

# Storm surges and extreme storms in Sakhalin Island and South Kuril Islands

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**Abstract.** Storm surges (the significant sea level rises due to a drop in surface atmospheric pressure and an increase in wind velocity during the passage of deep cyclones over the coastal areas) pose a formidable threat to the coastal settlements of Sakhalin and the South Kuril Islands. As a result of flooding of coastal areas, the impact of storm waves on the shores and coastal facilities is sharply increased. The greatest damage caused by surges on 10.11.1990 and 9.11.1995 which affected the most populated southern part of Sakhalin Island. A long-term sea level series were analyzed, recorded at 9 coastal tide gauges located on the coast of Sakhalin Island and South Kuril Islands. Estimates for the maximum heights of the storm surges and tidal level were obtained separately, as well as for the rare recurrence of the total sea level height with the probability of these individual components superposition. The maximum total height of the sea level was obtained for the Kurilsk station, where the highest storm surge was recorded. The minimum values were obtained for southwestern coast of Sakhalin Island (Kholmok and Nevelsk stations) where tides are small. Seasonal and inter-annual variations of strong waves were analysed from the data of visual observations.

## 1 Introduction

Storm surges (significant sea level rises due to a drop in surface atmospheric pressure and an increase in wind velocity during the passage of deep cyclones over the coastal areas) pose a formidable threat to the coastal settlements of Sakhalin and the South Kuril Islands. Surges are often accompanied by extreme storms, and the impact of storm waves on the shores and coastal facilities has sharply increased, resulting in flooding of the coastal areas. The strongest surge in the Far Eastern region happened on October 15-19, 1977 in Sakhalin Bay (2.7 m in the port of Moskalvo). The heaviest in their consequences were rather modest surges on 10-11.11.1990 and 8-9.11.1995 (height about 1 m), which affected the more populated southern part of Sakhalin Island. Of the recent events, the surge on 7.12.2012 and the overtaking and extreme storm on 2-3.10.2015 (caused by the typhoon Dujwan) stood out.

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The first one flooded the port of Korsakov, and the second caused considerable damage along the whole coast of the island.

In the South Kuril Islands, surges and extreme storms have increased dramatically since October 2006, and storms of comparable strength in Yuzhno-Kurilsk port have not been observed for about 50 years. The most severe in its consequences was the event of 17.12.2014, which caused significant material damage to the coastal settlements of the region (in particular, a new pier in Yuzhno-Kurilsk was damaged significantly).

To determine statistical characteristics of surges and extreme storms, both the series of long-term sea level measurements performed on shore tide gauges and data of visual observations for altitudes and periods of wind waves at coastal meteorological stations have been analyzed. We calculated sea level heights of rare recurrence taking into account the probability of surge and tide superposition. Besides, we estimated frequency of extreme storms in the vicinity of coastal meteorological stations. As the atmospheric disturbances such as cyclones or typhoons pass over the coastal area of the sea, a drop in surface atmospheric pressure and an impact of strong winds on the sea surface lead to a significant sea level rise - storm surges. Together with the accompanying storm waves, they represent natural hazards. A surge height depends on a number of factors, such as a bottom relief, configuration of shoreline, and size, intensity, direction and speed of a cyclone motion. The most significant surges occur in bays with a wide mouth and a sharp decrease in their depth or width.

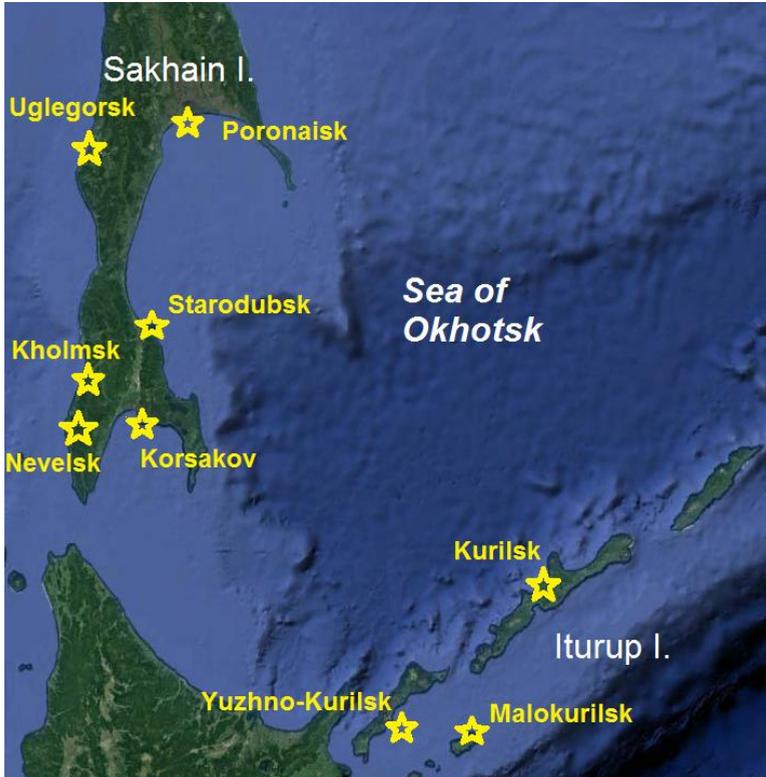
With respect to Sakhalin Island, the most significant surges are observed in Sakhalin Bay and Amur Liman. This is facilitated by a combination of several morphological and hydrometeorological factors - in particular, a vast bay with the low-lying shores, and stable northerly and northwesterly winds in the rear part of the cyclone that crosses the island from the west to the east. In this respect, conditions in this region are analogous to those in the Gulf of Finland (Baltic Sea), with appearance of stable and strong westerly and northwesterly wind when a cyclone enters the northern part of the Scandinavian Peninsula.

In Sakhalin Bay, the surges of over 2 m in height are frequent (every 2-3 years). An example of such an event is recorded at the temporary station in Moskalvo port in October 1981 [1]. The maximum surge (the largest in the entire Far Eastern region) was recorded at the same station on October 15-19, 1977. The deviation of the residual (de-tided) component from the mean sea level was 272 cm. The surge destroyed a roadbed of the 1,500 m long railway and the access roads, caused erosion of about 300 m of Okha – Moskalvo road, flooded piers and office space. In the village of Rybnovsk, the pier was destroyed, and the faucet and various material assets were washed away. In recent years, economic damage from surges has declined resulted from a significant population reduction in this area. However, this problem can again become acute in the case of commercial development of the offshore oil and gas fields in Sakhalin Bay.

In the southern part of Sakhalin Island, the magnitude of storm surges is much smaller - the maximum values are about 1.4 m in the southeast and about 1 m in the southern and southwestern parts of the coast. However due to the higher population density and development of the coast, the damage from them is much higher than in Sakhalin Bay. Thus, on December 15-16, 1981, November 9-10, 1990, and November 8-9, 1995, there were the events when surging waves reached the maximum intensity and led to significant material damage [Kato et al., 2001].

Surges are closely related with the extreme storms caused by strong winds during the passage of deep cyclones. Due to the surging sea level rise, the impact of storm waves on the coast and coastal infrastructure increases sharply. In connection with the foregoing, the purpose of this work was to determine statistical characteristics of these hazardous natural phenomena observed at the coastal meteorological stations of Roshydromet (their position is shown in Fig. 1).

Some of the most dangerous situations are considered in detail. However, estimates of storm surges heights are rarely used in practice. For a safe design of industrial facilities and transport communications in the coastal zone, it is necessary to estimate heights of the total sea level of rare recurrence. Such estimates can be obtained by compositing the distributions of meteorological and tidal sea level fluctuations [2, 3] that considers the probability of coincidence of the surge with low tide or with high tide. As an example, we give a two-week segment of sea level observations in Kurilsk in early November 1990.



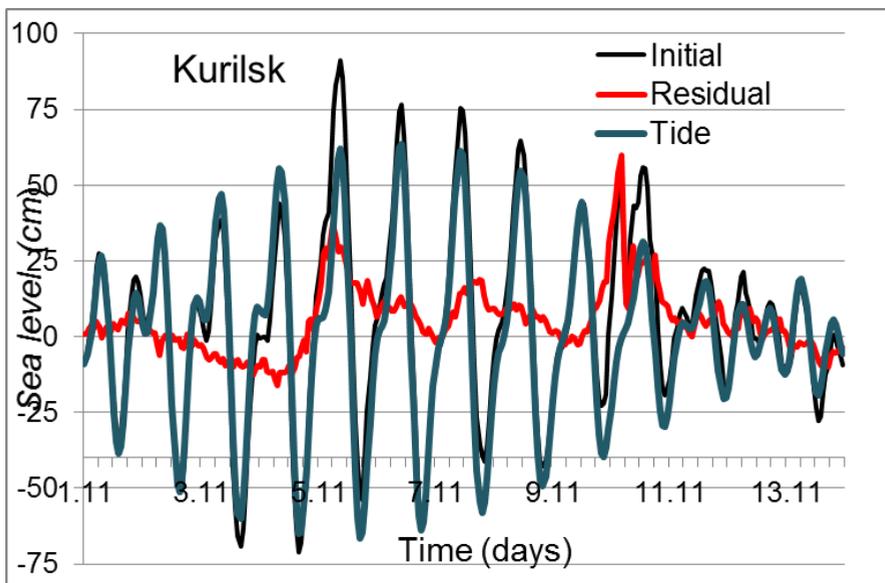
**Fig. 1.** The location of coastal meteorological stations on Sakhalin and the South Kuril Islands where sea level and wind waves are regularly monitored.

## 2 Examples of storm surges

Let's consider a few of the most dangerous storm surges, paying special attention to their superposition with the tidal oscillations. In some cases, the imposition of a moderate superposition with the high tide gives higher increases in the total level (namely, a total level affects flooding of the coastal areas and property damage) than the stronger surge that coincided with a low tide. As an example, let us consider the total, tidal and residual sea level fluctuations at the Kurilsk station (the Okhotsk Sea side of Iturup Island) from November 1 to 13, 1990 (Fig. 2). During this period, two relatively strong surges were recorded. One of them was 37 cm high (relatively mean sea level), but coincided with high tide, so that the total level reached 91 cm. A much more dangerous surge on November 10, 1990 (60 cm, its manifestations at south of Sakhalin Island are discussed in detail below) coincided with a low tide, and the total level had almost the same height.

Storm surge on November 10, 1990. A storm surge was recorded by 7 coastal tide gauges in various parts of the coasts of Sakhalin Island (see Fig.1). It was the most significant in

comparison with those observed earlier for a very long history of observations (the first tide gauges in the ports of Korsakov and Kholmok began operating in 1948). The surge heights were 90 and 97 cm, that is significantly higher than the previous maxima (61 and 70 cm at the indicated stations, respectively) in October 1981. This indicates the extreme nature of this surge with the period of its recurrence estimated approximately as 1 time in 500 years. This surge was also recorded at 3 stations located in the South Kuril Islands, where the level rises were more moderate.

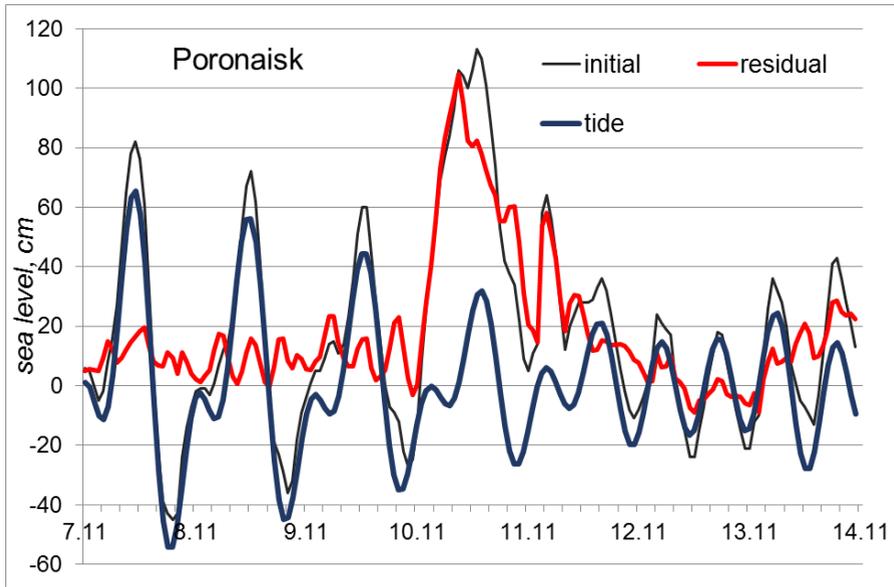


**Fig. 2.** Variations of the total sea level and tidal and residual components during the storm surges on 5.11.1990 and 10.11.1990 in the Kurilsk seaport (Iturup Island).

On the northeastern coast of Sakhalin Island (Nabil Bay), the diurnal tides dominate. For areas with the diurnal tide prevalence, the interannual (with a period of 18.6 years), seasonal (strengthening on solstice days and weakening for the days of the equinoxes), and fortnightly variabilities are typical. In the interannual aspect, the 1990 is referred to the time of sufficiently strong tides (maximum in 1987). A surge maximum (63 cm) occurred at the time of the high tide (33.6 cm); a height of the total level (97 cm above a zero mean level) was the highest for the 16-year observation period at this station. Mixed tides occur in the area adjacent to the southeastern coast of Sakhalin Island (Poronaik, Starodubskoye and Korsakov stations), where the amplitudes of diurnal and semidiurnal waves have a close magnitude. Interannual, seasonal and fortnightly variabilities are similar to those discussed above for Nabil station, but less expressed. At Poronaik station, the surge maximum (105 cm in Fig. 3) coincided with a small tide. The main maximum of the total level rise (113 cm) included a rather strong surge (82 cm) and high tide with a moderate value of 31 cm on November 10. At Starodubskoye station, the surge maximum was somewhat weaker (81 cm), with a tidal level close to zero. There was observed a maximum of the total level, the second maximum (71 cm) was formed later with a decreasing, but still significant surge (53 cm). The tide contribution was not significant as well, making 18 cm. A similar picture was observed in the port of Korsakov (Figure 4). The surge maximum was 88 cm at a tide height of -1 cm; the largest total height of 90 cm was formed with a still significant surge (55 cm) during the high tide (35 cm). Summing up the situation, we can say that the extreme surge on 10.11.1990 at most stations coincided with a close-to-zero tide. Predominantly the

maximum values of the total level were recorded later, with the decrease in surge and increase in tide.

Storm surge on November 9, 1995. The second extreme surge was formed on the coast of Sakhalin Island under meteorological conditions similar to those considered above. A storm surge was originated by the action of the Yellow Sea cyclone, which became visible on the weather maps at 12 o'clock on November 6 (pressure in the center of 1015 hPa). After crossing the Korean Peninsula and entering the area of the Sea of Japan, it began deepening rapidly.



**Fig. 3.** Variations of the total sea level and tidal and residual components during the storm surge on 10.11.1990 in the Poronaik seaport.



**Fig. 4.** Variations of the total sea level and tidal and residual components during the storm surge on 10.11.1990 in the Korsakov seaport.

On the southeast coast of the Tatar Strait and Aniva Bay the surge began its formation on November 7, when the cyclone center was located easterly of the Sangar Strait. The maxima recorded at Kholmsk, Nevelsk and Uglegorsk stations arose when the center of a very deep cyclone (945 hPa) was just above this area.

On the northeastern Sakhalin coast, the maximum of one of the most strong surges (85 cm) was observed at the low tide (-24 cm). Therefore, the maximum increase in the total sea level (87 cm) was found much later, with the residual component of 52 cm.

At Poronaisk station, the surge maximum (93 cm) was recorded at 18:00 Moscow time on November 8, at the low tide (-36 cm), so the maximum of the total level was formed 7 hours earlier (totally 111 cm at the surge height of 77 cm and tidal 34 cm).

No data were obtained for the port of Korsakov, since the sea level observations were discontinued in 1992. It is interesting to note that before 1990 only two moderate surges were recorded in this port, and only one of them, which took place in September 1986, led to a serious material damage because its maximum was at the full tide. However, in the last decade of the 20th century and in the beginning of the 21st century, emergencies happened more often. In addition to the situations discussed above, severe consequences took place in December 2012 and October 2015.

On December 6-7, 2012, the cyclone with a pressure at the center of 985 mB affected the weather conditions in the southern part of Sakhalin. It left the area of the Sea of Japan, crossed the southern part of Sakhalin Island and moved to Terpeniya Bay. On December 6, the easterly winds 17-22 m/s speed were observed in the cyclone front. The wind changed to the northwestern when the cyclone came out to south of the Sea of Okhotsk.

According to observations at Korsakov station, the storm surge and waves exceeded 2.0 m were forced by the southwesterly wind that started on December 6. The highest visually fixed wave height was 3.0 m and the maximum wind speed was 27 m/s. The southern and northern piers were flooded, as well as the territory of the tank farm (Fig. 5).

On October 2-3, 2015, a significant weather deterioration was caused by a very deep cyclone (945 mb) formed as a result of the regeneration of the typhoon "Dujwan". The cyclone moved from the Yellow Sea to the central part of Okhotsk and, filling, went to the Pacific Ocean. This event affected all the coastal areas adjacent to Sakhalin Island. The maximum wind speeds reached 33-45 m/sec in southern Sakhalin (63 m/sec at Krilion station and 47 m/sec at Moneron station). According to observations at Kholmsk station, the westerly storm wind produced dangerous wind waves up to 4.0 m in height. This event suffered a significant material damage to the port of Kholmsk; in particular, the port cranes were demolished.

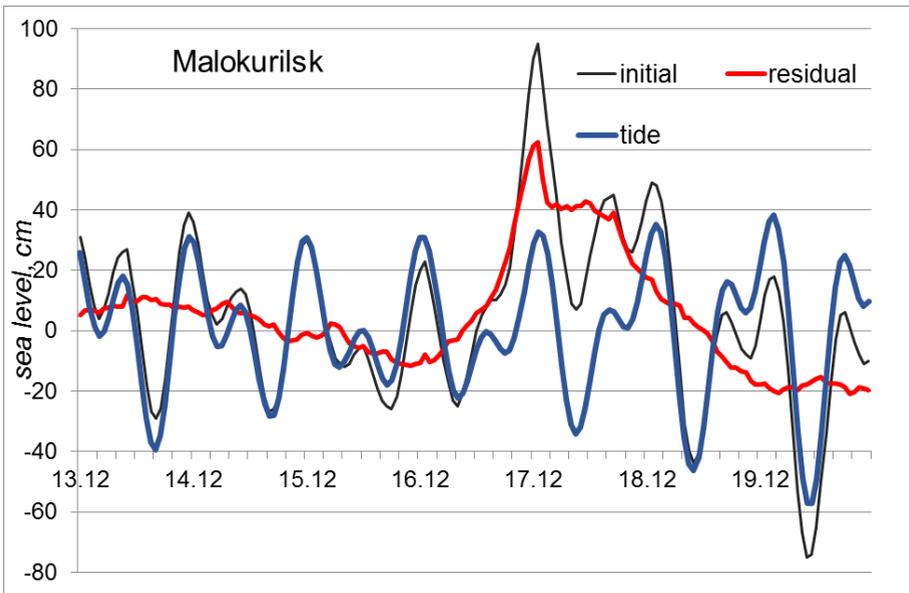
Port of Korsakov. A strong southwesterly wind (maximum gust reached 34 m/s) had generated wind waves of 4/0 m height. As a result, the storm surge provoked flooding of the port territory including northern and southern piers and adjacent to the port Vokzalnaya Street.

Storm surges are less dangerous on the South Kuril Islands. The settlements of Yuzhno-Kurilsk (Kunashir Island), Malokurilskoe and Krabozavodskoe (Shikotan Island) are located on the coast of the Yuzhno-Kurilskiy Strait which is protected from the Pacific Ocean by the islands of the Lesser Kurile Range and from the Sea of Okhotsk side by Kunashir Island. Therefore, strong surges and extreme storms are rarely observed at these points. Quite a different situation is observed on the open coast of Iturup Island (the town of Kurilsk); in its port an extreme surge with a height exceeded 2 m was recorded [3, 4].



**Fig. 5.** The northern pier of Korsakov seaport, flooded with a surge on December 7, 2012.

The most severe consequences on the coast of the South Kuril Strait were caused by a storm happened on December 17, 2014. Fig. 6 shows variation of the total, tidal and residual levels in Malokurilskaya Bay (the gage in Yuzhno-Kurilsk was closed by that time).



**Fig. 6.** Variations of the total sea level and tidal and residual components during the storm surge on 17.12.2014 in the port of Malokurilsk.

A height of the storm surge at this point (62 cm) was the largest for the entire observation period since 1970. Besides, the surge coincided with the high tide, so the rise in the total level

was 95 cm from a zero mean. In Yuzhno-Kurilsk seaport, according to expert estimates, the sea level elevation exceeded 1 m. The port and adjoining streets were flooded (photo in Fig. 7), and several places of the Yuzhno-Kurilsk - Golovnino highway were undergone to erosion.

These examples point to a high degree of threat posed by storm surges and extreme storms for the Sakhalin region.



**Fig. 7.** The Yuzhno-Kurilsk seaport flooded with the storm surge on December 17, 2014.

### 3 Estimation of rare recurrence sea level heights

The materials of observations were the hourly sea level series obtained at the SahUGMS coastal tide gauges in the main ports of the Sakhalin Region, the position of which is shown in Fig.1. Information on the duration of the analyzed series is given in Table 1. Data of visual observations of altitudes and periods of wind waves were also used (since 1950 at the most stations, waves observations were not performed at Nevelsk station).

From the initial sea level series, the predicted tides and quasi-periodic seasonal variations which were approximated by a combination of annual and semiannual harmonics were subtracted. To predict the tides, amplitudes and phases of 8 main waves were used: 4 diurnal (Q1, O1, P1, K1) and 4 semidiurnal waves (N2, M2, S2, K2). The resulting residual sea level variations are due to meteorological reasons - surface atmospheric pressure and wind speed. Typically, these oscillations are small, their mean square amplitude at most stations is 10-12 cm. Against the backdrop of these fluctuations, there are sharp sea level rises exceeding 50, 70 and sometimes 100 cm - storm surges, examples of which were considered above.

The calculation of the rare recurrence extreme surge heights was made using the standard method based on long-term hourly residual sea level series. The Gumbel's method of extreme statistics, adopted in the Russian practice of extreme sea level heights calculating [5] was applied. The maximum observed surge heights and calculated heights for the periods of recurrence 50 and 100 years are given in Table 1.

However, estimates of the possible heights of storm surges in tidal seas are rarely used for practical purposes. This requires estimates of the heights of the total sea level of rare recurrence that are used for the safety design of objects in the coastal zone. In present paper they were calculated by the joint probability method, the probability density of oscillations in the total level can be found from expression of residual and tidal components [2, 4].

$$P_{\xi}(y) \int_{-\infty}^{\infty} P_m(x) \int_{-\infty}^{\infty} P_t(y-x) dx \tag{1}$$

where  $P_m$  is the probability density of meteorological oscillations, including surges,  $P_t$  is the probability density of tidal and seasonal variations.

**Table 1.** Statistical characteristics of storm surges: duration of observations (years), observed maxima (relative to mean sea level) and calculated extreme surge heights for return periods of 50 and 100 years.

Station	Duration of observation, years	Observed maximum (cm)	Return period (year)	
			50	100
Kurilsk	30	205	164	181
Yuzhno-Kurilsk	41	76	80	87
Malokurilsk	43	62	63	68
Poronaisk	39	112	116	126
Starodubsk	23	132	125	137
Korsakov	44	89	79	85
Nevelsk	26	101	90	98
Kholmok	51	97	80	87
Uglegorsk	27	75	82	88

The probability of exceeding a certain value  $h$  (of the security function, taking into account all possible combinations of the level regardless of their actual or hypothetical occurrence), can be estimated from the formula

$$F(h) = \int_h^{\infty} P_{\xi}(y) dy \tag{2}$$

The recurrence period  $T$  corresponding to this estimate can be calculated as

$$T(h) = \frac{1}{nF(h)} \tag{3}$$

where  $n = 8766$  is the mean number of hourly counts per year. The main moments of the method are well known [2,4,5]. As noted above, the probability density of tidal oscillations is described by the histogram of predicted 19-year-long series. Seasonal fluctuations were set by including annual SA and semi-annual SSA harmonics. In order to approximate the probability density function of sea level variations of meteorological nature, a histogram of the whole available series of meteorological oscillations is used; the series is obtained by subtracting the predicted tide from the initial series.

The results of calculations for the periods of recurrence 50 and 100 years are given in Table 2, which also indicates the maximum value of the tidal level (positive deviation from the zero mean level).

As a characteristic of the intensity of wind waves, the number of days with strong waves (heights above 2 meters) was used. Due to the specific nature of visual observations, estimates of the maximum altitudes of wind waves are not reliable, since the probability of missing the maximum is high.

Therefore, usually the characteristics of waveforms are used from numerical simulation data, if there are no instrumental observations. At the same time, the number of days with strong waves is satisfactorily estimated from visual observations and can be considered as a relatively good estimate of storm activity.

**Table 2.** Maximum tide height (positive deviation from a zero mean level, cm) and JPM calculated extreme sea levels (cm) estimated as combination of tide and surge.

Station	Max tide (cm)	Return period (year)	
		50	100
Kurilsk	68.7	228	238
Yuzhno-Kurilsk	54.3	126	140
Malokurilsk	55.8	124	135
Poronaisk	73.7	157	164
Starodubsk	64.4	159	167
Korsakov	80.0	135	141
Nevelsk	21.6	104	107
Kholmsk	17.1	98	101
Uglegorsk	52.5	107	111

The highest height of the total level (2.4 m) was obtained at Kurilsk station on Iturup Island from the side of the Sea of Okhotsk. There, both the largest surge and the largest tide magnitude were recorded.

Large surges with a height of more than 1 meter were observed also on the southeast coast of Sakhalin Island at Poronaisk and Starodubskoye stations. The height of the tide here is about the same as at Kurilsk station, so the heights of the total level are large too (1.6 m). Large surges with a height of about 1 m were recorded in southwestern Sakhalin (Nevelsk and Kholmsk) too. However, the tides here are of negligible magnitude, and the calculated heights of the total sea level are the smallest in the region. The intra-annual variations of strong waves (3-4 days) are less intense in the southwestern part of the Sea of Okhotsk than in the Tatar Strait (up to 10 days). This is because of the stormier eastern coast of Sakhalin Island compared to the western one. This area is actually not protected from the waves developing in the deep area of the Sea of Okhotsk. The frequency of storm waves there is much higher even in summer.

## 4 Seasonal and inter-annual variations of strong waves

A quantitative indicator of strong waves in this work is the calculated parameter - the number of days when heights are more than 2 m. For visual observations this characteristic looks more adequate because it gives a low accuracy of determined maximum heights that depends significantly on the time of measurements and a good faith of the observer. For all of the considered stations, the multiyear mean numbers of days with the wave height over 2 m were calculated for each month. The distribution of this indicator by months gives an idea of the seasonal variability of storm waves. The intra-annual variations of strong waves in the investigated water areas have a well-defined seasonal character. For the areas of the Tatar Strait and Aniva Bay, pronounced annual minima (summer) and maxima (late autumn) of the number of days with strong waves are typical. In the intra-annual distributions of strong waves, against the backdrop of other stations, Kholmsk stands out prominently in the autumn-winter period, because the area adjacent to this station is free of ice all the year round. In contrast, the water areas of the north Tatar Strait, Aniva Bay and the southwestern part of the Sea of Okhotsk are covered with ice from November to April that damps storm waves.

In the area of South Kuril Islands, the stormiest months are November and December, in a lesser degree - January and October. The ice cover prevents the development of strong waves from the Okhotsk Sea side only in February-March. From the Pacific Ocean side the area is ice-free all the year round, so the intense wind waves are observed almost all-the-year-round too.

To study the variability of strong waves on a multi-year scale, the values of the number of days with wave heights of 2 m or more were calculated for each year of observations.

Investigations of the inter-annual variations of strong waves were carried out for the Tatar Strait, Aniva Bay, the southeast coast of Sakhalin, and the Kuril Islands. The southwestern coast of Sakhalin Island is adjacent to the extended and deep-water area of the Sea of Japan, therefore this region is characterized by a greater frequency of storm waves, especially in winter period (Kholmsk station). In the northern part of the Tatar Strait the wind waves are weaker due to the narrowing of its area and relatively shallow waters. In the Tatar Strait and Aniva Bay, the inter-annual variability of the number of days with strong waves is well expressed. There are both calm and stormier years. The greatest storm activity occurred in the 1950s and 1960s. The other years were noted predominantly with the moderate storm activity. A new increase of the storm activity in the southern part of Sakhalin Island was recorded in the 1990s. In the area of South Kuril Islands it has been observed in 1980-s, in the decrease of storm activity we found since 2000 despite the increase in the number of extreme storms since 2006.

## 5 Summary

The above examples have shown that storm surges and the associated extreme storms pose a formidable threat to the coastal settlements of Sakhalin and the South Kuril Islands. To the greatest extent, they affect the transport infrastructure (ports, road and railways). The obtained estimates of extreme level rise at surges can be useful for the safety design of different objects in coastal areas.

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