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Synoptic Level Fluctuations of the White Sea

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The level fluctuations of the White Sea (WS) in the synoptic range of time scales including tides and surge fluctuations are considered based on observational data covering the period 2004–2020. The hourly level observation data of the coast stations were used: Sosnovets, Severodvinsk, Solovki, Kem-Port, Kandalaksha, as well as in the area of the White Sea Biological Station of Lomonosov Moscow State University (WSBS MSU) in 2008–2009. The values of spring and neap tides at these points are refined, and their features such as parallax inequality and the influence of shallow water components are considered. The surge run-offs and run-ups are explored based on the analysis of residual sea level fluctuations (RSL), which is determined by removing the tidal component from the observational data. The RSL fluctuations in the Dvina Bay are characterized by the greatest variance. The RSL fluctuations at Solovki and Sosnovets have approximately the same variance, which is significantly lower than in the Dvina Bay. The lowest variance is observed at Kandalaksha. According to the data obtained at the Severodvinsk and Solovki stations, a noticeable increase in RSL variance is observed, which indicates that the intensity of RSL fluctuations increased during the time interval under consideration. This conclusion is also confirmed by the calculations of the positive RSL values survivor function, as well as by the fact that the number of surge run-ups with a height of no less than 100 cm for 11 years (from 2004 to 2014) was only two, and in the six-year period (2015–2020) there were already five such events. The largest surge run-ups at Severodvinsk during the period under review reached a height of 130 cm (August 22, 2018) and 153 cm (November 15, 2011). Significant surge run-offs occur less frequently than surge run-ups and, as a rule, are inferior to the latter in their absolute value. The surge run-off on January 31, 2005 was the strongest for the entire period of 2004–2020. At Severodvinsk RSL decreased by 123 cm below the average monthly mark. In other cases, the most significant RSL falls relative to the average monthly value were about 70 cm.

Keywords: Tides, residual sea level (RSL), storm surge fluctuations, variance, survivor function, synoptic situations, surge run-up and surge run-off characteristics, interannual variability

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Introduction

In this paper, the RSL sea level fluctuations in the WS are considered in the synoptic range, which includes time scales from several hours to several days and weeks [*Monin*, 1982]. The significant residual sea level fluctuations (RSL) are observed in the synoptic range, among which the surge run-offs and surge run-ups that occur as a result of meteorological factors, mainly such as changes in surface atmospheric pressure (SAP) and wind forcing, play the most important role. The synoptic range also includes tides. In this paper, the main attention is paid to the study of surge fluctuations of the RSL in the White Sea (WS), where they are often comparable in magnitude to the tides.

Storm surge run-ups, which are a significant increase of RSL relative to the mean position, are formed in coastal areas during the passage of cyclones as a result of the atmospheric pressure drop and wind forcing. Under certain conditions, significant sea level falls, called surge run-offs, also occur in coastal areas.

Storm surge run-up and associated flooding of coastal areas are among the most dangerous natural phenomena that require intensive fundamental and applied scientific research in order to ensure safe and efficient economic activity in the sea coastal zones. Since a significant rise in the mean sea level is predicted in the current century, and as a result, an increase in storm surge run-ups, studies of the latter are becoming increasingly important. In this paper, surge fluctuations in the level of the WS are considered based on the ob-

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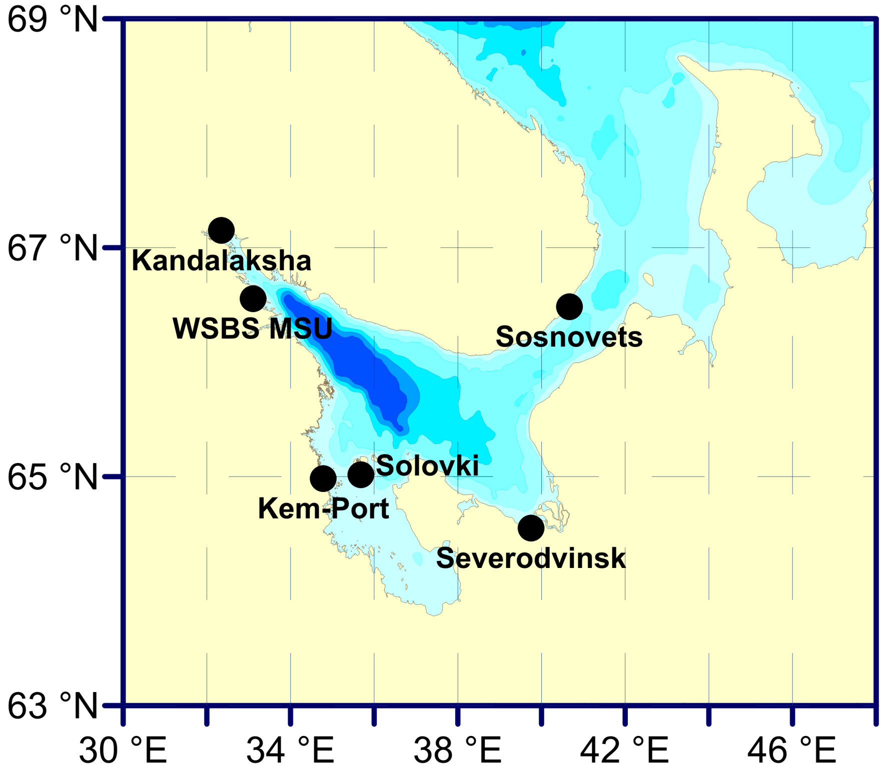


Figure 1: Scheme of observation stations location.

servational data analysis in 2004–2020 at a number of stations in the WS. Seventy cases of surge run-ups were identified, during which the maximum RSL rise in Severodvinsk relative to the average monthly values was at least 0.5 m. The surge run-ups, like surge run-offs, are considered in conjunction with the synoptic situations in which they occurred. In addition, the interannual variability of synoptic fluctuations in RSL was studied in order to establish the trend of changes in the intensity of the latter.

Materials and methods

The article uses the hourly sea level observations data at Sosnovets, Severodvinsk and Solovki stations for the period from 2004 to 2020, as well as some data obtained at the Kem-Port station in 2004–2005, and in the area of the White Sea Biological Station of Lomonosov Moscow State University (WSBS MSU) in 2008–2009, as well as at Kandalaksha in 2017–2019 (Figure 1).

Tidal fluctuations were obtained using harmonic analysis of observational sea level data. The harmonic analysis of tidal oscillations was performed using the T_TIDE software package [*Pawlowicz et al.*, 2002] using the least squares method. It should be emphasized that the harmonic constants used in this work are determined at a 95% confidence level; therefore, the tidal oscillations proper are calculated with a high degree of accuracy. The tidal component is subtracted from the observational data to obtain the RSL. However, it is not possible to completely exclude oscillations with tidal periods. The time series thus obtained contain minor fluctuations at tidal frequencies. It was shown in [*Horsburgh and Wilson*, 2007] that the residual level fluctuations at tidal frequencies are largely an artifact that arises in the process of subtracting the tidal component from the measured total level fluctuations. In order to quantify true sea level changes due to meteorological forcing, these residual tidal fluctuations must be eliminated. For this purpose, we used a 6th order tangential Butterworth filter with a cutoff frequency of 0.04 c/h, corresponding to a period of 25 hours. The Butterworth filter is widely used in oceanographic research due to its high efficiency in removing tidal variability [*Emery and Thomson*, 2001]. Its transfer function has an almost flat horizontal response in the pass and stop bands, and falls off steeply near the cutoff frequency. The steepness of the transition between the pass and stop bands increases with increasing filter order. However, too steep a transition between these bands leads to distortion of the output signal at the ends of the record in the form of false oscillations. With a sufficiently large slope of the 6th order filter transfer characteristic at the cutoff frequency, about 50 values turn out to be corrupted, which must be discarded. In our case, this is an insignificant loss, since series containing several thousand members are analyzed. Increases and decreases of RSL during surge run-ups and surge run-offs are given relative to average monthly values. All calculations and graphical constructions were performed in the MATLAB computing environment. The survivor function of RSL deviations from the mean value was calculated on the basis of a Nonparametric fit using the Distribution Fitting Tool (dfittool) software.

Synoptic situations were analyzed using SAP maps based on CFSR reanalysis and published on the website [http://www.wetterzentrale.de].

History of research

The study of synoptic level fluctuations in the WS, which include tides and storm surges, has a long history.

The results of these studies are summarized in monographs [*Filatov et al.*, 2005; *Terziev et al.*, 1991]. These results mainly refer to the period before the 1980s and therefore need to be refined and substantially supplemented with the involvement of new data. In particular, these works show that storm surges in the WS are often induced. Western cyclones passing over the waters of the Barents and White Seas generate a baric wave in the waters of the Barents Sea (BS), which then penetrates into the WS and induces surge run-up.

The work [*Inzhebeikin*, 2003] presents the results of studies of the White Sea level fluctuations over a wide range of time scales. On a synoptic scale, based on numerical calculations, the interaction of tides and surges is considered.

In recent years, synoptic level fluctuations in the WS have continued to attract much attention of researchers and have been considered in a number of works based on the observational data analysis, as well as with the numerical modeling involvement.

Three main types of surge run-ups were described in [*Kondrin*, 2012] on the basis of observational data at the WSBS MSU in Kandalaksha Bay. There are the following types: 1) baric, which is a static response of the sea level to a fairly long SAP decrease; 2) wind, resulting from the action of surge wind; 3) wave, induced by a baric wave arising in the BS.

In [*Kondrin*, 2016], based on observational data at 4 water gauges stations, the RSL fluctuations were considered on a synoptic time scale, which made it possible to study in more detail the characteristics and features of the storm surges formation in various synoptic situations. At the same time, an assessment is made of the relative role of the main meteorological factors, such as atmospheric pressure fluctuations and wind impact.

In [*Kondrin et al.*, 2018; *Korablina et al.*, 2017] a comprehensive quantitative description of surge run-ups in the WS is given based on the numerical simulation results. The quantitative distribution of surge run-up events by height and by individual months is given for various stations on the WS coast. The seasonal and interannual variability in the number of surge run-ups at various stations in the sea is considered based on these results. The contribution of wind, atmospheric pressure, and wind waves to surge run-up formation is estimated.

The discussion of the results

Tides. Tides in the WS, with the exception of a few locations, are of a pronounced semidiurnal nature and make the main contribution to sea level variability in the synoptic range. The spring tide reaches 6 m in the southern part of the WS Funnel (Russian: Voronka), and 8 m in the Mezen Bay. In the Basin, the spring tide is approximately 1.5 m, increasing to 2.9 m in the inner part of the Onega Bay [*Terziev et al.*, 1991]. Based on the data used in this study, the characteristics of tides at a number of stations along the WS coast have been refined. The magnitude of the spring tide reaches 4 m in the WS Throat (Russian: Gorlo), and the magnitude of the neap tide is 1.5–2.2 m. In the Dvina Bay, the magnitude of the spring tide does not exceed 1.5 m, and the neap tide is 0.6–0.8 m. The magnitude of the tide decreases on the Solovetsky Islands to 1.0 m (spring tide) and to 0.5–0.6 m (neap tide). However, at the Kem-Port station, the tide increases to 1.8 m (spring tide) and 0.8 m (neap tide). In Kandalaksha, the spring tide can reach 3 m and the neap tide – 2 m. In the WS, the parallactic inequality is also well pronounced, which is expressed by the difference in the magnitudes of two successive spring tides. For example, in October 2017 at Severodvinsk, the ratio of the magnitudes of two successive spring tides reached 1.3. At other points, this ratio was much smaller: 1.12 (Sosnovets), 1.06 (Solovki), 1.08 (Kandalaksha). The contribution of tides to the total variance of sea level fluctuations in the Throat (Gorlo) is 93%; in Dvina Bay it is 67%; on the Solovetsky Islands it is 65% [*Kulikov et al.*, 2018]. In Kandalaksha, according to the data obtained in this study, this value reaches 96%.

Shallow waves play an important role in the formation of tides in the WS. We accept the following notation. A_2 is the sum of the amplitudes of semidiurnal waves, A_4 is the sum of the amplitudes of quarter-day waves, A_6 is the sum of the amplitudes of 1/6-day waves. According to the data of measurements at WSBS MSU, located in the shallow estuary system in the Kandalaksha Bay [*Kondrin*

Table 1: The sums of amplitudes of tidal harmonics (cm) at some the White Sea stations. Ratios A_4/A_2 and A_6/A_2 are shown in brackets

	Kem-Port	Solovki	Severodvinsk	WSBS MSU
A_2	95.9	46.0	65.2	112.2
A_4 (A_4/A_2)	10.5 (0.109)	5.8 (0.126)	19.4 (0.297)	18.5 (0.165)
A_6 (A_6/A_2)	7.2 (0.075)	2.4 (0.052)	18.7 (0.287)	1.7 (0.015)

and Pantyulin, 2010], the A_4/A_2 ratio reaches large value of 0.17. This leads to a strong asymmetry of the tide in this area, when the rise time is 2–2.5 hours less than the fall time. In the Dvina Bay, this ratio increases to 0.3, while, along with the quarter-day tide, the sum of the amplitudes of the 1/6-day components is also large (Table 1). As a result, there is a strong distortion of the tidal profile and the so-called "manikha" (slack tide) appears, which is a temporary delay in the rise of the water level during high tide, followed by a slight fall, creating a misleading impression of high water coming (false high water). After some time, the level again continues to rise until the onset of real high water.

Statistics. Figure 2 shows the variance of the RSL deviations from monthly average values, which characterizes the intensity of synoptic level fluctuations. The variance was calculated as follows: for each month, the variance of the RSL deviations from the average monthly value was calculated, then, for each year, the arithmetic mean of 12 monthly values was calculated. The RSL fluctuations in the Dvina Bay are characterized by the greatest variance. The RSL fluctuations at Solovki and Sosnovets, have similar variance, which is significantly lower than the Dvina Bay. The lowest variance is observed in Kandalaksha. According to the data obtained at the Severodvinsk and Solovki stations, the least variance values were observed in 2004 and 2016. The relative minimum of variance compared to neighboring years took place in 2018. There were variance maximums in 2005, 2011, 2017, and 2019. The variance in 2006–2010 did not change significantly, but after the maximum of 2011 there was a decline. In 2012–2014 the variance was even lower than in 2005–2010. In 2016, the variance dropped approximately to the level of 2004. Its noticeable growth is obvious starting from 2017, which indicates an increase in the intensity of RSL fluctuations. The variance in 2017–2020, especially at Severodvinsk station, is significantly higher than in 2004–2010. If we compare five-year periods, then in Severodvinsk the average dispersion was 327.3 (in 2005–2009), 341.4 (in 2009–2013), and 386.8 (in 2016–2020). In Solovki these values are as follows: 242.1, 258.1, 270.8. These results indicate that the intensity of RSL fluctuations increases. This positive trend is also illustrated by the linear regression fits.

Let $\mathbf{Z}$ be the deviation of the RSL from the average monthly value, positive or negative. Then the survivor rate of a given value $\mathbf{Z}_k$ is the ratio of the cases number for which $|\mathbf{Z}| \geq |\mathbf{Z}_k|$ to the

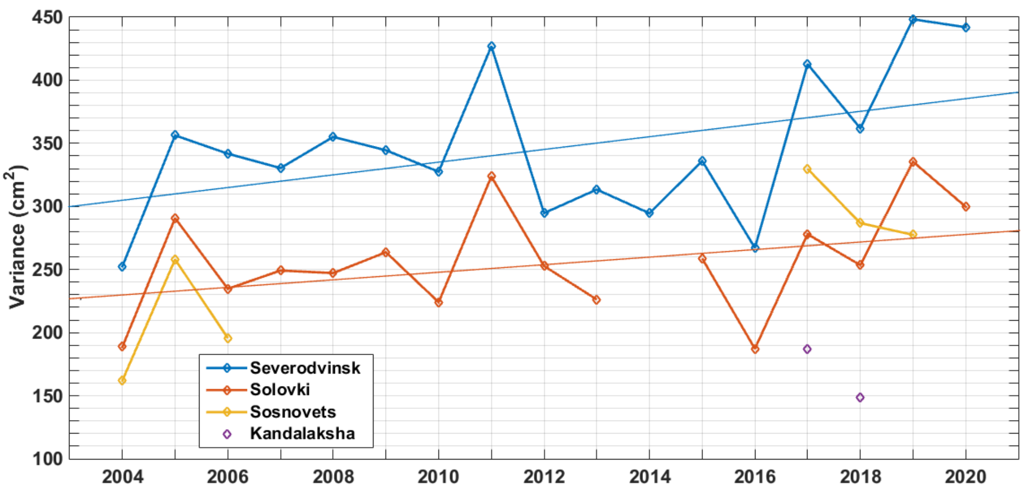


Figure 2: Variance of the annual series of the RSL fluctuations relative to monthly averages in 2004–2020 according to hourly measurements. Straight lines are linear regression functions for Severodvinsk $f(x) = 5.235(-0.3418, 10.81) \cdot x + 300.3(243.2, 357.4)$ and Solovki $f(x) = 2.901(-1.414, 7.217) \cdot x + 231.4(187.4, 275.4)$ posts.

total number of analyzed observations, expressed in %. Table 2 and 4 (see below) contain the survivor rates of RSL positive and negative deviations from the average monthly value in absolute value not less than 40 cm. The calculation was made for hourly RSL series of one-year duration. Data are presented for four "stormy" years – 2005, 2011, 2017 and 2019, and for the "calm" 2004, as well as for 2018, when there was a local minimum of variance, but the most significant storm surge run-up occurred over the period 2015–2020.

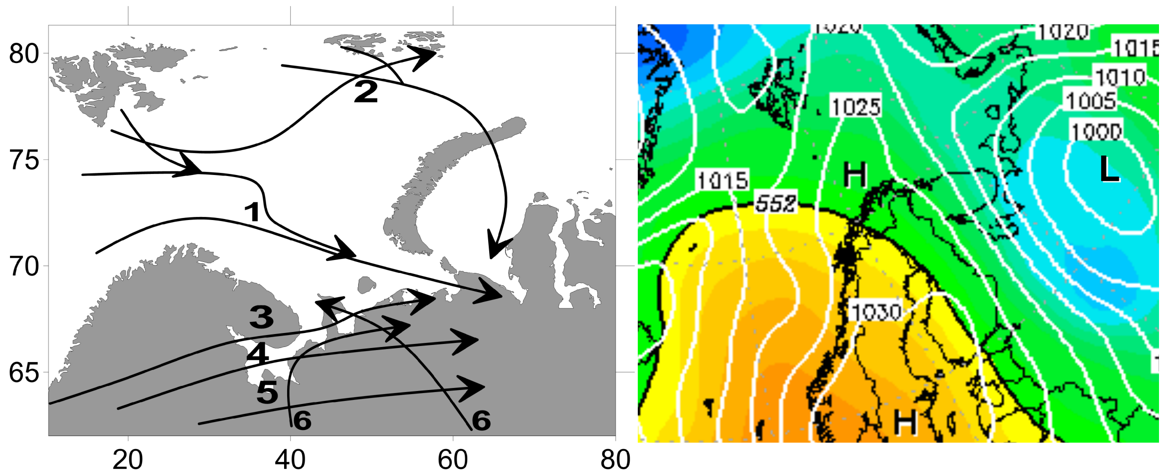
In general, the survivor rates of RSL positive deviations of 40 and 50 cm is larger, the larger the variance, and shows an upward trend over the considered time. For example, in 2011 at the Severodvinsk station, the probability of RSL positive deviations no less than 50 cm was much higher (1.58%) than in 2004 (0.87%). The maximum survivor rate for such deviations was in 2019 (2.04%). The same patterns are inherent for the RSL fluctuations at the Solovki and Sosnovets stations. Since hourly series of observations were used, it is possible to calculate how long a certain level was exceeded during the year. For example, in 2019, the survivor rate of the RSL value 50 cm was 2.04%. The length of the analyzed annual series is 8712 values. Thus, RSL was above 50 cm for 178 hours in total during this year. In 2004, this value was equal to 76 hours, with a survivor rate of 0.87% and a series length of 8736. At Solovki station, the survivor rate of the RSL value 50 cm in 2019 was 1.13%, i.e., RSL in total during the year was above or equal to 50 cm for 98.4 hours, and for 11.4 hours (in 2004); in Sosnovets – for 30.5 hours and 2.6 hours, respectively. In 2018, the survivor function of the RSL height of 50 cm with the series length of 8760 in Severodvinsk was 1.85% (162 hours), in Solovki –1.12% (98.1 hours), in Sosnovets – 0.56% (49 hours), in Kandalaksha – 0.41% (35.9 hours).

Atmospheric processes. The monographs [*Filatov et al.*, 2005; *Terziev et al.*, 1991] give a classification of cyclones according to their trajectory in relation to the problems of studying the BS and WS storm surges. The moving cyclones were divided into "diving", western, southern and anomalously shifting ones. Later, the cyclones classified as western ones were divided into "western along the BS" and "western along the WS" cyclones. At the same time, according to these studies, the frequency of cyclones of the "diving" and western types is about 88%.

The analysis of SAP fields in relation to surge events performed in the framework of this study made it possible to identify 7 types of synoptic situations in which surge run-ups occurred (Figure 3a, 3b).

1st type. Cyclone of the BS. The trajectory passes through the BS from the west or northwest to the southeast, less often east part of it. This type includes both cyclones passing through the western border of the BS and "diving" cyclones. Before and during surge run-up, the centers of cyclones of this type are located in the southeastern part of the BS (Funnel WS, Kanin Nos Peninsula, Kolguev Island; Pechora Sea, Pomorsky Strait.), or over the adjacent northern part of the European territory of Russia (ETR), or to the east over the southern part of the Kara Sea (KS) and in the area of the Yamal Peninsula.

The **2nd type** includes arctic cyclones, the trajectory of which runs along 80°N – Greenland Sea – Svalbard – the northern border of the BS – Franz Josef Land and further to the east or south-east. In the considered cases, during the surge run-up, it forms a sedentary extensive depression in the subpolar region north of the BS or KS, or in the KS itself.



(a) (b)

Figure 3: Synoptic situations 1–6 (a), synoptic situation 7 (b).

Table 2: The survivor function rates (%) of RSL positive deviations from average monthly values

$\mathbf{Z}_k$(cm)	Severodvinsk						Solovki					
	2004	2005	2011	2017	2018	2019	2004	2005	2011	2017	2018	2019
40	1.86	2.07	2.89	3.91	2.62	4.22	0.71	1.32	2.34	1.73	2.03	2.24
50	0.87	0.82	1.58	2.00	1.85	2.04	0.13	0.53	1.32	0.80	1.12	1.13
60	0.40	0.35	0.95	1.01	1.08	1.11	0	0.10	0.62	0.46	0.83	0.68
70	0.08	0.13	0.75	0.54	0.76	0.66		0.02	0.32	0.20	0.56	0.26
80	0	0	0.63	0.26	0.54	0.38		0	0.26	0.06	0.27	0.04
90			0.50	0.20	0.38	0.23			0.20	0	0.07	0
100			0.34	0.12	0.28	0.03			0.15		0	
$\mathbf{Z}_k$(cm)	Sosnovets						Kandalaksha					
	2004	2005	2018	2017	2019		2017	2018				
40	0.74	0.78	1.09	3.27	1.45		0.71	0.81				
50	0.03	0.24	0.56	1.73	0.35		0.20	0.41				
60	0	0.17	0.29	0.97	0.07		0.07	0.15				
70		0.11	0.18	0.58	0		0	0.04				
80		0	0.14	0.20				0				
90			0.09	0.07								
100			0.02	0								

In a situation of the **3rd type**, the trajectory of cyclones passes through the Scandinavian and Kola Peninsulas with access to the southeastern part of the BS and further to the east. The centers of cyclones during surge run-ups were located in the southeastern part of the BS near the WS, in the Pechora Sea and over the Gulf of Ob.

In a situation of the **4th type**, the trajectory of cyclones passes from the North Sea through the Scandinavian Peninsula, the Gulf of Bothnia, Finland, further to the east over the WS water area to the Subpolar Urals.

Situation 5 is similar to situation 4, but in this case, the cyclone trajectories pass south of the WS.

The **6th type** includes cyclones that originated within the ETR and at the time of surge run-up are located to the east of the WS, or to the northeast (KS).

7th type. The WS between a high-pressure area (1020–1030 hPa) in the west (Norwegian Sea, Scandinavian Peninsula) and a cyclone (990–1000 hPa) in the east (ETR, Northern Urals, Western Siberia). It should be noted that situations 2 and 7 have not been previously described.

Characteristics of surge run-ups. When describing surges, the following conventions are used: M is the mean monthly sea level height relative to the datum, R_M is the maximum RSL height during surge relative to M; H_M is the maximum measured (total) level height relative to M; H_0 is the maximum measured (total) level height relative to the datum, SAP is the surface atmospheric pressure in the center of the cyclone.

The 70 events of surge run-ups with $R_M \geq 0.5$ m at Severodvinsk were analyzed according to the results obtained for the 2004–2020 years. Among which twenty-five surge run-ups occurred in the situation of type 1; six surge run-ups in type 2 situation; seven surge run-ups in type 3; nine surge run-ups in type 4; and two surge run-ups in type 5. Thus, western cyclones (types 1, 2, 3, 4, and 5) account for 49 surge run-ups, i.e. 70% of all events under consideration. Sixteen surge run-ups occurred in type 6. The remaining five surge run-ups occurred in type 7.

Table 3 contains the characteristics of some storm surge run-ups in the White Sea described below.

Of the greatest interest from a practical point of view are the *hazardous* events when the sea level total increase H_0 is above the critical level. There were thirty-two such events at Severodvinsk (critical level 612 cm), five at Sosnovets (critical level 725 cm), and sixteen at Solovki (critical level 605 cm). Let us denote the ratio R_M/H_M, expressed as a percentage, by the letter k. Thus, the coefficient k characterizes the relative contribution of the RSL increase to the total increase in the level relative to the average monthly value. Although the achievement of the critical level depends not only on the height R_M, but also on the average monthly level$M$and the phase of the tide, nevertheless, in the majority of such cases (28 out of 32) at Severodvinsk, k took values from 51.4 to 81.4%. At Solovki, in 15 hazardous cases out of 16, k varied from 52 to 87.9% and only in one case was equal to 48.4%. At Sosnovets, the picture is quite different. Here, in 5 hazardous cases, k was in the range from 12.2 to 22.8%. This is explained by the fact that at Gorlo (Throat) the tides contri-

Table 3: Characteristics of some storm surge run-ups in the White Sea. Here M is the mean monthly sea level height relative to the datum, R_M is the maximum RSL height during surge relative to the monthly mean level M; H_M is the maximum measured (total) level height relative to M; H_0 is the maximum measured (total) level height relative to the datum. SAP is the surface atmospheric pressure at the center of the cyclone (hPa), TS – synoptic situation type. In the second line, in parentheses, the critical sea level heights (cm) relative to the datum are indicated. Critical sea level indicates the water level above which flooding and property damage begin

#	Date	SAP/TS	$R_M/H_M/M/H_0$ (cm)		
			Sosnovets (725)	Severodvinsk (612)	Solovki (605)
1	13.01.2006	985/1	50/227/456/683	83/132/478/610	66/90/487/577
2	25.09.2006	980/1	37/200/487/687	52/112/509/621	33/72/509/581
3	23.12.2006	975/1	53/238/495/733	77/140/519/659	54/98/513/611
4	02.02.2009	985/1	91/231/454/685	111/155/462/617	87/109/479/588
5	06.11.2010	970/1	62/272/476/748	96/161/494/655	70/112/500/612
6	15.11.2011	970/1	–	153/188/513/701	112/140/513/653
7	18.11.2013	970/4	60/218/491/709	94/152/503/655	47/97/508/605
8	12.12.2013	960/1	88/205/486/691	84/120/505/625	88/110/510/620
9	16.03.2016	970/1	80/215/464/679	105/166/482/648	85/112/486/598
10	21.01.2017	970/1	77/191/460/651	107/142/481/623	81/106/501/607
11	22.08.2018	985/6	93/182/462/644	130/163/475/638	85/109/495/604
12	21.11.2018	980/2	71/206/479/685	105/144/486/630	81/113/500/613
13	17.02.2019	985/4	67/212/475/687	94/153/473/626	82/117/496/613
14	23.01.2020	970/1	69/222/500/722	100/151/493/644	68/101/513/614

bution to the total variance of level fluctuations is much greater than at other stations under consideration, with the exception of Kandalaksha. Nevertheless, in a number of cases, the RSL contribution to H_M here was quite large. For example, on December 12, 2013, k = 42.9%, on January, 21, 2017, k = 40.3%, on August 22, 2018,k = 51.1%.

Note that the R_M and H_M values are calculated relative to monthly mean levels, so seasonal changes are excluded from these data.

As an illustration of the conclusions presented here, let us consider some specific cases of surge run-ups. For example, on January 13, 2006, when the R_M height in the Dvina Bay was 83 cm, the critical level was not reached, since the average monthly level was low (478 cm). At the same time, the tide was in an intermediate phase between neap tide and spring tide (the 1st quarter was on January 6, the Full Moon was on January 14). In this case, k = 62.9%; k = 22.0% (at Sosnovets), k = 73.3% (at Solovki). The surge was caused by a fast (63 km/h), deep cyclone of the 1st type, and its center during the surge run-up was located in the region of Naryan-Mar. The maximum RSL increase occurred on January 12 at 23:00 at Sosnovets, 7 hours later at Severodvinsk, and more 3 hours later at Solovki.

On September 25, 2006, with a much lower height R_M = 52 cm, the total level rise H_0 at Severodvinsk was 621 cm. This was due to the spring tide (New Moon was on September 22) and the high average monthly sea level (509 cm), with k = 46.4%. The surge run-up was caused by a deepening type 1 cyclone that crossed the BS from Svalbard (995 hPa) to the eastern part of the sea near the Southern Island of Novaya Zemlya (985 hPa) at a speed of 42 km/h. At Sosnovets k = 18.5% and at Solovki k = 45.8%. Before the surge run-up, a slight RSL decrease to minus 10 cm at Severodvinsk and to minus 13 cm at Solovki took place.

During the surge run-up on December 23, 2006, the total level at Severodvinsk was very high (H_0 = 659 cm) with a significant, but still not the largest RSL increase (R_M = 81 cm). Here the main role was played by a very high value of the average monthly level (M = 519 cm) and spring tide (New Moon was on December 20). Note that in this case k = 58%. The surge run-up occurred during the 1st type deep cyclone passage from Svalbard (970 hPa) to Novaya Zemlya (960 hPa) at a speed of 42 km/h, the center of which within approximately 24 hours from 12:00 on December 22 to 12:00 on December 23 remained in the area of Novaya Zemlya. During the surge run-up, the WS was on the periphery of this extensive cyclone, where the winds of the western and northwestern rhumbs prevailed at a speed of up to 20 m/s. At Sosnovets, the surge run-up characteristics were: k = 22.3%, R_M = 53 cm, H_M = 238 cm, H_0 = 733 cm. The maximum increase in RSL was reached at 13:00 on December 23. At Severodvinsk the maximum increase in RSL was reached at 21:00 on December 23 and remained in this position until 12:00 on December 24. At Solovki the maximum RSL rise (51 cm) occurred at 18:00 on December 24 with $k = 52.0\%$, $H_M = 98$ cm, $H_0 = 611$ cm. The critical level was exceeded in all three stations.

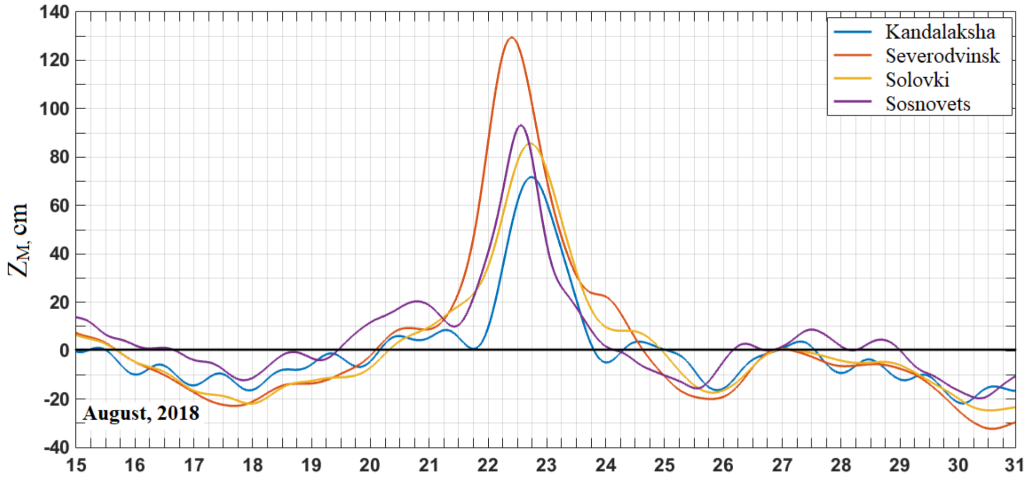
It should be noted that in the cases of major surge run-ups, the RSL rise still plays the main role. For example, on February 2, 2009, with the maximum value of $H_0 = 617$ cm at Severodvinsk, there was a very low average monthly level ($M = 462$ cm), but a very strong RSL elevation ($R_M = 111$ cm). The total excess of the level over the average monthly value H_M was 155 cm. Thus, $k = 71\%$, i.e., the surge run-up contribution to the total level increase was predominant. The surge run-up occurred when the type 1 cyclone moved south of Svalbard through the center of the BS to its southeastern part with a deepening from 990 to 980 hPa at a speed of about 70 km/h. The tide is intermediate between spring tide and neap tide: Moon 1st quarter was on February 3; New Moon was on January 26.

The surge run-up on November 6, 2010 was formed as a result of the deep western cyclone impact (type 1). The center of this cyclone (975 hPa) on November 6 was over the Yugorsky Peninsula, and strong northerly and northwestern surge winds prevailed in the WS with a speed of up to 21 m/s and more. At Severodvinsk on November 6, at about 08:00, RSL has reached the maximum mark ($R_M = 96$ cm). At 12:00 on the same day, this surge run-up reached the Sosnovets station (62 cm), and a little later at 14:00 it reached the Solovki station (70 cm). Hence it follows that this surge run-up was initially formed in the Dvina Bay under the prevailing effect of the wind factor, and then spread to other parts of the WS. At Severodvinsk, the surge run-up contribution to the total level increase ($H_M = 161$ cm, $k = 60\%$) was the main one. It should be noted a very large value $H_0 = 655$ cm, although the average monthly level was not high, $M = 494$ cm, and the tide was in an intermediate phase between neap tide and spring tide (New Moon on November 6, 2010).

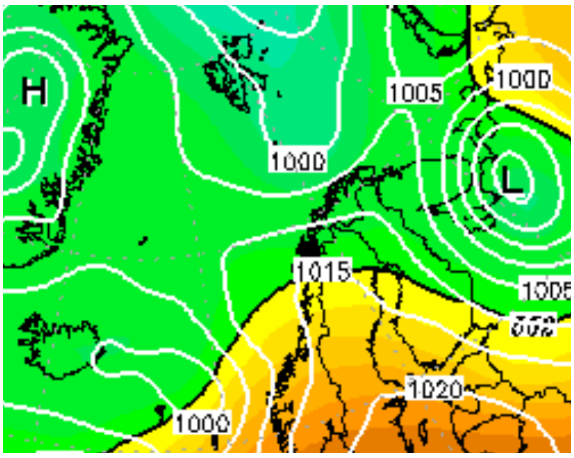
The surge run-up on November 15, 2011 [*Kondrin et al.*, 2018] occurred during the passage of a deep cyclone (960 hPa) over the BS eastern part (type 1). On the periphery of this baric formation, a very strong surge wind from 20 to 30 m/s was blowing over the BS and WS water areas. This surge coincided with the spring tide (Full Moon was on November 11), enhanced by parallactic inequality, with a very high average monthly level (513 cm). At Severodvinsk, the greatest level rise was observed for the period under review 2004–2020 ($H_0 = 701$ cm, $H_M = 188$ cm, $R_M = 153$ cm at 13:00). The relative contribution of the RSL increase was very large, $k = 81\%$. In Solovki $R_M = 112$ cm at 16:00, $k = 80\%$, $H_0 = 653$ cm.

The surge run-up on November 18, 2013 arose as a result of the action of a very fast (up to 80 km/h) deep (975 hPa) type 4 cyclone, the center of which was located above the Dvina Bay before the surge run-up, then moved to the southeast and created a strong surge wind of northwestern directions. In Severodvinsk, at $R_M = 94$ cm and $H_M = 152$ cm, $k = 62\%$. The total elevation of the level relative to the datum reached a very large value, $H_0 = 655$ cm, with a rather high mean monthly level $M = 503$ cm. In Sosnovets $R_M = 60$ cm, $H_M = 218$ cm, $k = 28\%$, the critical level was not reached. The maximum RSL rise was observed in Severodvinsk and Sosnovets simultaneously, at about 02:00 on November 18, and after 6 hours in Solovki. Thus, there was a predominantly wind surge in the Dvina Bay and the northeastern part of the sea, which then reached the Solovetsky Islands. Before the surge run-up, we note a RSL decrease of the order of minus 30 cm relative to the average monthly value in Severodvinsk and Solovki. This surge run-up almost coincided in time with spring tide: the 1st quarter was on November 10; Full Moon was on November 17.

The surge run-up on January 21, 2017 occurred during the passage of a deep (970 hPa) "diving" cyclone of the 1st type with an average movement speed of about 35 km/h. During this surge run-up, the tide was in an intermediate phase between spring tide and neap tide (3rd quarter was on January 20; New Moon was on January 28). In Severodvinsk, the surge run-up contribution to the total level increase was very large: $R_M = 107$ cm, $H_M = 142$ cm, $k = 75\%$. At a low average level M = 481 cm, the total level rise ($H_0 = 623$ cm) exceeded the critical level by 11 cm. In Solovki, the surge run-up contribution ($R_M = 81$ cm) to the total sea level rise ($H_M = 106$ cm) is also very large, $k = 76\%$. The total level rise relative to datum ($H_0 = 607$ cm) slightly exceeded the critical level. In Sosnovets, the surge run-up characteristics are as follows: $R_M = 77$ cm, $H_M = 191$ cm, $k = 40\%$. At a rather low value of $M = 460$ cm, the total level rise relative to datum ($H_0 = 651$ cm) was much lower than the critical value. At Kandalaksha, the maximum RSL rise ($R_M = 58$ cm) was significantly lower than at other stations. With $H_M = 127$ cm, the surge run-up contribution to the total level rise is $k = 45.7\%$. The maximum RSL rise occurred first in Sosnovets (11:00), then after 4 hours in Severodvinsk (15:00), and after another 2 hours in Solovki (17:00) and at 18:00 in Kandalaksha. This sequence of events is characteristic of an induced surge run-up. Before the surge run-up on January 18, RSL dropped to minus 38 cm in Severodvinsk, minus 41 cm in Solovki, and minus 38 cm in Kandalaksha. Surge run-off wasn't observed in Sosnovets.



(a)



(b)

Figure 4: The surge run-up on August 22, 2018. Z_M (cm) is the RSL height relative to the monthly mean value M(a), synoptic situation for this surge run-off (b).

Figure 4 shows the RSL distribution during the strongest storm surge for the 2015–2020 period on August 22, 2018. This surge run-up occurred during the synoptic situation of the 6th type, when the WS was under the influence of a sufficiently deep cyclone (985 hPa), the center of which was in close proximity east of the Winter Coast (Zimniy Bereg). At Severodvinsk, the height of this surge run-up was greatest for the specified period: $R_M = 130$ cm, $H_M = 163$ cm. Although the surge run-up coincided with the neap tide (1st quarter was on August 18, Full Moon was on August 26), the maximum level rise relative to the datum ($H_0 = 638$ cm) exceeded the critical value by 26 cm. The surge run-up contribution to the total level elevation was decisive, $k = 80\%$. This surge run-up arose directly in the WS, the RSL maximum rise first occurred in the Dvina Bay, then after about 3 hours the maximum was observed in Sosnovets ($R_M = 92$ cm, $k = 51.1\%$) and later after 5 hours in Solovki ($R_M = 86$ cm, $k = 78\%$) and in Kandalaksha ($R_M = 72$ cm, $k = 55.8\%$).

The surge run-up on February 17, 2019 occurred during the passage of a fairly deep (985 hPa) type 4 cyclone with a movement speed of 45 km/h, the center trajectory of which passed over Funnel and the Mezen Bay, where the initial level disturbance obviously occurred. At the time of the surge run-up, it was located to the east of the WS, creating a strong northern wind. In Severodvinsk, the surge run-up contribution to the total level increase was the main one ($R_M = 94$ cm, $H_M = 153$ cm, $k = 61.4\%$). Despite the low mean monthly level $M = 473$ cm and neap tide (1st quarter was on February 13, Full Moon was on February 19), the critical level was still exceeded ($H_0 = 626$ cm). At Sosnovets with $R_M = 67$ cm and $H_M = 212$ cm, $k = 31.6\%$. The surge run-up contribution was predominant at Solovki, $k = 70.1\%$, with $R_M = 82$ cm and $H_M = 117$ cm. In Kandalaksha, the surge height was higher than in Sosnovets, but lower than in Solovki ($R_M = 77$ cm, $H_M = 156$ cm, $k = 49.4\%$). The maximum RSL rise occurred on February 17 at 19:00 in Sosnovets, on February 17 at 22:00 in Severodvinsk, on February 18 at 00:00 in Solovki, on February 18 at 01:00 in Kandalaksha. From this, it can be concluded that an induced surge run-up with a significant wind component took place in the basin.

It is interesting to compare the number of surge run-ups with R_M over 100 cm at different time intervals. For 11 years from 2004 to 2014, there were only two such surge run-ups, and in the six-year period 2015–2020, there were already five such surge run-ups. It can be assumed that the intensity of cyclonic activity in the BS-WS is increased in the last period compared to the previous one.

Characteristics of surge run-offs. In the WS, in addition to surge run-ups, the RSL falls often occur, which are caused by meteorological reasons.

Table 4 contains the survivor function rates of the RSL negative deviations at various stations along the WS coast. In general, the survivor function rates of the RSL negative deviations from the average monthly values is significantly less than positive ones. This suggests that significant surge run-offs occur less frequently and, as a rule, are inferior to surge run-ups in their absolute value. However, the exception is 2005, when the most significant surge run-off occurred in the 2004–2020 time period.

Let us give examples of significant surge run-offs, when the RSL decreased by 70 cm or more in one of the coastal points under consideration.

The surge run-off on January 31, 2005 Figure 5 was formed as a result of the action of a very strong (25–30 m/s) southwestern wind over the WS at the periphery of an intense deep (965 hPa) cyclone. The center of which, before and during the surge run-off, was in the northern part of the Scandinavian Peninsula, in the area of the North Cape. This cyclone remained in one place for 1.5 days, as it was blocked from the east by a powerful anticyclone in the north of Western Siberia with a pressure in the center of 1055 hPa. In Severodvinsk, the RSL dropped by 123 cm below the average monthly mark, in Solovki by 112 cm, in Sosnovets by 68 cm. This surge run-off was the strongest for the entire period of 2004–2020.

The surge run-off on November 6, 2011 was formed as a result of the action of a powerful anticyclone, which formed at 00:00 on November 5 with a center (1040–1045 hPa) in the area of the Dvina Bay. Then the center of this anticyclone shifted to the southeast. Thus, the WS water area was located in the rear part of this anticyclone and for a long time was exposed to the action of a southwestern wind of about 15 m/s. The RSL decrease in Severodvinsk, Solovki and Solombala was minus 85 cm, minus 70 cm and minus 80 cm, respectively.

The surge run-off on January 25–26, 2017 was formed as a result of the action of a deep (970 hPa) western cyclone. The center of which was in the central part of the BS. From the east, this cyclone was blocked by an area of high (more than 1030 hPa) SAP. At the time of the surge run-off, the WS was located on the southern periphery of this cyclone, where the western, southwestern wind was blowing up to 20–25 m/s. In Severodvinsk, the RSL decrease relative to the average monthly level was minus 70 cm on January 25 at 22:00, in Solovki was minus 74 cm on January 26 at 00:00, in Sosnovets was minus 42 cm on January 25 at 14:00, in Kandalaksha was minus 62 cm on January 26 at 01:00.

Conclusions

1. Based on the data used in this paper, the tides characteristics at a number of stations along the WS coast have been refined: Gorlo (Sosnovets), Dvinsky Bay (Severodvinsk), Solovki, Kem-Port, Kandalaksha. There is a pronounced parallactic inequality in the WS, which is expressed by the difference in the values of two successive spring tides. Shallow waves play an important role in the formation of the tides in the WS.

2. The RSL fluctuations in the Dvina Bay are characterized by the greatest variance. At Solovki and Sosnovets, the RSL fluctuations have approximately the same variance, which is significantly lower than in the Dvina Bay. The lowest variance is observed in Kandalaksha. According to the data obtained at the Severodvinsk and Solovki stations, the noticeable increase of RSL fluctuations variance is observed over the considered time. If we compare five-year periods, then in Severodvinsk the average dispersion in 2004–2008 was 327.3, in 2009–2013 was 341.4, and in 2016–2020 was 386.8. In Solovki, these values are respectively the following: 242.1, 258.1, 270.8. These results indicate that the RSL fluctuations intensity increases.

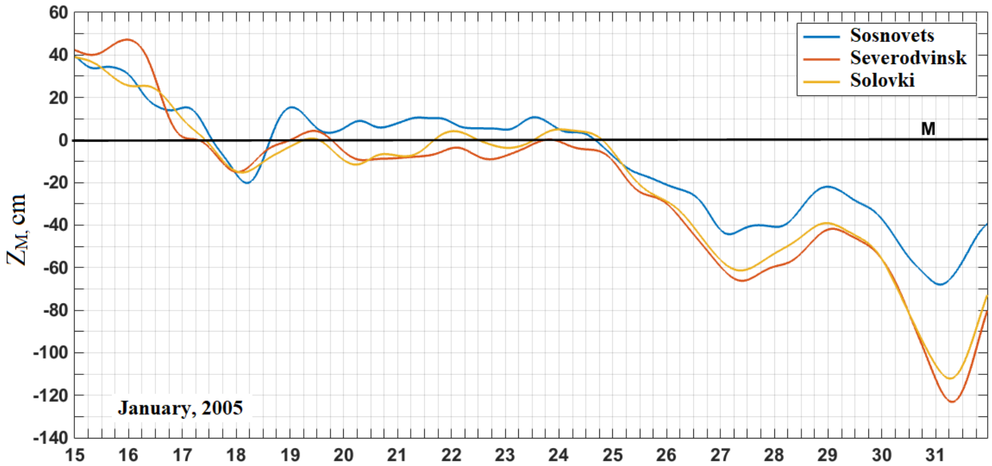
This conclusion is also confirmed by calculations of the RSL positive deviations survivor function. In general, the RSL positive deviations survivor function of 40 and 50 cm is the greater, the greater the variance and, accordingly, demonstrates an upward trend during the considered time. In this regard, it should also be noted that the number of surge run-ups with R_M no less than 100 cm for 11 years (from 2004 to 2014) was only 2, and in the six-year period (2015–2020) there were already 5 such surge run-ups.

3. Seven types of synoptic situations were identified, in which surges run-up occurred in the WS. Types 1–5 include western cyclones of various trajectories. Type 1 are cyclones passing over the water area of the BS, type 2 are Arctic cyclones pass-

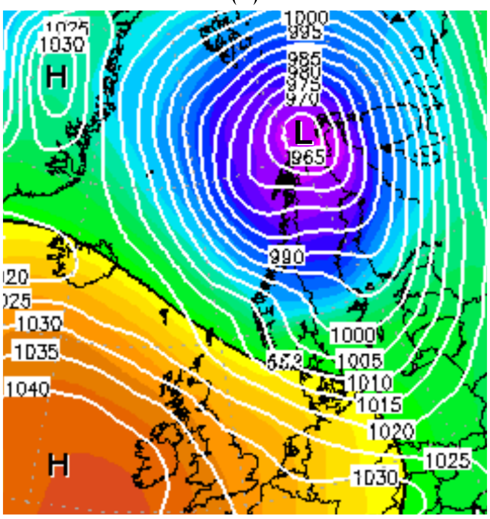
Table 4: Survivor function rates of the RSL negative deviations from average monthly values (%)

$\mathbf{Z}_k$(cm)	Severodvinsk						Solovki					
	2004	2005	2011	2017	2018	2019	2004	2005	2011	2017	2018	2019
−40	1.20	2.36	1.62	1.69	1.33	2.22	0.65	1.97	1.19	0.90	0.71	1.31
−50	0.38	1.27	0.66	0.57	0.42	0.87	0.14	1.05	0.54	0.42	0.33	0.48
−60	0.07	0.77	0.48	0.31	0.16	0.38	0	0.60	0.31	0.19	0.16	0.11
−70	0	0.42	0.32	0.05	0.01	0.01		0.41	0.10	0.06	0	0
−80		0.34	0.16	0	0	0		0.33	0	0		
−90		0.26	0		0			0.23				
−100		0.17						0.11				

$\mathbf{Z}_k$(cm)	Sosnovets					Kandalaksha	
	2004	2005	2018	2017	2019	2017	2018
−40	0	1.35	1.44	1.60	1.12	0.44	0.12
−50		0.55	0.41	0.36	0.37	0.13	0
−60		0.24	0.17	0.19	0.02	0	
−70		0.14	0.12	0.03	0		
−80		0	0	0			



(a)



(b)

Figure 5: The surge run-off on January 31, 2005 (a), synoptic situation for this surge run-off (b).

ing approximately along 80°N, types 3–5 include western cyclones passing through the Scandinavian Peninsula either with access to the southeastern part of the BS, or through the WS water area, or to the south of the latter. The 6th type includes cyclones that have arisen within the ETR and at the time of surge run-up are located to the east of the WS, or to the northeast (KS). In a situation of the 7th type, the WS is located between a high pressure area (1020–1030 hPa) in the west (Norwegian Sea, Scandinavian Peninsula) and a cyclone (990–1000 hPa) in the east (ETR, Northern Urals, Western Siberia). It should be noted that situations 2 and 7 have not been previously described.

4. During the period under study (2004–2020), there were 70 cases of surge run-ups in WS with a maximum RSL height relative to the average monthly value (R_M) at Severodvinsk of about 50 cm and above. Western cyclones (types 1, 2, 3, 4, and 5) account for forty nine surge run-up events, i.e. 70%. The highest surge run-ups occurred on November 15, 2011 and August 22, 2018. At Severodvinsk, in the first case, $R_M = 153$ cm, in the second, $R_M = 130$ cm.

5. In the WS, in addition to surges run-up, the RSL drops often occur due to meteorological reasons. On the whole, the survivor function for the RSL negative deviations from the average monthly values is significantly less than for positive ones. This suggests that significant surges run-off occur less frequently than surges run-up and, as a rule, are inferior to the latter in absolute value. The surge run-off on January 31, 2005 was the strongest for the entire period 2004–2020. The RSL decreased by 123 cm below the average monthly mark in Severodvinsk, by 112 cm in Solovki, and by 68 cm in Sosnovets.

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