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An estimation of extreme sea levels in the northern part of the Sea of Japan

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Abstract: Extreme sea levels arising from combination of tides, storm surges, seasonal sea level variations, and tunamis were estimated for the Russian coasts of the Sea of Japan by the joint probability method. The individual sea level components were studied separately and subsequently their combined effects were considered. The highest extreme elevations were found at the stations De Kastri and Rudnaya Pristan, the lowest ones at the stations Nakhodka and Kholmsk. Several components play the essential role in the different sea areas: tides in the northernmost part of the Tartar Strait, tunamis in the region of Rudnaya Pristan, surges all over the coast. The tunami influence is negligible for short return period but may be important for long return periods.

1. Introduction

The intensive development of coastal areas, the construction of complex and expensive structures (such as nuclear power stations) increase the risk of flooding (or draining) and require the precise estimation of extreme high (or low) sea levels. The variability of sea level near the coast is related to various factors: tides, storm surges, seasonal fluctuations, tsunamis etc. The coincidence of these factors causes abrupt growths of the sea level, as it was observed, for example, on 5 November, 1952 in Severo-Kurilsk, Paramushir Is., where the catastrophic tsunami occurred at the high water of the spring tide (RABINOVICH and SKRIPNIK, 1984). With the enlargement of the time period, the probability of the coincidence of different unfavorable factors increases. It is natural that the relative importance of these factors (sea level components) depends sufficiently on the physical and geographical peculiarities of the specific regions.

The Sea of Japan is a proper object in this respect. Strong tides are observed in the northern part (in the region of the Tartar Strait) and in the south (in the Korean Strait). Devastating storm surges are common for the coastal regions finally. The tragic events due to the tsunami on 26 May, 1983, when more than 100 persons were killed (ABE and ISHII, 1987), have demonstrated a serious danger of this phenomenon for human lives and industrial activities on the coasts of the Sea of Japan. The reliable estimates of extremely high sea levels in this region as result of superposition of different sea level components, and the investigation of their relative role are an interesting scientific theme and also an important applied science problem.

The Gumbel's method based on annual extreme analysis of long observational series is commonly used for estimating maximum and minimum sea level elevations caused by storm surges and tides (for example, LENNON, 1963; GRAFF, 1981; WALDEN *et al.*, 1981; GERMAN and LEVIKOV, 1988). However, this method has limitation to evaluate extreme height which is related to superposition of tides or surges with rare events such as tsunami.

There are other methods devised specially to estimate tsunami risk and to construct tsunami zoning schemes without taking into account other dangerous factors (RASCON and VILLAREAL, 1975; GO *et al.*, 1985). These methods are quite suitable for the regions where tsunami

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waves are manifested, being the most important cause of marine flooding (or draining), e. g. for the Pacific coasts of Russia or Japan, but are of little importance for the coastal areas exposed to various disasters of equal worth.

There are only a few attempts to deliberate tsunamis together with other sea level components. GARCIA and HOUSTON (1974) considered statistical effects of the astronomical tide in the prediction of tsunami runup for southern California coast. RABINOVICH and SKRIPNIK (1984) used joint probability method (PUGH and VASSIE, 1978, 1980) to estimate contribution of tsunamis, tides and storm surges to extreme levels for the region of Severo-Kurilsk. The appropriate method based on separate analysis of different sea level components and subsequent combination of their probability functions have been later improved by RABINOVICH and SHEVCHENKO (1990) to analyse the possible flooding on the northeastern coast of Sakhalin Island. The same method is chosen in this paper to evaluate extreme sea levels for the Russian coast of the Sea of Japan and to estimate the relative importance of various factors.

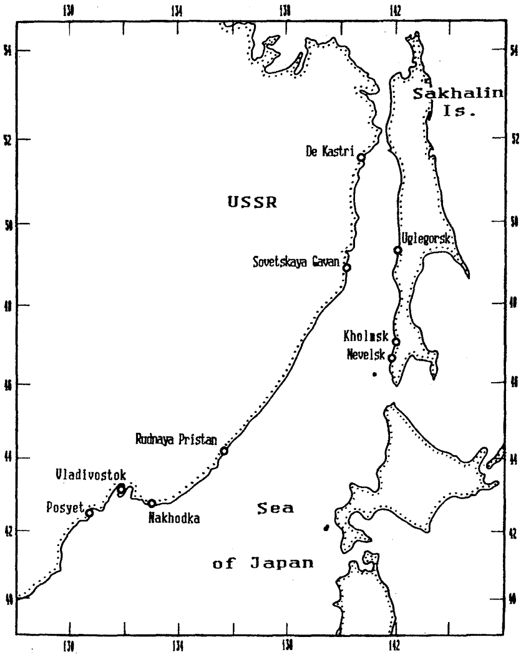

Fig. 1. Location of coastal tidal gauge stations.

2. The analysed data

Hourly tidal gauge values obtained in the World Data Center-B1 Obninsk at 9 coastal stations (Fig. 1) were used for analysis. The lengths of the records varied from 3.8 years for Sovetskaya Gavan to 12 years for Posyet, Nakhodka and Uglegorsk (Table 1). Most of the records were quite complete except for a few gaps when tidal gauges were out of work or had data of low quality. Two and half years were absent in the records of Vladivostok (1 July 1980–31 December, 1982), eight and half months in Rudnaya Pristan (19 December 1985 – 31 August 1986), two months (November–December, 1980) in Sovetskaya Gavan, one month (January, 1983) in Kholmsk, and two weeks in Posyet (1–14 February 1980). All available data carefully edited and corrected were used to estimate probability distributions of tidal and storm surge (non-tidal residual) components. Non-systematic gaps in the data are of no consequence to this kind of analysis (PUGH and VASSIE, 1978).

Time series of monthly mean and maximal sea levels for these stations (Table 1), and data on

Table 1. The list of sea level data.

Stations	Hourly data		Monthly data	
	Duration, years	Period	Duration, years	Period
Posyet	12	1977-88	36	1950–85
Vladivostok	9.5	1977–80, 1983–88	59	1926–45, 1947–85
Nakhodka	12	1977–88	38	1948–85
Rudnaya Pristan	11.4	1977–88	46	1948–79
Sovetskaya Gavan	3.8	1977–80	32	1974–86
De Kastri	11.4	1977–88	13	1974–86
Uglegorsk	12	1977–88	24	1963–86
Kholmsk	11.9	1977–88	40	1974–86
Nevelsk	11	1978–88	37	1974–50, 1954–86

individual storm surges for Vladivostok (1926–1953) and Posyet (1951–1985) completed by FIRSOV (1989) were used to obtain more accurate estimates of extreme sea levels.

3. Methods

The joint probabilty method (JPM) at first was proposed by PUGH and VASSIE (1978, 1980) to investigate combining probability functions of surge and tide, and to estimate extreme sea levels based on relatively short observational series. Similar methods for the same purposes were used also by WALDEN (1982), and RABINOVICH and SKRIPNIK (1986, 1984). RABINOVICH and SHEVCHENKO (1990) improved the method by taking into account tsunamis and other sea level components. Following their work, we describe briefly the philosophy of the method.

Sea level elevation (ζ) at any time (t) may be described as the sum of a few individual components

$$\zeta(t) = Z_0 + \zeta_T(t) + \zeta_S(t) + \zeta_W(t) + \zeta_t(t) \tag{1}$$

where Z_0 is mean level, ζ_T tides, ζ_S seasonal component, ζ_t tsunami, ζ_W meteorologically-induced (storm surge) component, which remains after mean level, tides and seasonal oscillations have been removed from the original records.

An analysis of sea level oscillations in the Sea of Japan made by SOKOLOVA *et al.* (1992) proved that the residual (non-tidal) variations and tides are practically independent, i.e. that the interaction of tides and meteorologically-induced oscillations in this region is weak.

In such a case, probability density P_Σ of oscilations caused by various uncorrelated factors may be represented by

$$P_\Sigma(y) = \int_{-\infty}^{\infty} P_1(x_1) \int_{-\infty}^{\infty} P_2(x_2) \ldots \int_{-\infty}^{\infty} P_{N-1}(x_{N-1}) P_N(y - x_1 - x_2 - \ldots - x_{N-1})\, dx_1 dx_2 \ldots dx_{N-1}, \tag{2}$$

where, P_j are the probability density of each type variations, y and x_j are their levels, N is number of components.

Based on Eq. (2) with accounting (1), the probability of the total sea level height h can be expressed as the sum of probabilities of all possible combinations of individual components.

The probability of the sea level exceeding height h is

$$F(h) = \int_h^{\infty} P_\Sigma(\zeta)\, d\zeta . \tag{3}$$

The corresponding return period may be calculated as

$$T(h) = (nF)^{-1}, \tag{4}$$

where n is a coefficient related to the sampling intervals and duration of corresponding processes approximately equal to a number of independent samples in a year (PUGH and VASSIE, 1980).

Therefore, the problem of estimation of probability function and return period for extreme sea levels can be expressed by the probability densities of individual components.

For evaluating sea level components, it is important to consider their physical process. Tide is a determnistic part; based on 1 year observational series, it is possible to predict hourly tidal levels and extreme high tides for any reasonable periods (ZETLER and FLICK, 1985; WOOD, 1986). Seasonal oscillations are quasidetermeinistic. Their phases and amplitudes may be changed from one year to another but, in general, they are relatively stable. Tidal and seasonal components may be combined. Tsunamis and storm surges are stochastic processes. To estimate their extreme heights it is possible to use double exponential distribution (GUMBEL, 1958; PUGH, 1987) as

$$F(h) = 1 - \exp(-\exp(-Y)), \tag{5}$$

where $Y = a(h - B)$ is the "reduced variate", a and B are the distribution parameters, which may be determined from observations.

An analysis of individual components and their extreme values is a subject of independent interest. That is why we present here only concise description of this analysis as well as estimation of their combination.

4. Tidal analysis and calculation of extreme tidal levels

High quality 1-year time series of hourly data

Table 2. Characteristics of tidal oscillations.

Stations	Form factor	Mean amplitude, cm	h max, cm
Posyet	0.95	11.9	20.4
Vladivostok	0.97	11.8	20.5
Nakhodka	1.08	10.7	18.9
Rudnaya Pristan	1.22	10.2	16.9
Sovetskaya Gavan	0.41	22.9	47.5
De Kastri	0.13	79.2	143.6
Uglegorsk	0.31	30.0	57.3
Kholmsk	1.39	8.8	18.1
Nevelsk	1.91	10.9	22.0

were used for harmonic tidal analysis by least square method. Harmonic constants of 67 constituents were computed for each station. In practice, however, for these sites it is not necessary to estimate all these harmonics for all the stations except De Kastri, because strong tides are observed only in the northern part of the sea. The average amplitude of tides $\overline{H}$ determined as

$$\overline{H}=\left(\sum_{j=1}^{8}H_j^2\right)^{1/2}, \qquad (6)$$

where H_j are amplitudes of 8 main tidal constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2 and K_2), for all southern stations (Posyet, Vladivostok, Nakhodka, Rudnaya Pristan, Nevelsk and Kholmsk (less than 12 cm), and De Kastri (about 80 cm), Table 2).

Using the harmonic constants hourly time series of predicted tides for period of 19 years (1980–1998) were simulated for all stations. Diurnal, semidiurnal and shallow-water tidal harmonics with amplitudes more than 0.5 cm were taken into account. Period of 19 years (more accurately 18.6 years) is a nodal period of tidal harmonics. This interval is necessary for estimation of high tides and correct generation of probability density functions (p. d. f.) (PUGH, 1987). Fig. 2 shows plots of annually extreme high tides and tidal variances for 4 stations: De Kastri, Uglegorsk, Sovetskaya Gavan and Posyet. Plots for all other stations are very similar to Posyet's ones.

Nodal cycle is well seen in variance changes. For northern stations the highest tides correspond to 1980 and 1997–98, the weakest tides to 1987-88; for Posyet and other southern stations

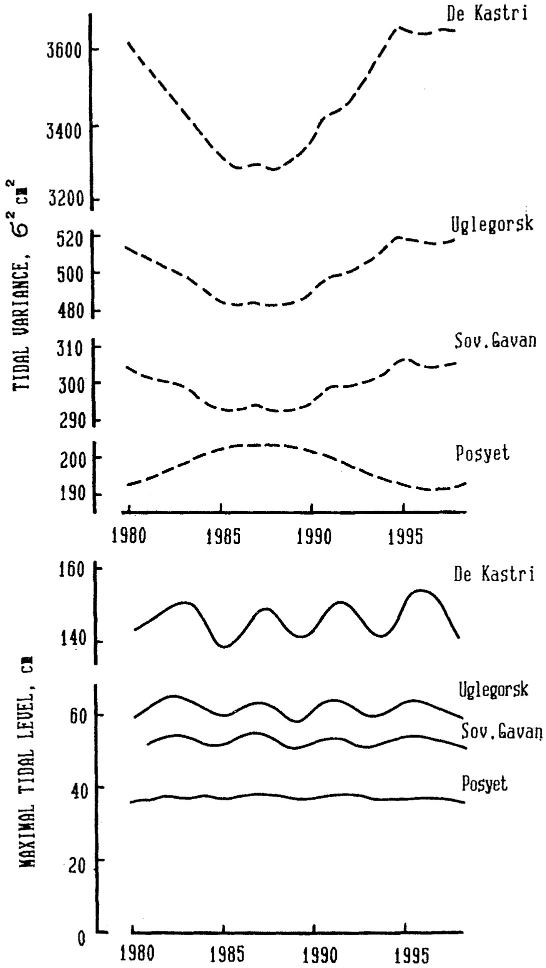

Fig. 2. Interannual variability of tidal variance and maximal tidal level at De Kastri, Uglegorsk, Sovetskaya Gavan and Posyet.

the tidal variance change is out of phase with northern stations. Such a tidal character is connected to a Form factor

$$F=\frac{(H_{K1}+H_{O1})}{(H_{M2}+H_{S2})}, \qquad (7)$$

indicating relative importance of the diurnal and semidiurnal constituents. Posyet and other southern stations have mixed tidal regime. For Nevelsk and Kholmsk diurnal tides are even prevailed. In contrast with that, in De Kastri, Uglegorsk and Sov. Gavan semidiurnal tides are dominant (Table 2).

The periodicity of annual tidal extreme is very different from the periodicity of variances. The 18.6-year cycle is practically not seen on the

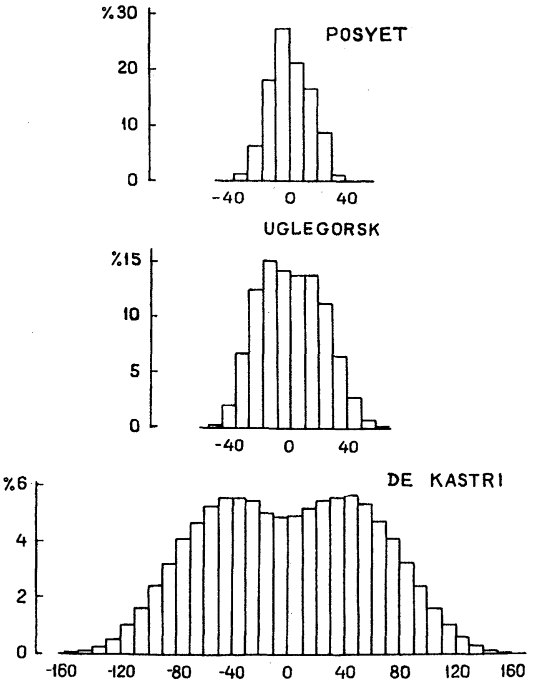

Fig. 3. Probability density distributions of tidal level based on 19-year hourly predictions.

plots but cyclic variability of about 4.4 years appears obviously for northern stations (Fig. 2). These results differ from the estimation of extreme high (and low) tides for Kuril and eastern Sakhalin stations (RABINOVICH and SKRIPNIK, 1986; RABINOVICH and SHEVCHENKO, 1990) where only 8.6-year variabilities were strongly manifested. We have provided special tests for De Kastri. It showed that the 4.4-year cycle is caused by K_2 constituent, which has strong nodal anomaly (+0.315) and opposite in phase to that of M_2 and other semidiurnal harmonics.

The computed extreme high tides for all the stations during 1980–98 are presented in Table 2. Computations were done for 90 years (1901–1990) for three northern stations. The difference was less than 0.8 % (142.5 and 143.6 cm for De Kastri, 57.1 and 57.3 cm for Uglegorsk, 47.1 and 47.5 cm for Sov. Gavan). Thus it is not necessary to use so long tidal series in every station for estimation of high tides.

Tidal series for 19 years were used to make up p. d. f. with class interval of 5 cm (Fig. 3). Seasonal harmonics Sa and Ssa (see next section) also included in these calculations. The functions were relatively simple and unimodal for southern stations. They were more complicated and asymmetric for Uglegorsk, Sov. Gavan and intricate bimodal for De Kastri. These tidal p. d. f. were used for further computation of extreme sea level heights.

5. Seasonal variations

Seasonal changes of mean sea level in the Sea of Japan are related with many different factors: long period tides, atmospheric pressure, wind, solar heating, water density, circulation etc. (MIYAZAKI, 1955; GALERKIN, 1960; LISITZIN, 1967; SEKINE, 1991). Due to various reasons and their year-to-year changes, phases and amplitudes of the observed seasonal harmonics Sa and Ssa are more variable from year to year than those of the diurnal or semidiurnal tidal constituents (PUGH, 1987).

The whole series of mean monthly sea levels were used to compute amplitudes and phases of

Table 3. Characteristics of seasonal oscillations of sea level.

Stations	Duration, years	Sa H, cm	Sa $\phi°$	Ssa H, cm	Ssa $\phi°$	*Fs*
Posyet	36	16.4 (21.1)	205.0	2.5 (7.9)	65.7	6.7
Vladivostok	58	15.1 (21.3)	207.0	1.8 (6.0)	57.9	8.6
Nakhodka	38	12.3 (18.6)	206.9	2.6 (6.6)	43.2	4.7
Rudnaya Pristan	46	9.0 (13.2)	206.2	2.2 (8.0)	57.8	4.2
Sovetskaya Gavan	32	6.7 (10.8)	212.9	0.6 (5.0)	69.7	12.0
De Kastri	13	12.4 (16.0)	205.1	0.4 (5.7)	227.9	30.2
Uglegorsk	24	8.0 (12.4)	218.0	1.1 (6.5)	322.0	7.3
Kholmsk	40	3.9 (7.4)	255.5	3.2 (7.0)	8.4	1.2
Nevelsk	55	3.0 (7.9)	279.4	3.2 (6.9)	8.1	0.9

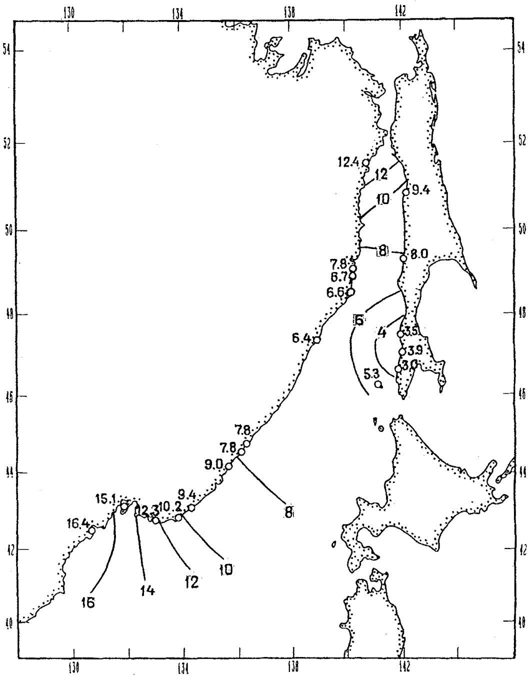

Fig. 4. Amplitudes (in cm) of annual constituent Sa in the northern part of the Sea of Japan.

annual (Sa) and semiannual (Ssa) constituents (Table 3). Individual yearly series were also processed to estimate maximal amplitudes which are presented in brackets. Computed values of seasonal constants are relatively stable and agree well with each other. Phase differences of the annual harmonic for all stations except Nevelsk and Kholmsk are less than 15°. Seasonal Form Factor, similar to those for usual tides

$$F_S = H_{Sa}/H_{Ssa} \tag{8}$$

is from 4.2 (for Rudnaya Pristan) to 30.2 (for De Kastri), suggesting the seasonal variations have annual character for the greater part of the investigated region with maximum level in July-August and minimum level in January-February. Similar results were obtained also by MIYAZAKI (1955), GALERKIN (1960) and others.

There is an anomaly at the southwestern coasts of Sakhalin, where annual cyclicity is much weaker and semiannual one is stronger than at the other parts of the sea (F_S is 0.9 for Nevelsk and 1.2 for Kholmsk). There are two maxima (stronger one in December-January and weaker one in July-August) and two minima in this region.

A general picture of annual variation of sea level for the region under study is presented in Fig. 4 based on hand water level data. It is well seen that the seasonal oscillations are small in the southern part of the Tartar Strait and increase to the north (De Kastri) and to the south (Vladivostok, Posyet).

Average values of seasonal harmonics were used to calculate probability density functions together with tides. Usually maximal semidiurnal tides are observed during the time of the equinoxes in March and September when the constituents S_2 and K_2 are in the same phase; diurnal (or mixed) tides are enhanced in December–January and in June–July when K_1 and P_1 are in phase (ZETLER and FLICK, 1985). The summer maximum tides are summed up with seasonal maximum, providing total annual sea level maximum at this time.

Differences between average and extreme values of amplitudes are of about 4–6 cm (Table 3). This indicates that for some anomalous years seasonal oscillations may sufficiently exceed their average values. For example, the average value of mean monthly sea level in Vladivostok in August is 16.5 cm, and extreme mean monthly level is 25.3 cm; in Posyet they are 18.4 and 26.0 cm. The total range of extreme seasonal changes (from minimum to maximum) is 49 cm for Posyet and Vladivostok, 35 cm for Uglegorsk and 37 cm for De Kastri. An analysis of these extreme events and their influences on the entire extreme sea levels may be a subject of future study. In any case, results of seasonal variations analysis show that they play an important role in forming sea level elevations in the Sea of Japan and make significant contribution to their extreme heights.

6. Storm surges and meteorologically-induced oscillations.

Storm surges are one of the most widespread and ruinous marine hazards for coastal area of the Sea of Japan. A catalogue of storm surges for the Russian coasts for 1977–88 is elaborated now in IMGG (RABINOVICH and SOKOLOVA, 1991). All extreme sea level elevations related with atmospheric forcings were listed up and

Table 4. Characteristics of storm surges.

Stations	Observed maxima, cm	Frequency		h_{100}, cm
		≫30 cm	≫50 cm	
Posyet	73	1.75	0.17	89 (85)
Vladivostok	69	2.0	0.17	82(78)
Nakhodka	53	2.0	0.17	66
Rud. Pristan	68	3.7	0.75	84
Sov. Gavan	52	4.0	0.25	67
De Kastri	78	6.0	1.10	91
Uglegorsk	74	4.0	0.50	89
Kholmsk	71	3.0	0.10	74
Nevelsk	64	4.3	0.50	81

were used in this paper.

The residual series (after subtracting tides and seasonal variations) were used for analysis. These non-tidal residuals are related to meteorologically-induced sea levels. Storm surges are extreme manifestations of these oscillations; for correct estimates of the probability (or return periods) of high sea levels, it is necessary to take into account not only extreme but also usual meteorologically-induced background by similar way as it was made for tides.

The most important characteristics of natural marine disasters (average number per year) with heights $h \gg 30$ cm (surge phenomenon) and also with $h \gg 50$ cm (strong storm surge) are presented in Table 4.

For southern stations (Posyet, Vladivostok, Nakhodka) there are about 2 surges per year and a strong surge in 6 years. Strong surges occur 4 times more frequently for Rudnaya Pristan and 6 times more for De Kastri. Strong surges for the Sakhalin stations Nevelsk and Uglegorsk are occurred once in 2 years, but for the station Kholmsk located between Uglegorsk and Nevelsk only once in 10 years. This fact is apparently related to some topographical peculiarities of this region.

Gumbel's method was applied to estimate storm surge intensity. Computed values of surge heights (h_{100}) with probability 0.01 (i. e. with return period of 100 years) are given in Table 4.

The accuracy of these values depends on obsevational series length. To improve the estimates, additional information for the stations Vladivostok and Posyet was used. Weekly series of hourly sea level data with storm surges for some previous years (1926–53 for Vladivostok and 1951–1976 for Posyet) compiled by FIRSOV (1989) were cleared up from the tides and the obtained maxima were supplemented to the existing ones. New values of h_{100} for these relatively long series were calculated and given in brackets in Table 4. Small differences (about 4 cm) prove the reliability of the estimates. The decrease of values is apparently caused by possible exclusion of some strong surges which had occurred at low tides.

The residual hourly series for 1977–88 were used to generate p. d. f. as it was made for tides. Fig. 5 contains some typical examples of these distributions. About 100,000 individual sea level values were employed to obtain them. Probability density functions had appearance close to Gaussian function except on both sides of their tails. Results of extreme statistics based on Gumbel's distribution (5) were used to describe the maximal sea level elevations and to supplement actual p. d. f. Then, compound distributions applied in expression (1).

7. Tsunamis in the Sea of Japan

Tsunamis in the Sea of Japan are not so common as for the Pacific coasts. Nevertheless, a number of catastrophic tsunamis were observed in this area, e. g. on 12 May 1701; 2 August 1887; 29/30 August 1741, etc. (SOLOVIEV and GO, 1974). These tsunamis killed thousands of inhabitants and destroyed completely many villages and coastal structures. At least 4 tsunamis affected the Russian coasts of the Sea of Japan in this century: 2 August 1940; 16 June 1964; 1 September 1971 and 26 May 1983 (SOLOVIEV, 1978; SOLOVIEV *et al.*, 1986). All these tsunamis were generated by earthquakes

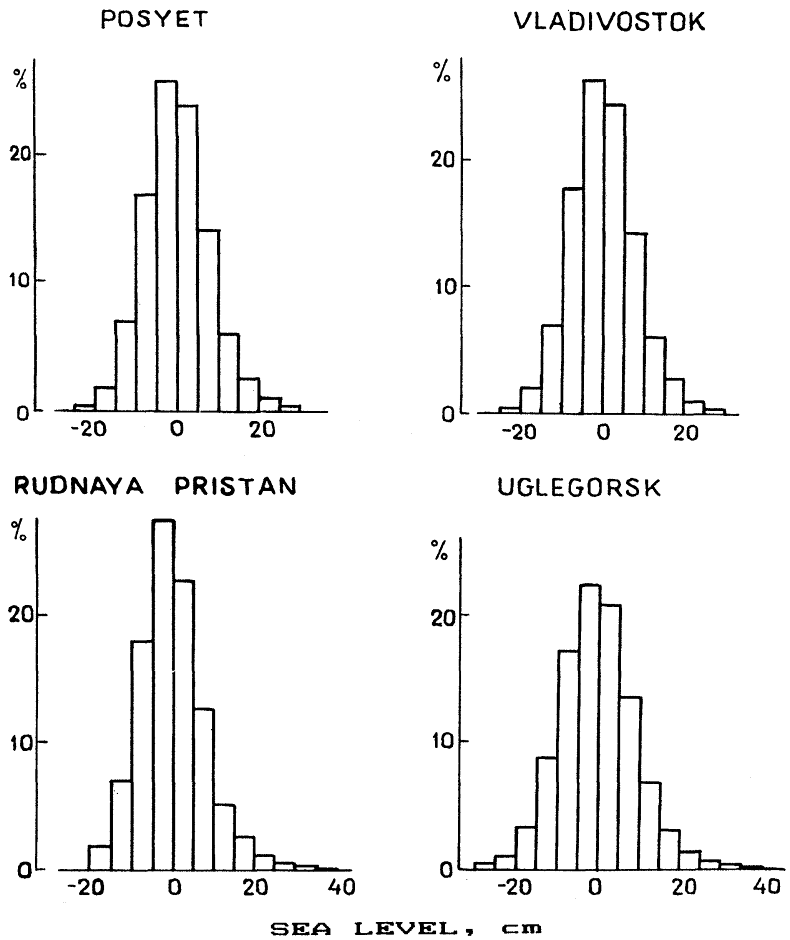

Fig. 5. Probability density distributions of residual (non-tidal) levels.

with epicenters near the coasts of Honshu, Hokkaido or South Sakhalin. In principle, Pacific tsunamis may also penetrate into this area through the Soya Strait as it was for the Chilean Tsunami on 22 May 1960 and for the Urup Tsunami on 13 October 1963 but usually these tsunamis are strongly faded out.

The tsunami on 26 May 1983. strongest tsunami in this century, was more than 10 m hight near the coast of Honshu Island (ABE and ISHII, 1987). Tidal gauge records of this tsunami at the Russian stations are presented in Fig. 6.

An estimation of tsunami risk for the Russian coast of the Sea of Japan was made by GO *et al.* (1984, 1985, 1988). In accordance to this method, the function describing the tsunami recurrence with wave height exceeding 0.1m may be represented as

$$N/T = A \exp(-h/h^*) \qquad (9)$$

for any coastal point. Here, N is the number of tsunamis with wave height $h \gg 0.1$ m recorded in the given point during T years, and A is a coefficient determined by observational data and physical cosiderations. Parameter A represents the frequency of large tsunamis and coefficient h^* characterizes relative amplification of tsunami waves near the coast. It is important that parameter A varies very insignificantly within one region.

The values of parameters A and h^* for the investigated points as well as maximal height of observed tsunamis are presented in Table 5. They are taken from works of GO *et al.* (1984, 1988) and corrected by the authors. Higher values of A for the Sakhalin stations in comparison

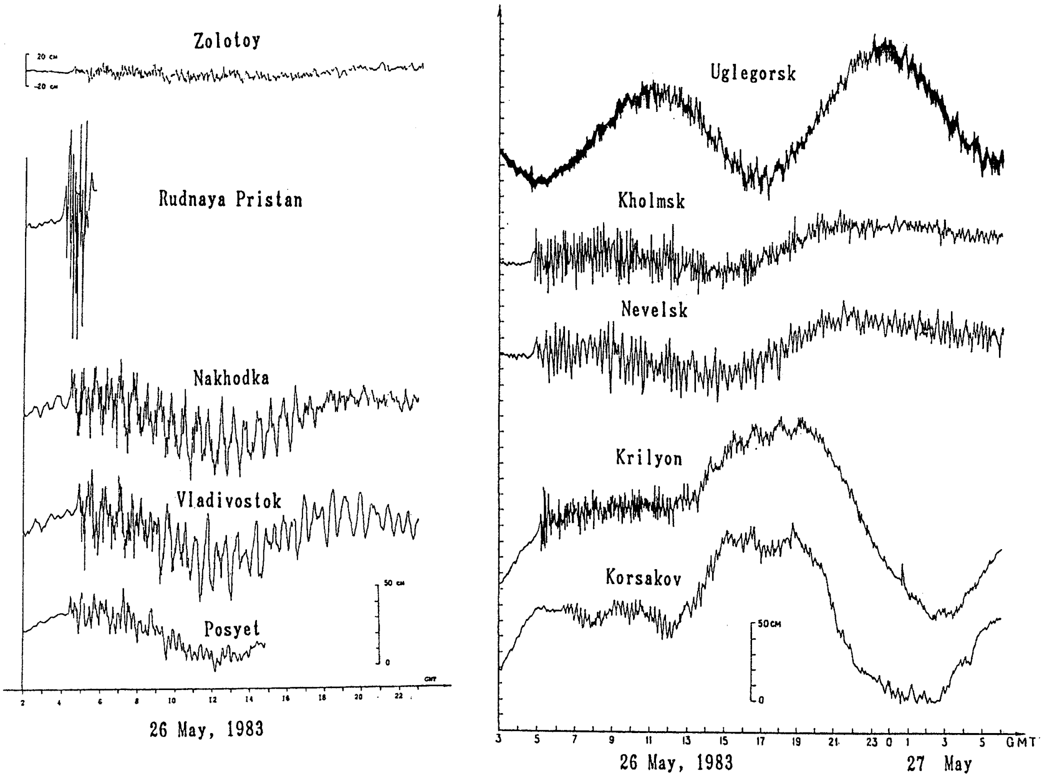

Fig. 6. Tidal gauge records of the tsunami on 26 May 1983 at USSR stations (from Go *et al.*, 1984).

Table 5. Parameters of tsunamis for the Russian coasts of the Sea of Japan.

Stations	Observed maxima, cm	A, year^{-1}	h^*, cm	h_{100}, cm
Posyet	15	0.10	17	40
Vladivostok	33	0.10	43	100
Nakhodka	30	0.10	35	80
Rud.Pristan	100	0.10	75	170
Sov. Gavan	4	?	?	?
Uglegorsk	15	0.18	17	50
Kholmsk	38	0.27	21	70
Nevelsk	50	0.23	25	80

with the continental ones are explained by influence of Pacific tsunamis reaching northeastern part of the sea but not the western coasts.

It follows from expression (9) that the maximum tsunami height for 100 years is proportional to the calibrated wave height h^*:

$$h_{100} = h^* \ln(100\,A) \qquad (10)$$

Calculated h_{100} are also given in Table 5.

To the authors' knowledge, there is only one record of tsunami in Sovetskaya Gavan. The small tsunami with wave height less than 4 cm was caused by the Moneron Earthquake on 1 September 1971 (Schetnikov, 1978). It is not sufficient to estimate tsunami risk for this point.

Tsunami records in De Kastri are absent at all. Apparently tsunami waves have not reached this point.

Estimated values of h^* for most stations are less than 1 m. The exception is Rudnaya Pristan. Relatively strong tsunami waves for this

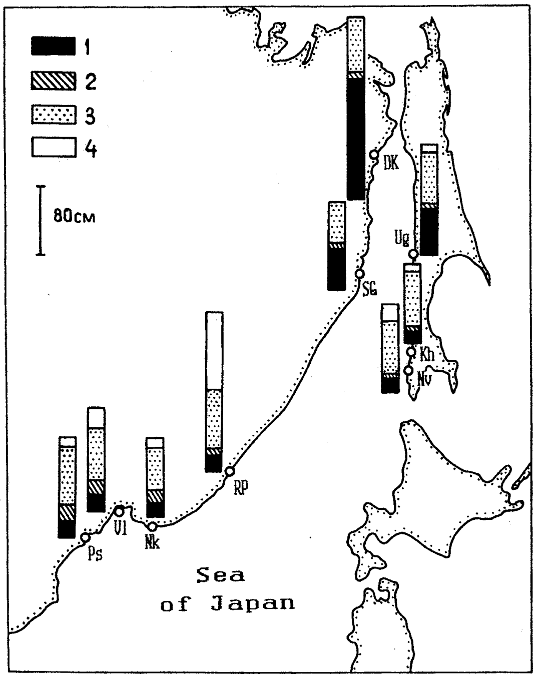

Fig. 7. Extreme sea level heights in the northern part of the Sea of Japan computed by superposition of tides (1), seasonal variations (2), storm surges (3) and tsunamis (4) for the stations Posyet (Ps), Vladivostok (Vl), Nakhodka (Nk), Rudnaya Pristan (RP), Sovetskaya Gavan (SG), De Kastri (DK), Uglegorsk (Ug), Kholmsk (Kh), and Nevelsk (Nv).

station are probably caused by resonance effects. This supposition is confirmed by significant seiche oscillations which are usually observed in the region of Rudnaya Pristan (FIRSOV, 1989).

Tsunami sequence in the area has approximately Poisson's character (GO *et al.*, 1985, 1988). The probability of tsunami height during T years will never exceed the value expressed by the formula

$$P(h,T)=\exp(A\exp(-h/h^{*}). \qquad (11)$$

Expression (11) was used to calculate possible superposition of tsunamis with other sea level components and to estimate total extreme sea level elevations caused by various factors in accordance to (1). Results are presented in Fig.7 and Table 6.

8. Summary and discussion

Joint probability method allows us to produce realistic estimates of extreme sea levels based on relatively short observational series and to take into account several different factors.

Absolute estimates of total maximal levels for various stations at the Russian coast of the Sea of Japan with a return period of 100 years (Table 6) is one of the main results of this study. Specifically, it was found that the highest sea level elevations are related to De Kastri and Rudnaya Pristan, and the lowest ones to Nakhodka and Kholmsk.

Another interesting and new result is an estimation of extreme heights and relative importance of individual sea level components. Different components were shown to play essential role different parts of the sea: tides are especially strong in the northern part of the Tartar Strait, tsunami is the most dangerous factor in the region of Rudnaya Pristann, and surges have similar heights all over the Russian coasts of the Sea of Japan.

Table 6. Predicted maximal sea level heights by tides, seasonal oscillation, surge and tsunami (accumulated height) .

Stations	Predicted level h_{100}, cm			
	Tides	+seasonal	+surge	+tsunami
Posyet	20	39	106(101)	116
Vladivostok	21	37	97(93)	119
Nakhodka	19	33	81	94
Rudnaya Pristan	17	28	93	185
Sovetskaya Gavan	48	54	102	?
De Kastri	144	151	216	216
Uglegorsk	57	63	123	133
Kholmsk	18	22	87	95
Nevelsk	22	26	85	97

Table 7. Extreme sea level estimated without (upper row) and with (lower row) consideration of tsunami waves

Stations	Return periods, years			
	10	25	50	100
Nevelsk	74	79	82	85
	80	85	90	97
Rudnaya Pristan	82	86	89	93
	94	104	135	185

Furthermore, subsequent contribution of various factors in total extreme sea level heights was also described (Fig.7). It is important to note that tsunamis have proved to be secondary factor for recurrency 1/100 years for all the stations except Rudnaya Pristan. It is clear that the probability of coincidence of two random dangerous factors, strong surge and tsunami, is small for short periods but may increase drastically with increase of return periods. An influence of tsunami waves on estimates of maximal sea level heights for different return periods is illustrated in Table 7. The additional increase of the total extreme sea level due to the tsunamis is only 6 cm for Nevelsk and 12 cm for Rudnaya Pristan for $T = 10$ years, but 12 and 92 cm for $T = 100$ years. Therefore, for short periods, the extreme heights are determined by tides, surges, and seasonal oscillations for all stations; for longer periods, tsunamis may play an essential role in forming extreme levels.

It would be interesting to verify the estimates with more complete observational data. Another question is inclusion of additional factors (e. g. seiches) and an estimation of extreme sea level oscillations together with wind waves.

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