
Voejkovo, 26063			PULK			Russia	28,8
59 57	30 41	78,0	59 46	30 20	101,2		
Tropical latitudes							
Guam, 91212			GUAM			USA	15,8
13 28	144 47	75	13 35	144 52	201,9		
Singapore, 48698			NTUS			Singapore	35,4
1 22	103 59	16,0	1 20	103 40	79,0		
Pago Pago, 91765			ASPA			USA	1,8
-14 20	-170 43	3,0	-14 19	-170 43	53,7		

1. Interpolation meteorological parameters. The nearest GNSS station with known zenith tropospheric delays was selected to each of the aerological stations. As can be seen from Table 1, the smallest distance between stations is 1.2 km, and the longest is 35 km. Since the selected GNSS stations are located closest to the neighboring aerological, it can be assumed that the vertical profiles of the main meteorological values at these stations are the same. Some authors, in their studies, used data from stations, the distance between which was, for example, 50 km [15]; 70 km [10]; 100 km [11].

For analysis, we used the values of ZTD obtained from aerological sounding data (0 UT), which we adopted as reference (although, of course, this is a relative such name, because the tropospheric delay value will contain some minor errors, first of all, caused by errors in the measurement of such elements quantities such as atmospheric pressure, temperature and humidity of air). Since the maximum heights achieved by bullets - the probes during the radiosonde on the selected stations were on average about 35 km, from this height to 80 km, the pressure and temperature were chosen from the standard atmospheric model (SMA-81) [1]. This allows the most accurate calculation of the full tropospheric delay, since even a layer of 70-80 km still gives an error of 0.1 mm due to the hydrostatic component. Above 80 km this error is - 0.01 mm or less than can be neglected.

According to Table 1, there is a significant elevation difference between aerological and GNSS-stations, which varies from 23 to 290 m. That corresponds to atmospheric pressure differences from 1.8 to 23.2 hPa. It should be noted that the accuracy of measurement of meteorological elements by digital meteorological stations reaches 0.1 hPa of atmospheric pressure, 0.1 ˚C of air temperature and 3% of relative humidity, and optimal errors make for atmospheric pressure 0.5 hPa, air temperature 0.5 ˚ C and relative humidity of 5%, which gives an error in the size of the ZTD at the sea level due to: atmospheric pressure 13,3 mm; air temperature 2,5 mm; and relative humidity 14 mm. Taking into account that, atmospheric pressure P plays a major role in the formation of ZTD, then reduce it follows the formula (1) [6]. As far as air temperature t and relative humidity U are concerned, in small layers of probing their values with sufficient accuracy can be determined by linear interpolation (formulas 2 and 3):

$$\Delta P = P_0 \exp\left[-\frac{g}{R \cdot T_m} (H_{i+1} - H_i) \right] \quad (1)$$

$$\Delta t = \frac{(H_{i+1} - H_i) \cdot (t_{i+1} - t_i)}{H_{i+1} - H_i} + t_i \quad (2)$$

$$\Delta U = \frac{(H_{i+1} - H_i) \cdot (U_{i+1} - U_i)}{H_{i+1} - H_i} + U_i \quad (3)$$

where g - gravity; , - the height limiting the atmosphere in which the GNSS station is located is the average temperature in the atmosphere layer. R - constant gas became.

Table 2 shows, averaged over a ten-day period, the values of the hydrostatic component of the ZTD, calculated from the data of the radio sensing and the model Saastamoinen. These values are given both taking into account the following, and without taking into account the reduction of the atmosphere to the altitudes of the corresponding GNSS stations.

Table 2

Averaged values of the hydrostatic component of ZTD

The name of the stations	ΔH	Aerology			Model Saastamoinen			Min deviations from average values	Max deviations from average values
		${}_{cep}d_h^z$		Δd_h^z	${}_{cep}d_h^z$		Δd_h^z		
		Not Reduced	Reduced		Not Reduced	Reduced			
		January							
		Middle latitudes							
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Praha-Libus - GOPE	289,6	2218,0	2138,1	80,0	2217,4	2137,4	80,1	-19,5	22,1
Kyiv - GLSV	59,8	2274,5	2257,2	17,3	2267,1	2250,1	17,0	-26,4	26,1
Legionovo - BOGI	43,9	2276,2	2263,6	12,7	2274,4	2261,4	13,0	-32,0	24,8
Budapest - BUTE	41,1	2286,3	2274,6	11,7	2283,0	2271,5	11,4	-20,7	21,8
Poprad-Ganovce - GANP	39,2	2096,0	2085,6	10,4	2097,5	2087,0	10,5	-28,2	13,6
Voejkovo - PULK	23,2	2298,7	2291,8	7,0	2292,1	2285,2	6,9	-15,4	30,8
Tropical latitudes									
Guam - GUAM	126,9	2284,5	2252,1	32,4	2291,9	2259,4	32,5	-4,2	3,9
Singapore - NTUS	63	2300,0	2283,7	16,3	2302,3	2286,6	15,8	-4,7	11,7
Pago Pago - ASPA	50,7	2287,2	2274,2	13,0	2294,1	2281,2	12,9	-8,1	7,8
July									
Middle latitudes									
Praha-Libus - GOPE	289,6	2241	2166,7	74,7	2243,6	2168,8	74,8	-13,7	11,2
Kyiv - GLSV	59,8	2260	2244,2	15,7	2263,0	2247,5	15,5	-18,0	10,2
Legionovo - BOGI	43,9	2289	2277,4	11,8	2292,4	2280,4	12,0	-25,7	15,2
Budapest - BUTE	41,1	2279	2268,4	10,8	2282,3	2271,6	10,7	-12,8	18,7
Poprad-Ganovce - GANP	39,2	2131	2121,5	9,6	2135,5	2125,7	9,7	-8,7	11,2
Voejkovo - PULK	23,2	2281	2274,3	6,3	2281,2	2275,0	6,1	-17,7	14,2
Tropical latitudes									
Guam - GUAM	126,9	2277,4	2245,5	31,9	2286,2	2253,8	32,4	-2,7	3,4
Singapore - NTUS	63	2286,7	2270,5	16,2	2297,1	2280,4	16,7	-2,3	3,1
Pago Pago - ASPA	50,7	2298,6	2286,0	12,5	2307,1	2294,4	12,7	-2,4	4,7

Table 2 presents the following designations - elevation difference between aerological and GNSS stations; - averaged over a ten-day period the magnitude of the hydrostatic component of the ZTD; - the difference of the hydrostatic components, determined both taking into account and without interpolation of meteorological parameters.

Analyzing the data in Table 2, it can be argued that the higher the vertical displacement between the heights of the stations, the greater the difference between the hydrostatic component. So at = 289.6 m the difference of the hydrostatic components is ≈ 80.0 mm, and at = 23.2 m, respectively, ≈7.0 mm. It should be noted that similar results are given in [10]. Similarly, the obtained values of the wet component of ZTD, their indicators are shown in Table. 3.

Table 3

Averaged values of the wet component of the ZTD

The name of the station	ΔH	Aerology			Saastamoinen			Min deviations from average values	Max deviations from average values
		$_{cep}d_w^z$		Δd_w^z	$_{cep}d_w^z$		Δd_w^z		
		Not Reduced	Reduced		Not Reduced	Reduced			
		January							
		Middle latitudes							
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Praha-Libus - GOPE	289,6	49,5	43,9	5,7	43,0	38,8	4,2	-11,3	17,7
Kyiv - GLSV	59,8	56,7	55,7	1,0	34,7	34,7	0,0	-51,5	34,6
Legionovo - BOGI	43,9	50,1	46,8	3,3	38,7	38,7	0,0	-39,3	23,2
Budapest - BUTE	41,1	59,2	58,1	1,1	58,1	56,9	1,1	-35,3	31,0
Poprad-Ganovce - GANP	39,2	64,4	63,5	0,9	48,7	47,7	1,0	-35,7	27,9
Voejkovo - PULK	23,2	44,5	44,2	0,3	24,3	24,8	-0,4	-25,6	25,6
Tropical latitudes									
Guam - GUAM	126,9	209,1	194,9	14,2	280,6	251,8	28,8	-81,7	72,8
Singapore - NTUS	63	326,0	319,2	6,7	231,9	255,1	-23,1	-76,8	47,3
Pago Pago - ASPA	50,7	325,8	319,5	6,3	299,2	277,0	22,3	-62,8	109,5
July									
Middle latitudes									
Praha-Libus - GOPE	289,6	121,6	116,6	5,0	137,5	119,6	17,9	-47,0	14,7
Kyiv - GLSV	59,8	149,5	145,7	3,9	144,8	143,9	0,9	-38,6	32,5
Legionovo - BOGI	43,9	144,7	141,9	2,8	143,2	142,8	0,4	-83,5	51,8
Budapest - BUTE	41,1	159,1	156,3	2,8	154,4	152,1	2,2	-50,5	49,2
Poprad-Ganovce - GANP	39,2	119,6	117,5	2,1	129,3	110,1	19,2	-22,0	26,8
Voejkovo - PULK	23,2	136,9	135,6	1,3	123,4	125,1	-1,7	-43,2	25,5
Tropical latitudes									
Guam - GUAM	126,9	310,2	294,6	15,6	323,4	278,7	44,7	-26,7	25,8
Singapore - NTUS	63	332,6	325,1	7,5	264,6	316,9	-52,3	-35,6	76,4
Pago Pago - ASPA	50,7	284,1	278,1	6,0	303,2	269,6	33,6	-38,9	57,4

Table 3 gives the following notation: - averaged over a ten-day period of the value of the wet component of the ZTD; - the difference between wet components, determined both with and without interpolation of meteorological parameters.

Having analyzed the table. 3, it should be noted that there is no clear pattern between the differences and the differences in the wet component, although, according to the radio sounding data, the differences mostly fall down. As far as the values obtained for the Saastamoinen model are concerned, both negative and positive values are present, and this confirms once again that the moisture content of the ZTD can not be modeled with satisfactory accuracy on the analytical models.

Table 4 for some stations shows the interpolated values of the wet components of the ZTD (for 0 hours UT), obtained from aerological sounding data and derived from GNSS observations. The values are submitted in ten days in January and July 2013.

Table 4

Daily values of the wet component of ZTD and their differences

Kyiv-GLSV			Praha-libus-GOPE			Pago Pago-ASPA		
$d^z_{w_{AER}}$	$d^z_{w_{GNSS}}$	Δd^z_w	$d^z_{w_{AER}}$	$d^z_{w_{GNSS}}$	Δd^z_w	$d^z_{w_{AER}}$	$d^z_{w_{GNSS}}$	Δd^z_w
January, 2013								
43,9	41,7	2,2	55,1	65,3	-10,2	290,4	326,2	-35,9
48,4	47,4	1,0	26,1	36,1	-9,9	250,6	300,8	-50,2
83,1	92,4	-9,4	36,7	44,5	-7,8	365,4	370,4	-5,0
107,2	112,9	-5,8	38,4	46,5	-8,2	352,7	411,0	-58,3
42,7	43,9	-1,2	44,4	51,4	-6,9	363,8	396,3	-32,5
21,1	15,3	5,8	39,8	51,0	-11,2	382,3	428,9	-46,6
29,9	32,8	-2,9	53,9	65,3	-11,4	360,9	427,5	-66,6
52,1	56,3	-4,2	49,9	56,1	-6,2	370,7	380,9	-10,2
48,3	48,4	-0,1	51,8	65,7	-14,0	210,0	232,0	-22,0
80,1	91,7	-11,6	42,4	52,8	-10,3	248,7	285,9	-37,3
July, 2013								
140,2	148,7	-8,5	102,0	113,1	-11,1	277,2	320,1	-42,9
130,8	137,8	-6,9	121,4	127,1	-5,7	283,6	316,9	-33,3
184,3	217,3	-32,9	118,9	136,0	-17,1	264,6	301,1	-36,6
158,0	160,0	-2,0	116,5	129,3	-12,8	314,2	340,6	-26,4
134,8	126,9	7,9	105,1	128,0	-22,8	317,0	341,0	-24,0
176,2	176,0	0,1	108,0	127,1	-19,1	278,7	320,4	-41,7
123,4	129,8	-6,4	163,6	168,0	-4,4	302,3	345,1	-42,8
169,6	166,1	3,5	106,0	114,7	-8,7	225,3	274,3	-49,0
126,4	103,1	23,3	111,7	118,6	-6,9	297,3	352,9	-55,5
113,2	100,9	12,3	113,2	132,7	-19,5	220,7	263,3	-42,6

2. Distribution of the contents of the wet component in height. In order to analyze the high-altitude distribution of the wet component content, its integration into different layers of the troposphere, limited by standard isobaric surfaces, was performed: P0 - pressure at the GNSS station level, 850 hPa, 700 hPa, 500 hPa, in. - the upper limit of sensing the relative humidity. The thickness of the layers bounded by height with such isobaric surfaces is approximately P0 - 850 hPa = ~ 1500 m in the metric extent; 850 - 700 hPa = ~ 1500 m; 700 - 500 hPa = ~ 3000 m; 500 is the upper limit of the sensing of relative humidity U. For the analysis of the distribution of the content of the moist component with height, vertical profiles of the main meteorological values obtained from radio sounding with unconstrained meteorological parameters were selected because they include the lower layers of probing, which in turn will allow more accurate estimation of the content of the wet component ZTD. The obtained results are presented in figures 1 and 2.

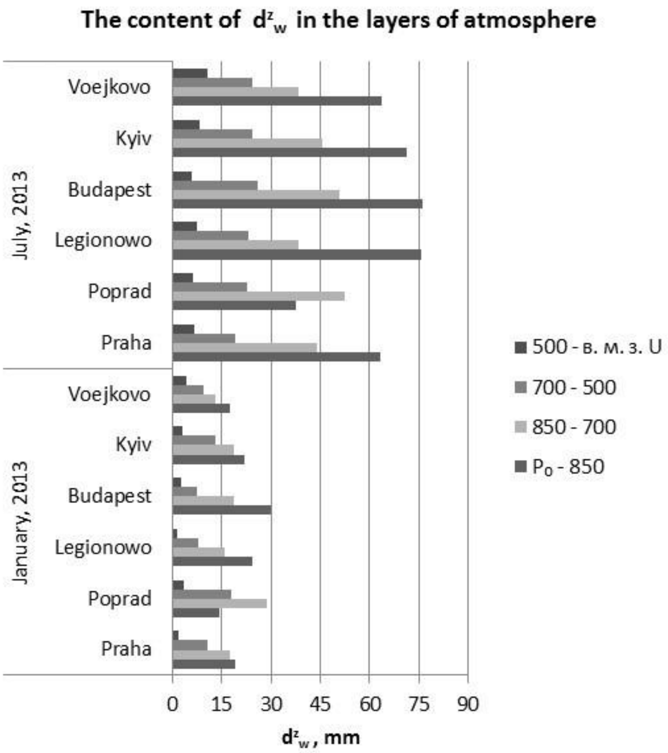

Fig.1 Averaged values in different layers of the atmosphere in the middle latitudes

From the figure it is clear that more than 90% of the content of the wet component of the ZTD is concentrated in the three lower layers of the troposphere, namely in the total layer P0 - 500 hPa. The largest value falls on the layer P0 - 850 hpa, except for Poprad station. This is directly related to the height of the aerological station, which is 706 m and is the highest of all other stations. According to the results presented in Fig. 1, it is evident that the values in different layers of the troposphere during the winter period on average vary in the range from 2 mm in the upper to 30 mm in the lower one. In the summer, this indicator grows almost more than twice, due to much higher temperatures and, consequently, the content of water vapor in the atmosphere.

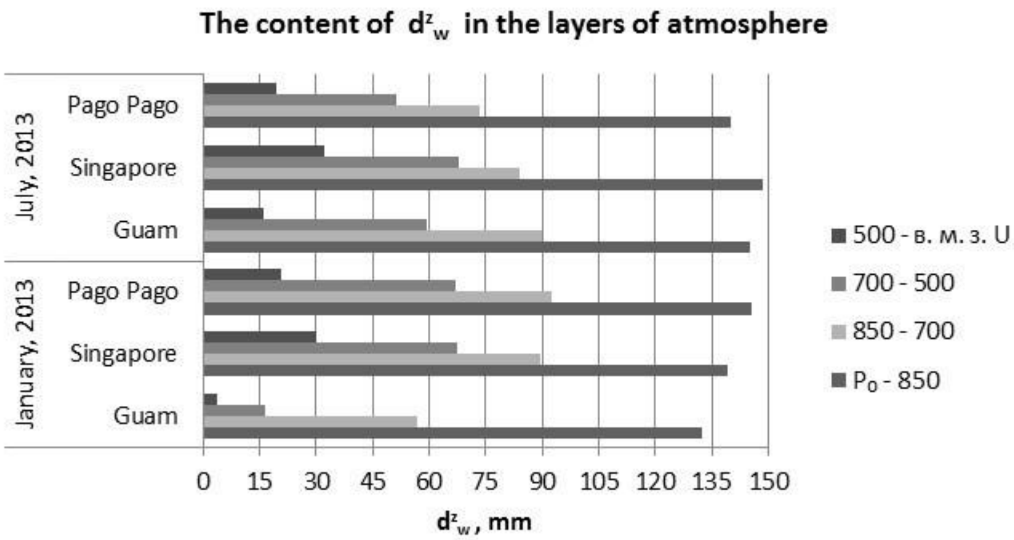

Fig.2 Averaged values in different layers of the atmosphere in tropical latitudes

As for temperate and tropical latitudes, it is characteristic that the main part of the wet component of the ZTD is concentrated in the three lower layers of the troposphere to an altitude of about 6 km. However, as can be seen from the schedule, in the tropical zone of magnitude both in the summer, both in the winter and in the winter, practically the same. For the corresponding layers, they range in the range from 5 to 150 mm, but almost twice the average latitudes in July, and approximately four times in January. Such stable values are associated with the same climatic conditions, usually with high temperatures that are typical of the tropics throughout the year.

3. Comparison of wet component obtained from radio sounding and GNSS measurements. To obtain the value of the wet component of the GNSS measurements, it is necessary to subtract the hydrostatic component, calculated as a rule by the formula Saastamoinen ($d^z_{w_{GNSS}} = d^z_{GNSS} - d^z_{h\,SA}$), from the complete ZTD. It should be noted that the values of the complete ZTD with a time interval of 5 minutes and 1 hour are given in the tropospheric files that are created at the centers of GNSS measurement for every day. They contain an array of averaged values of the total ZTD and are stored in the archives of Internet resources, in particular in documents [9, 12] respectively. For these stations, these files were downloaded to the same day of the radio sounding. For objective comparison of the values d^z_w, the data of aerological sounding with reduced meteo-objects ($_{\text{інт.}}d^z_{w_{AER}}$) was taken into account. It should be noted that the values δd^z_w ($\delta d^z_w = d^z_{w_{GNSS}} - {}_{інт.}d^z_{w_{AER}}$) characterize the accuracy of the determination of the wet component of the ZTD.

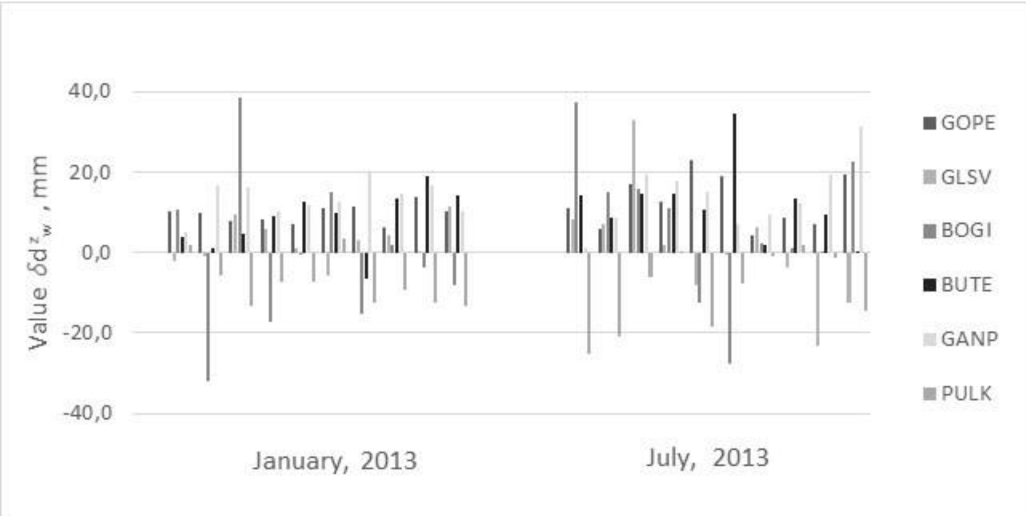

Fig. 3 Changes in the values for the middle decades of January and July 2013 at mid-latitudes

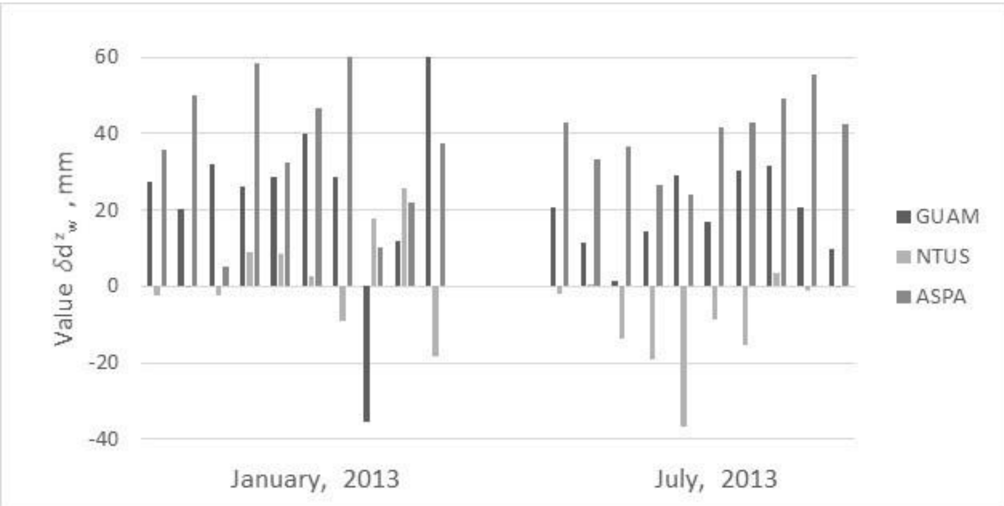

Fig.4 Changes in values for the middle decades of January and July 2013 at tropical latitudes

As can be seen from the graphs shown above, the magnitudes, as already noted, characterize the accuracy of the wet component, according to the stations of the middle latitudes, are both positive and negative, and in most cases fluctuate within -20 to 20 mm. In tropical latitudes, these indices are mostly positive and average values reach 40 mm.

Conclusions

As a result of the carried out researches it is possible to draw conclusions:

• Reducing of meteorological elements of aerological stations is carried out with the purpose of objective estimation of the values of the wet component received both from radio sounding and from GNSS measurements. But since the reduction of meteorological elements is carried out to the altitudes of GNSS stations (which are usually higher than their corresponding air stations), the lower layers of sounding are not taken into account when reducing, since they are limited to the height of the GNSS stations. Basically, this vertical displacement of stations affects the value of the hydrostatic component: at = 289.6 m, the difference of the hydrostatic components reaches 80.0 mm, and at = 23.2 m, 7.0 mm.

• The results of the integration of the wet component on the standard isobaric surfaces show that, as in the middle and tropical latitudes, the lion's share of the wet component is concentrated in the three lower tropospheric layers. For moderate latitudes, the values in the winter range on average vary in the range from 2 mm in the upper layer to 30 mm in the lower. In the summer, this indicator is almost doubling, as at this time the content of water vapor in the air is also increasing. In the tropics, these values range from 5 to 150 mm during the year, and about twice the average latitudes in July and approximately four times in January.

• When comparing the wet components of the ZTD obtained from the data of radio sounding and GNSS measurements, the values characterizing the accuracy of the wet component are calculated. According to the stations of the middle latitudes, they are both positive and negative, and in most cases fluctuate within -20 to 20 mm. In tropical latitudes, these indices are mostly positive and averaging 40 mm.

Subsequently, on the basis of the obtained results, after conducting additional calculations, it is planned to determine the content of the deposited water vapor in the atmosphere, as well as increase the number of research stations and experimental data.

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