La mer 30: 191–212, 1992
Société franco-japonaise d'océanographie, Tokyo

On the atmosphere-induced sea level variations along the western coast of the Sea of Japan

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Abstract: Simultaneous 3-month observational series (July - September, 1986) of sea level, atmospheric pressure and wind stress were used to investigate atmosphere-induced sea level variations along the Korean and USSR coasts of the Sea of Japan. Multi-input system spectral analysis and multiple regression analysis were applied to examine the data. An amount of 46 to 77 % of the total sea level energy was found to be coherent with atmospheric pressure and 5 to 37 % with additional influence of wind stress. The barometric factor for the period under study was changed gradually northward from −0.67 cm/mb for the southernmost station Sogwipo to −1.50 cm/mb for the northernmost station De Kastri. Influence of wind waves on mean sea level was studied for the stations Muko (Mugho) and Ulsan. It was found that wave set-up may sufficiently increase storm surge heights. The storm surge caused by the typhoon No 8613 "VERA" was examined in detail. Main parameters of this surge such as 'surge height', 'duration', 'steepness', 'variance', 'pressure factor' as well as meteorological characteristics in time of the storm surge were estimated for all 15 stations. Hindcasting of the surge by multiple regression equations gave quite satisfactory results. Non-linear interaction of storm surges and tides was also studied but found to have small effect.

1. Introduction

The Northwest Pacific is a region of high atmospheric activity. Annual number of typhoons is about one-third of the total world amount (AOKI, 1985). A great number of typhoons and severe extra-tropical cyclones pass over the Sea of Japan and have an influence on sea level variations. Deep atmospheric depressions accompanied by strong winds create extreme sea levels in this region. Storm surges cause heavy floods at the coastal areas with significant destructions and people sacrifices. To mitigate possible damages it is important to explore weather-induced sea level variations and their extreme manifestations.

Investigations of storm surges and sea level response to atmospheric disturbances for the northwestern part of the Pacific were carried out by many scientists. In particular, the region of Kuril Islands has been studied in detail at the Institute of Marine Geology and Geophysics (IMGG) (LAPPO *et al.*, 1978; LIKHAEVA and SKRIPNIK, 1981; LIKHACHVA, 1984; LIKHACHEVA and RABINOVICH, 1986b; SKRIPNIK and SOKOLOVA, 1990). This region as a boundary between the Pacific Ocean and the marginal Sea of Okhotsk is an area of great interest from scientific point of view, but Kuril Islands are populated sparsely. Therefore the practical importance of these works is limited.

On the contrary, the population density around the Sea of Japan is very high. Many complex and expensive constructions were made here in the recent years; that is why appropriate research of the region has the significant meaning. At the same time it would be interesting to compare forming mechanism of sea level variations at the Sea of Japan coasts and at the coasts of Kuril Islands, because the two regions have very different physical and geographycal conditions: the Sea of Japan is practically

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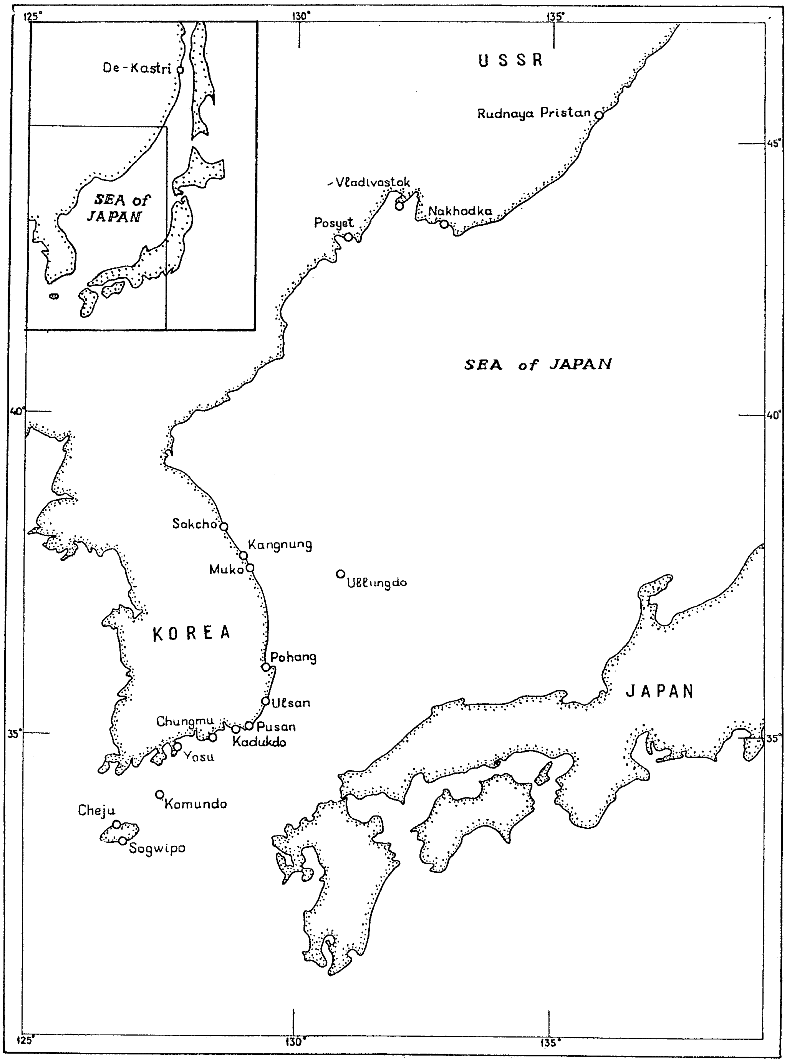

Fig. 1. Location of the coastal stations.

closed; the Pacific coast of the Kurils is open and has a narrow shelf with steep slope.

Sea level variability near the east (Japanese) coast of the Sea of Japan was investigated thoroughly by UNOKI (1959), ISOZAKI (1968, 1969) and other Japanese scientists. However, for the west (Russian and Korean) coasts this subject has been studied only fragmentarily. FIRSOV (1988) has analysed observed data to construct an empirical model of storm surges for the northwestern part of the Sea of Japan. The storm surges on the Korean coasts (first of all for the region of the Korea Strait) have been inspected by data analysis (HWANG, 1971; CHU, 1987; OH *et al.*, 1988) and by numerical modelling (KANG, 1988; OH and KIM, 1990).

The main purpose of this study was investigation of low-frequency (1-20 days) sea level variations on the Russian and Korean coasts of the Sea of Japan and estimation of their generating mechanism in different regions based on hydrometeorological data.

Typhoons are the main cause of strong storm surges at the coasts of the Sea of Japan. As it was shown by KANG *et al.* (1988), 240 out of 259 typhoons for the period 1904-1987 occurred

Table 1. The list of observational data.

Stations	Sea level			Atm. pressure			Wind			Wind waves		
	J	A	S	J	A	S	J	A	S	J	A	S
Sogwipo	1	1	1	3	3	3	1	1	1	*	*	*
Cheju	1	1	1	3	3	3	1	1	1	*	*	*
Komundo	1	1	1	—	—	—	—	—	—	—	—	—
Yosu	1	1	1	3	3	3	1	1	1	*	*	*
Chungmu	1	1	1	3	3	3	1	1	1	—	—	—
Kadukdo	1	1	1	—	—	—	—	—	—	—	—	—
Pusan	1	1	1	3	3	3	1	1	1	*	*	*
Pohang	1	1	1	3	3	3	1	1	1	—	—	—
Ullungdo	1	1	1	3	3	3	1	1	1	—	—	—
Ulsan	1	1	1	3	3	3	1	1	1	3	3	3
Muko	1	1	1	—	—	—	—	—	—	6	6	6
Kangnung	—	—	—	3	3	3	1	1	1	—	—	—
Sokcho	1	1	1	3	3	3	1	1	1	—	—	—
Posyet	1	1	1	3	3	3	3	3	3	—	—	—
Vladivostok	1	1	1	3	3	3	3	3	3	—	—	—
Nakhodka	1	1	1	3	3	3	3	3	3	—	—	—
Rud. Pristan	—	—	1	3	3	3	3	3	3	—	—	—
De Kastri	1	1	1	3	3	3	3	3	3	—	—	—

J is July, A is August, S is September; 1, 3, 6 are time intervals (in hours); * means fragmentary data

during three months: 74 in July, 103 in August and 63 in September. Therefore, just these months were chosen for the present analysis.

2. Data

Sea level data obtained at 18 stations on the coasts of Korea and Russia were used to investigate sea level response to meteorological forcing. These stations situated along the west coast of the Sea of Japan (Fig.1) are related to the regions with different topography and tidal regime. The shallowest water zones are located near the southern part of the Korean Peninsula and in the northern part of Tatar Strait (De Kastri station). The narrow shelf and steep shore are typical for the eastern Korean coast.

Observational data were supplied by the Hydrographic Office (Korea) and Hydrometeorological Administration (Russia). These data were represented by the time series of sea level and atmospheric forcing for July-September, 1986 (Table 1). The sea level data consisted of hourly tide gauge records. Atmospheric pressure and surface wind data were obtained mainly from the local observations at the same statinos. Complete 3-month simultaneous series were available for the majority of the stations, except Rudnaya Pristan where sea level data were absent and Komundo, Kadukdo where there were no meteorological data. For the Muko station atmospheric pressure and wind were taken at the neighbouring meteorological observatory of Kangnung. Series of atmospheric pressure had 3-hour time interval for all cases; wind data had time step of 1 hour for Korean and 3 hour for Russian stations. There were fragmentary wind waves data for some Korean stations, but only two of them (Muko and Ulsan) had complete 3-month series (of maximum wind wave heights) with 3-hour time step for Ulsan and 6-hour for Muko (Table 1). Series of significant wave heights had many gaps and their use was limited.

3. Methods

General analysis scheme is shown in Fig.2. Original data were carefully tested and corrected. Two different ways were used to represent surface wind data: by wind velocity components $W_x = |W| \sin \Psi$, $W_y = |W| \cos \Psi$ and wind stress components $T_x = k \rho \, |W| W_x$, $T_y = k \rho \, |W| W_y$, where W, Ψ are the wind speed and direction, ρ is the air density, k $(=0.0025)$ is the wind drag coefficient. Two pairs of wind stress components were used: (1) onshore, longshore $(T_x,\ T_y)$ and (2) zonal, meridional

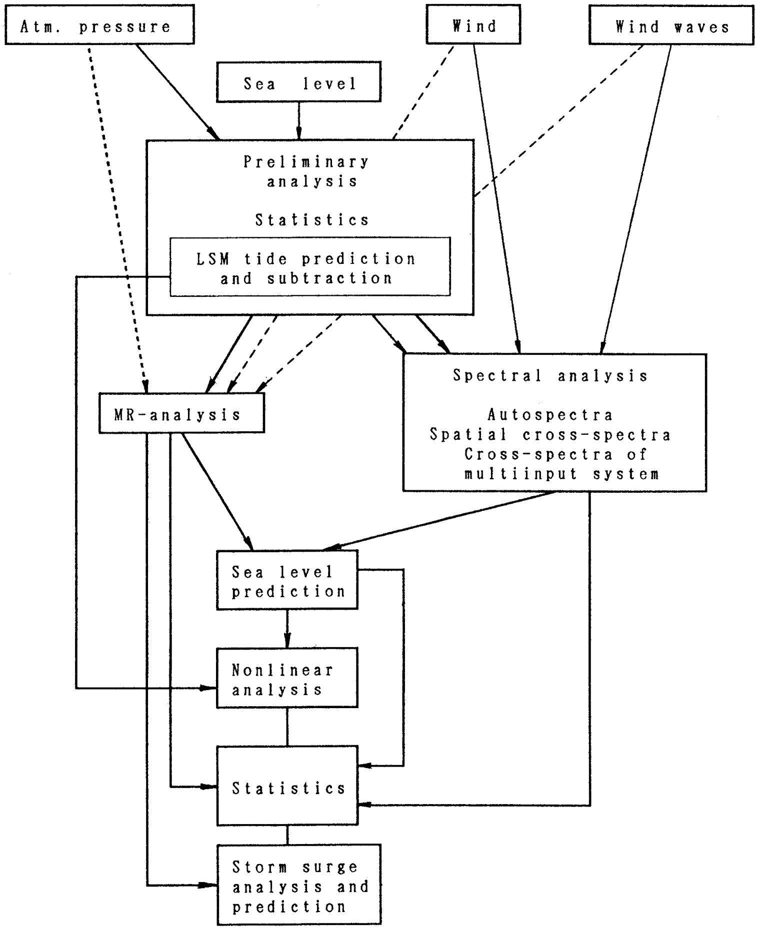

Fig. 2. Scheme of analysis.

(T_z, T_M). Meteorological and wind waves data were interpolated by spline function to obtain synchronous hourly series. Astronomical tides were removed from the initial sea level and then residual series were used for further analysis.

Two methods of data processing were applied: spectral analysis and multiple regression analysis (MRA). The first one included auto-and cross-spectral data examination and multi-input system analysis (MISA). The second method was realized in time domain which enabled to analyse not only full 3-month series, but also short segments connected with individual storm surges. It was possible to find response functions of the sea level to the atmospheric disturbances and to estimate contribution of different meteorological forces by both methods. Influence of additional factors on sea levels (wave set-up and non-linear tide-surge interaction) was also estimated.

The observational period was remarkable by propagation of typhoon No 8613, "VERA", one of the strongest and most distructive in the last 20 years (OH *et al.*, 1988; KANG *et al.*, 1988; KANG, 1988; OH and KIM, 1990). Significant storm surge was observed all over the Korean coasts and also in the Primorye Region of Russia. Statistical parameters of this storm surge were estimated for all stations except the northernmost station De Kastri where it was not revealed. MRA results were used for the storm surge hindcasting.

4. Tidal analysis

Tides are usually predominant in sea level oscillations. In particular, results of tidal analysis

Table 2. The amplitudes of major tidal constituents computed for the August, 1986.

Stations	Tidal variance, %	Tidal amplitudes, cm							
		Q_1	P_1	O_1	K_1	N_2	M_2	S_2	K_2
Sogwipo	96.7	4.3	8.4	18.1	25.2	16.4	73.4	32.5	8.8
Cheju	97.5	4.0	8.1	17.0	24.2	16.0	65.7	26.6	7.2
Komundo	98.4	3.3	8.3	17.0	24.2	18.8	85.6	38.5	10.1
Yosu	98.1	1.9	6.3	13.4	19.3	19.5	94.4	44.2	12.0
Chungmu	97.5	1.4	4.9	10.2	14.7	15.5	75.3	35.4	9.6
Kadukdo	96.4	0.5	2.0	4.3	7.2	10.3	54.0	27.3	7.6
Pusan	91.5	0.2	1.5	1.7	4.5	7.4	38.6	18.4	5.0
Ulsan	65.7	0.8	1.3	3.3	3.8	2.6	15.6	7.7	2.0
Pohang	22.9	1.2	1.3	4.3	3.9	0.8	3.0	0.7	0.2
Ullungdo	31.6	0.9	1.5	4.7	4.6	2.6	4.5	1.6	0.4
Muko	23.8	0.9	1.6	4.7	4.7	1.6	6.2	2.2	0.6
Sokcho	22.2	0.8	1.6	4.7	4.4	1.6	6.8	2.5	0.7
Posyet	28.0	0.7	1.8	4.7	5.2	1.7	7.5	3.2	0.9
Vladivostok	31.5	1.0	1.8	5.1	5.4	1.8	7.6	3.2	0.9
Nakhodka	32.1	0.9	1.9	5.1	5.5	1.5	6.6	2.7	0.7
Rud.Pristan*	39.5	1.3	1.8	5.0	5.4	1.2	6.0	2.7	0.7
De Kastri	94.7	1.6	2.3	6.4	6.9	19.0	68.7	25.4	6.6

* Tidal amplitudes in Rudnaya Pristan have been computed for September, 1986.

of the investigated region have demonstrated that for the stations located in the Korean Strait and De Kastri more than 94 % of total sea level variance is related to the tides (Table 2). For the stations situated at the east coast of Korea and for the southern Russian stations this percentage is less (22 to 40 %) but in any case it is significant. For correct examination of weather-induced elevations including storm surges, it is necessary to eliminate tidal oscillations.

It is possible to remove tides from the initial records by applying special low-pass or band-pass numerical filters (PUGH, 1987). The shortage of such method consists in distortion of the processes with near-tidal frequencies and reduction of extreme sea level deviation (i.e. actual storm surge heights).

Therefore it is better to predict tides based on results of harmonic analysis and to subtract them from the initial observational series. This method was used by OH *et al.* (1988) to analyse storm surges near the southern coast of Korea. They have calculated 64 tidal constants based on 1-year series of hourly data, then used these constants to predict tides during typhoon passages (including typhoon "VERA") and to remove them. The oscillations with period of about 12 hours which appeared distinctly in the residual records were, by the opinion of OH and KIM (1990), connected with influence of tidal currents.

In this paper we applied a similar method but with certain modification. Least square method was used to compute 37 tidal harmonics and to subtract tides from initial records for every monthly series separately. The use of additional harmonics in excess of 37 did not give further improvement of the residuals. This method gave good results: residual series were visually quite clean without tides except some small pieces of records of apparently poor quality (Fig.3); their spectra did not have any prominent maxima of tidal frequencies (Fig.4), either.

Amplitudes of major tidal constituents (Table 2) were in good agreement with those obtained by OH *et al.* (1988) from yearly series.

5. Spectral analysis of sea level and atmospheric pressure

We made spectral analysis of 3-month data series with FFT procedure. Kaiser-Bessel window (HARRIS, 1978) was used to improve spectral estimates. Power spectra of atmospheric pressure and sea level are shown in Fig.4. There is a good spectrum correspondence for different stations in the frequency band 0.07–1 cpd, i.e. in the 'synoptical frequency range' (LICHACHEVA,

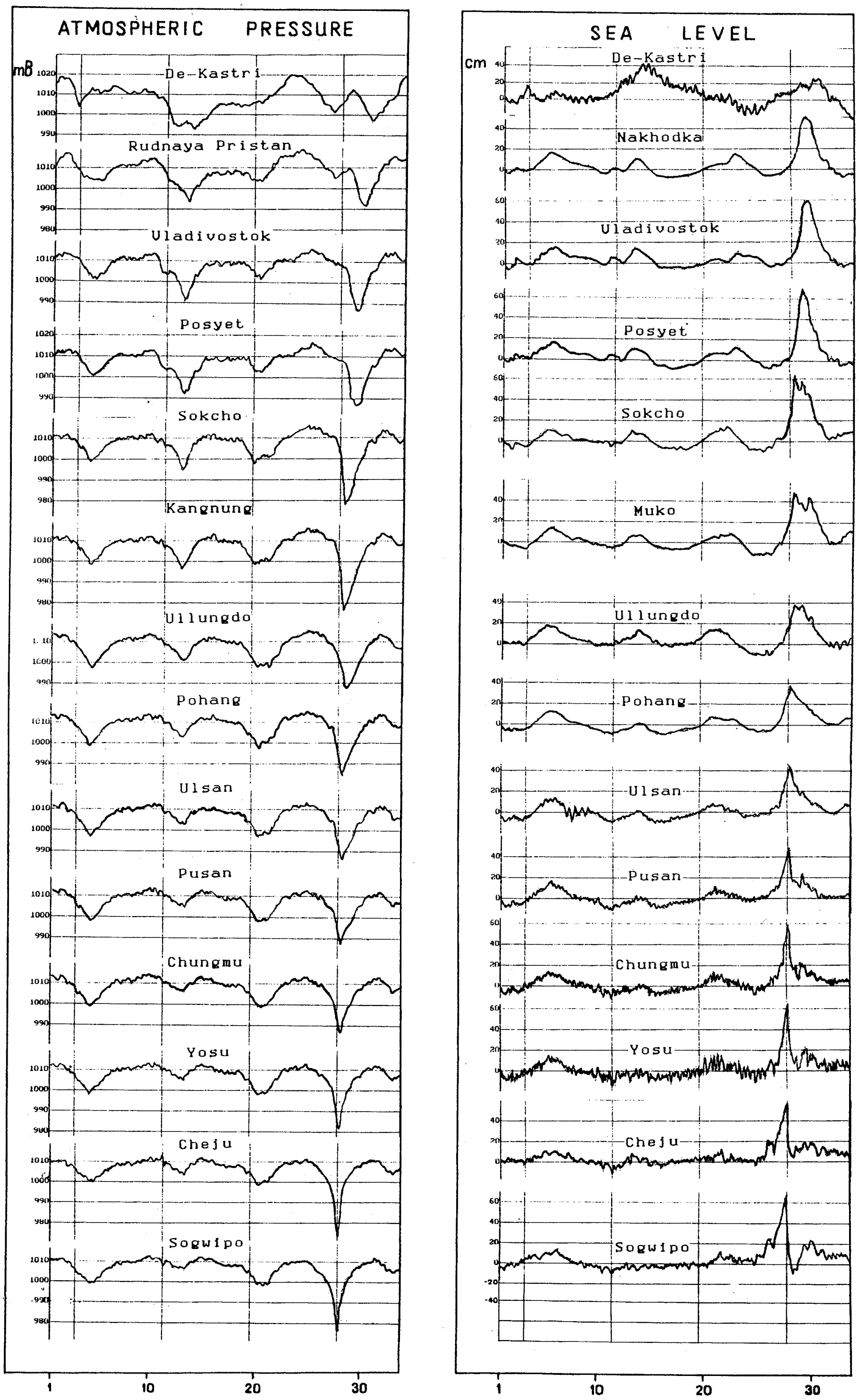

Fig. 3. Records of atmospheric pressure and non-tidal sea level variations in August, 1986.

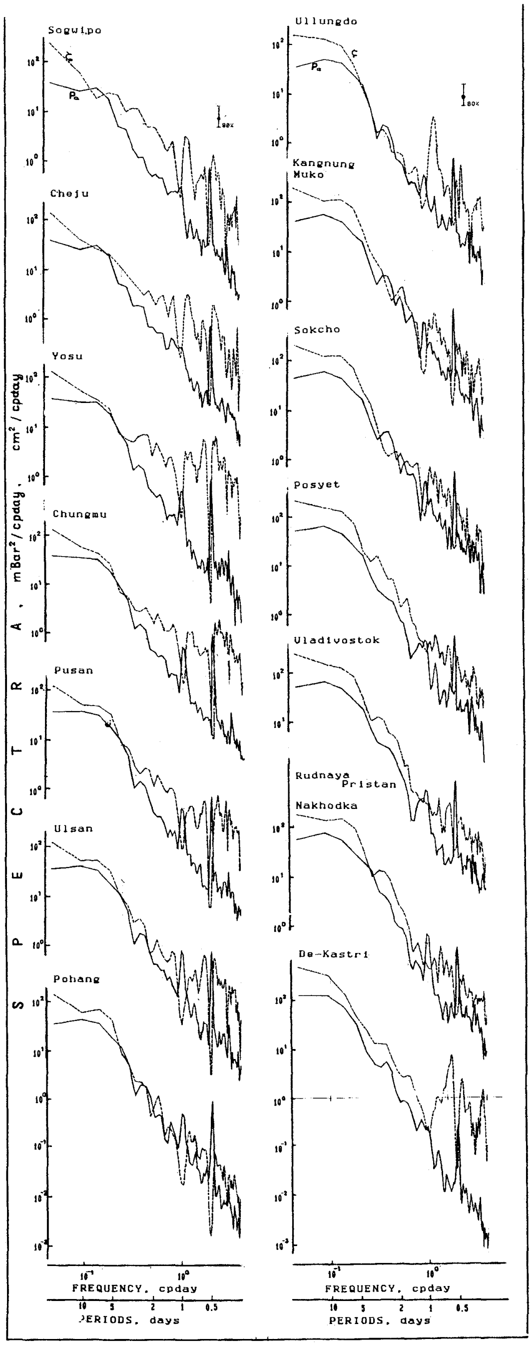

Fig. 4. Spectra of atmospheric pressure and sea level.

1984). The shape of low frequency sea level spectra resembles to that of atmospheric pressure, but their energy level is a little higher, which agrees well enough with results of ISOZAKI (1969) for the eastern coast of the Sea of Japan. Prevalence of sea level spectrum is manifested better for the northern stations. At higher frequencies there is increasing divergence in sea level and pressure spectra.

There is a prominent peak in the atmospheric pressure spectra at the frequency of 2 cpd caused by semidiurnal atmospheric tides. Diurnal maximum is not so notable; for some stations (Sogwipo, Cheju, De Kastri) it is practically absent (Fig. 4).

There is no obvious maximum in atmospheric spectra at the periods of about 5–6 days ('the synoptical maximum'), though usually well seen in the Northwestern Pacific (LIKHACHEVA and RABINOVICH, 1986a).

The sea level spectra are relatively smooth and have no evident peaks. However, there are a few exceptions. At the Ullungdo station an obvious maximum with period of 19.7 hours is well seen. This period is exactly equal to the inertial period for this station $T=\pi/\Omega\sin\Psi$, where Ω is the Earth's angular speed and Ψ is the geographical latitude. This coincidence is scarcely casual, especially taking into account that Ullungdo is a small isolated island in the open sea. Apparently corresponding sea level variations are caused by inertial currents or by internal waves of inertial period.

There is another interesting spectral feature. Results of the spectral analysis show that the least square procedure of tidal analysis has removed from the initial sea level series not only real tides but also some part of background noise, leaving deep troughs in appropriate parts of the spectra. Around these troughs there are peaks with periods: 29–30 and 21–22 hours for Sogwipo and Cheju, 13.5–14 and 11 hours for Cheju, Yosu and De Kastri (Fig. 4), i.e. these peaks are observed generally for the stations with strong tides. Although there are no tidal constituents with these periods, it is clear that these maxima are connected with tides and probably are the residuals of wide tidal extremes. MUNK *et al.* (1965) called this phenomenon 'tidal cusps' and explained the cause of this cusping as 'the non-linear interaction of the tidal spectral line with the low frequency continuum'. Apparently in our case these cusps are related to the non-linear interaction of tides and mean flow.

Some spectral features of sea level may be related to eigen oscillations of the Sea of Japan. RIKIISHI (1986) computed these oscillations with periods of several hours and demonstrated that semidiurnal tidal structure corresponds very well with structure of appropriate proper oscillations. SATAKE and SHIMAZAKI (1988) made a similar investigation for tsunami frequency band and showed that spectral peaks in the period range of 50 to 210 min excited by the 1964 Niigata and 1983 Japan Sea tsunamis agreed quite well with the numerically computed periods of normal modes in the sea. Unfortunately there are no such investigations of subtidal modes of the Sea of Japan It may be interesting in future to compare meteorologically-induced sea level variations with normal mode structure.

We made a cross-spectral analysis of the data to examine spatial-temporal relations of the atmospheric and sea level variations. Coherence and phase functions were calculated between the southernmost station Sogwipo and all the others. Atmospheric pressure coherence is decreased gradually with increase of distance from Sogwipo. An exception is the frequency of semidiurnal atmospheric tides where coherence peaks exceeding 0.80 are practically independent of the distance (Figs. 5a, 6a). Sea level coherence along the coast at periods of 1–5 days is quite stable. Significant values persisted for a long distance (Figs. 5b, 6b).

We describe spatial-temporal changes of the atmospheric pressure coherence γ^2 (Fig.6) in the synoptical frequency range as

$$\gamma^2(L, T)=\exp(-aL^{\nu}/T^{\beta}), \qquad (1)$$

where a, ν, β are the empirical constants, T is period (in hours), L is length scale (in km). With this formula $\gamma^2 \rightarrow 1$ when $L \rightarrow 0$ or $T \rightarrow \infty$; on the contrary $\gamma^2 \rightarrow 0$ when $L \rightarrow \infty$ or $T \rightarrow 0$.

Based on Eq. (1) and coherence functions $\gamma^2_{ij}(L, T)$ between Sogwipo and all other stations, parameters a, ν and β were computed by least square method (LSM) from the expression

$$\sum_{i=1}^{N}\sum_{j=1}^{M-1}[\log(-\ln(\gamma^2_{ij}))-\log a-\nu\log L_j - \beta\log f_j]^2 \rightarrow min, \qquad (2)$$

where $f_i=1/T_i$, N is the number of frequencies in chosen band, M (=15) is the number of stations. Following values were obtained: $a=9.37\times10^{-3}$, $\nu=1.11$, $\beta=0.688$. Empirical formula (1) may be used for description of temporal and spatial coherent scales of atmospheric processes. For example, for T = 5 days: L=336 km for γ^2=0.8 and L=709 km for γ^2=0.6. Appropriate lengths estimated directly from Fig. 6a are approximately 340 and 705 km.

In this investigation only one-dimensional coherence scales were examined. Two-dimensional spatial and temporal scales of atmospheric processes had been inspected by LIKHACHVA and RABINIVICH (1986a) based on yearly series of atmospheric pressure for the whole Far East region. It was shown that coherence field is quasi-isotropic over the continental area and the Sea of Japan, and anisotropic only on the continent-ocean boundary. The typical scales were found to be 300–500 km for T=5 days and γ^2 = 0.8, which are in good agreement with those obtained in the present study.

Phase functions of both atmospheric pressure and sea level are close to be linear in the synoptical frequency band (Fig.5). LSM procedure was used to estimate the average speed and direction of atmospheric disturbances based on phase lags between the stations. It was found that the atmospheric processes were propagated to the northeast with mean speed of 40–50 km/h. Sea level variations moved longshore northward with almost the same velocity.

6. Spectral analysis of multi-input system

Sea-level continuum may be regarded as an output of multiple linear system with a number of input functions (weather variables) which are in general mutually coherent (GROVES and HANNAN, 1968; CARTWRIGHT, 1968; WUNSCH, 1972). To investigate such a system and to examine relations between meteorological forces and non-tidal residual sea level it is possible to apply multi-input system cross-spectral analysis (MISA) (BENDAT and PIERSOL, 1986). Three

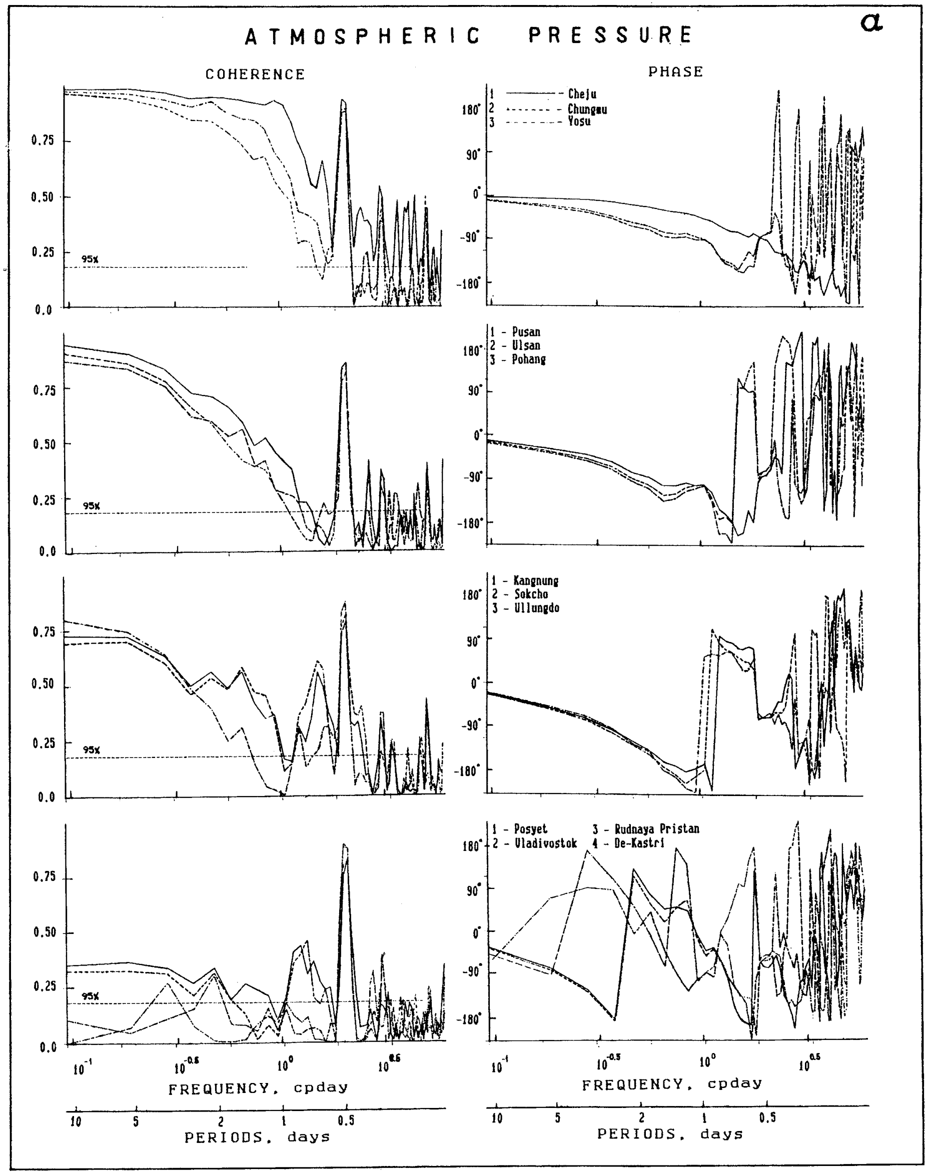

Fig. 5a. Coherence and phase functions of atmospheric pressure between Sogwipo and all the other stations.

input functions, atmospheric pressure, onshore and longshore wind stress components, were used for most stations. For two stations (Ulsan and Muko) the fourth input (wind wave height) was also used.

Multiple and partial coherence functions (BENDAT and PIERSOL, 1986) were calculated for all examined stations. Fig. 7 shows a high multiple coherence between external forces and sea level in the synoptical frequency band. Low-frequency coherency band has a certain tendency to narrow toward the north. The stations of the Korea Strait (Cheju, Sogwipo) have the zone of maximal coherence in the frequency range of 0.4–0.7 cpd with values over 0.90. There is another coherence maximum at the frequency of about 1.5 cpd which is manifested better for Cheju and the eastern Korean and Russian stations and

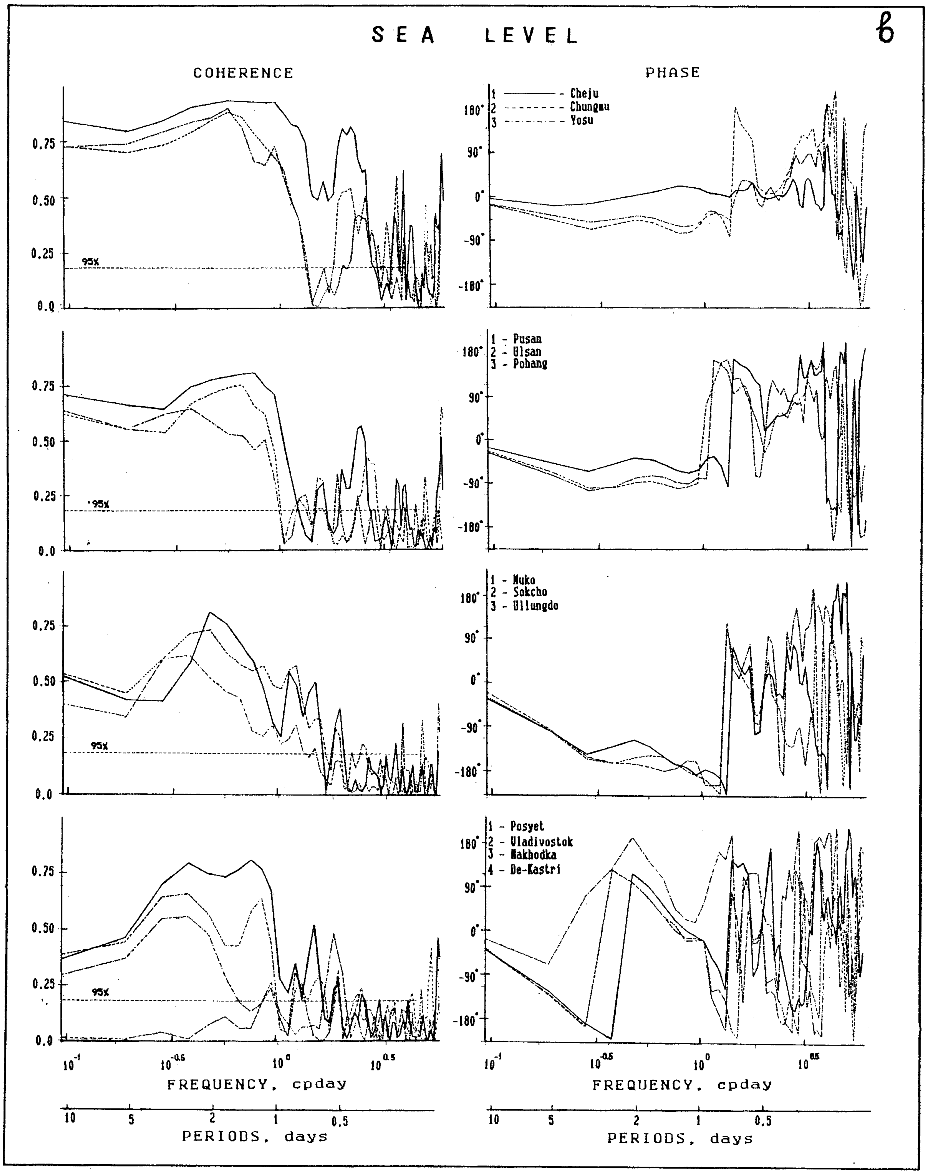

Fig. 5b. Coherence and phase functions of sea level between Sogwipo and all the other stations.

reaches highest values in excess of 0.8 at stations Muko, Sokcho and Posyet (Fig.7). These stations have also the third maximum at short periods.

Multiple coherent spectrum of output process is defined as (BENDAT and PIERSOL, 1986)

$$G_{vv}(f)=G_{yy}(f)\,\gamma^2_{y:x}(f), \qquad (3)$$

where G_{yy} is the spectrum of output, $\gamma^2_{y:x}$ is the multiple coherence of the system, f is the frequency. Coherent spectrum was integrated over the whole frequency band

$$R_{y:x}=\int_0^\infty G_{vv}(f)df \qquad (4)$$

to estimate total coherent part of the variance (Table 3). Similar expression but with re-

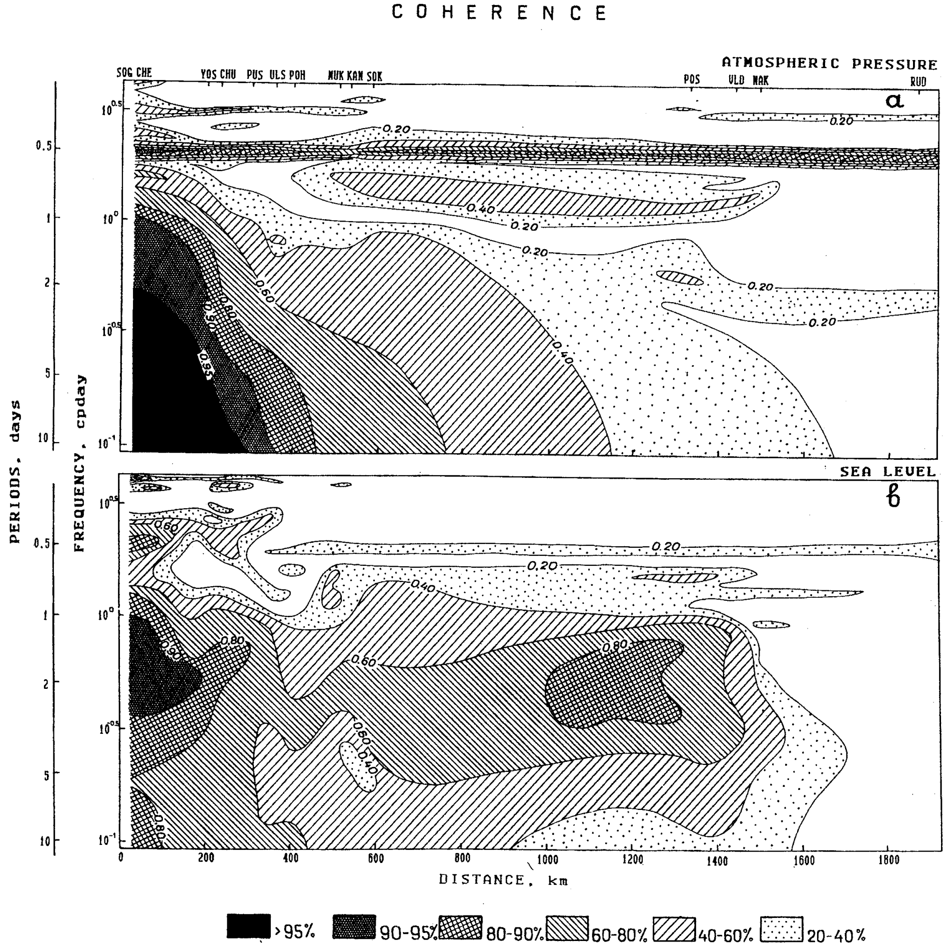

Fig. 6. Spatial coherence field of atmospheric pressure (a) and sea level (b) relative to the Sogwipo station.

placement of a multiple coherence by a partial one had been used for estimation of relative importance of individual inputs (WROBLEWSKI, 1978).

Energy of non-tidal sea level variations is reduced from Sogwipo (76 cm^2) to Pusan and Ulsan (49 cm^2) and then is increased northward reaching maximum in De Kastri (132 cm^2). These values are of the same order as for Japanese coasts (ISOZAKI, 1969) but less than in the region of Kuril Islands (80–175 cm^2) (LIKHACHEVE, 1984; RABINOVICH and SOKOLOVA, 1985).

Table 3 shows that atmospheric pressure is considered to be the main factor forming non-tidal sea level oscillations; 46 to 77 % of initial variance are coherent with pressure. The relative contribution of atmospheric pressure in the total sea level budget for the coasts of the Sea of Japan is about the same as that in the Kuril region (50–78 %), but additional deposit due to wind stress (9–33 %) is much higher here than there (0.3–9 %). Relatively higher role of wind stress in generation of weather-induced sea level oscillations, specifically storm surges, in the marginal seas with broad shallow water areas in comparison with zones of open ocean shelf with steep slope is well known (MURTY, 1984; PUGH, 1987). As a result amount of energy accounted by both wind stress components and atmospheric pressure is about 60–90 % of the total variance at the coasts of the Sea of Japan in

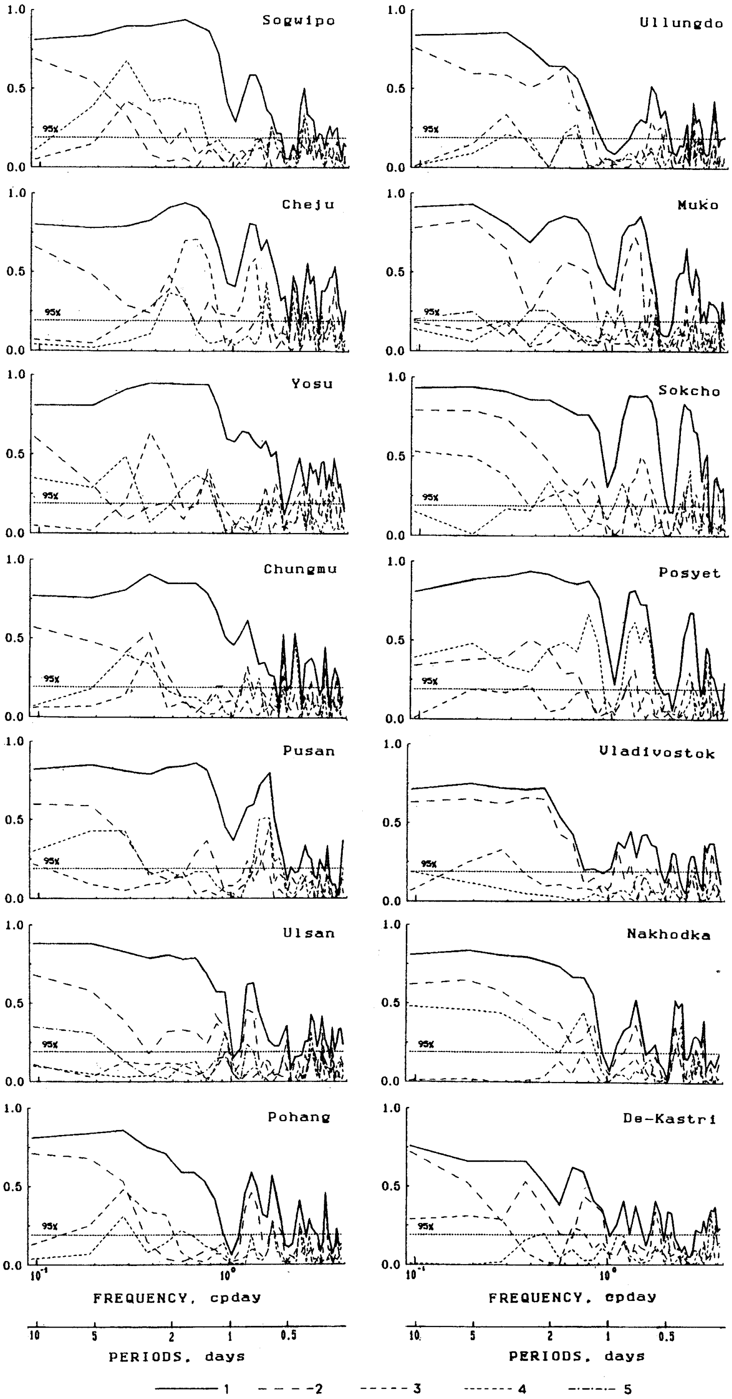

Fig. 7. Multiple and partial coherence functions for sea level oscillation. 1 - multiple coherence, 2 - partial coherence between sea level and atmospheric pressure, 3, 4 - partial coherence between onshore and longshore wind stress components, 5 - partial coherence between sea level and maximal wave height.

Table 3. Weather coherent and predicted (by MRA) non-tidal sea level variances.

Stations	Sea level variance, cm^2	Coherent variance, cm^2/%			Predicted variance, cm^2/%
		atm. pressure	wind	total	
Sogwipo	75.9	43.2/56.9	20.8/27.4	64.0/84.3	40.6/53.5
Cheju	57.6	36.9/64.1	5.1/8.9	42.0/72.9	27.0/46.9
Yosu	68.5	39.3/57.4	7.7/11.2	47.1/68.7	35.5/51.8
Chungmu	54.1	34.9/64.5	4.7/8.7	39.7/73.3	29.0/53.7
Pusan	48.6	28.9/59.5	9.5/19.5	38.4/79.1	29.0/59.7
Ulsan	48.9	30.5/62.4	7.7/15.7	38.2/78.1 (40.6/83.1)	27.2/55.6 (32.6/66.6)
Pohang	52.3	33.4/63.9	9.1/17.4	42.5/81.2	29.0/55.4
Ullungdo	74.4	49.3/66.3	11.1/14.9	60.3/81.1	44.8/60.2
Muko	84.7	63.0/74.4	10.2/12.0	73.3/86.5 (75.5/89.1)	54.1/63.9 (56.5/66.7)
Sokcho	99.4	76.7/77.2	14.6/14.7	91.3/91.9	68.0/68.4
Posyet	111.5	59.3/53.2	36.8/33.0	96.1/86.2	86.7/77.7
Vladivostok	103.5	53.2/51.4	20.7/20.0	73.3/73.9	62.6/60.5
Nakhodka	91.0	48.0/52.7	25.9/28.5	73.9/81.2	67.9/74.6
De Kastri	131.5	60.8/46.2	17.1/13.0	77.8/59.2	78.6/59.7

comparison with 55–70 % for the Pacific coast of the Kuril Islands (RABINOVICH and SOKOLOVA, 1985).

The largest wind contributions in sea level variance were found at the Sogwipo, Posyet and Nakhodka stations. Values in brackets in Table 3 are related to the 4-input system including wind wave heights.

Analysis of partial coherences for southern Korean stations showed that atmospheric pressure plays dominant role at the lowest frequencies to 0.2–0.3 cpd, but at the higher frequencies wind influence on sea level becomes comparable with or exceed that of atmospheric pressure (Fig. 7). For the eastern Korean and the Russian stations except Posyet sea level is more closely correlated with atmospheric pressure than with wind, practically for all examined frequencies.

7. Multi-regression analysis

We performed also the investigation of sea level response to weather forces in time domain, using multilple regression technique (GROVES and HANNAN, 1968; AMIN, 1978, 1982; RABINOVICH and SOKOLOVA, 1985; SKRIPNIK and SOKOLOVA, 1990). The appropriate regression equation may be represented as

$$\zeta(t)=\sum_{j=1}^{M}\sum_{i=1}^{L_j} w_j(\tau_{ij})\cdot F_j(t-\tau_{ij})+\varepsilon(t), \quad (5)$$

where ζ is the sea level (output), t is the time, F_j are the external forces (input), w_j is the set of regression coefficients (response weights) for each input, L_j is their number, M is the number of input processes, τ_{ij} are the time lag, ε is background noise uncorrelated with input functions.

Based on expression (5) it is possible to hindcast sea level variations by known input functions and response weights. Multiple regression analysis (MRA) is an efficient instrument to construct empirical forecasting formulae to predict storm surges.

An effective MRA computer program with arbitrary number of inputs and response coefficients was elaborated by RABINOVICH and SOKOLOVA (1985). This program was applied to analyse sea level variations with the same inputs as in cross-spectral analysis (MISA). The high-frequency oscillations uncorrelated with sea level were eliminated from the input functions by Kaiser-Bessel filter (HARRIS, 1978) with time window of 24 hours. The regression model was tested both with wind stress and wind velocity. Better results were achieved when wind stresses had been used.

The regression coefficients in expression (5) were determined by the least square method. Residual variances were minimized. Values of the coefficients M and time lags L_j were selected to optimize the computation.

Table 4. MRA results for 3-months serie and the individual storm surges.

Stations	3-month series				Storm surges			
	Regression coefficients on			Direction of eff. wind, (in degrees)	Regression coefficients on			Direction of eff. wind, (in degrees)
	P_a	T_z	T_M		P_a	T_z	T_M	
Sogwipo	−0.67	−87.2	18.5	102	−1.07	−78.8	4.2	93
Cheju	−0.79	−28.7	26.3	132	−1.62	−44.7	−27.1	58
Yosu	−0.98	−45.1	11.7	105	(−1.63)	(−55.5)	(52.6)	133
Chungmu	−1.06	−50.2	11.8	103	−2.25	−37.5	−27.1	54
Pusan	−0.99	−61.3	0.1	90	−1.07	− 8.8	18.7	111
Ulsan	−0.89	−50.4	83.6	150	−1.65	−50.3	19.3	111
Pohang	−1.04	−31.4	− 2.8	85	−1.53	−28.2	5.6	101
Ullungdo	−1.15	−35.4	48.1	143	−1.44	38.3	3.6	265
Muko	−1.22	58.4	− 2.9	273	−1.24	−65.7	426.1	171
Sokcho	−1.46	25.8	−12.9	296	−2.12	23.9	−70.7	341
Posyet	−1.36	−49.3	− 2.5	87	−2.20	−23.1	− 1.0	87
Vladivostok	−1.47	−29.9	− 1.5	87	−2.30	−35.7	−11.8	72
Nakhodka	−1.27	−49.2	−13.4	74	−2.06	−21.9	−8.5	69
De Kastri	−1.50	−75.9	−16.7	77	−	−	−	−

Three-month data series were processed with MRA. The weights were employed to restore non-tidal sea level (Table 3). For better comparison all input functions were taken with the same number of regression weight ($L_j = 4$) and with the same time lag (0, 6, 12 and 18 hours). Table 3 shows that generally it is possible to predict 47 to 77 % of sea level variance by this method. Use of four weights instead of one for every input (as it was made, for example, by Amin, 1978) gave a slight improvement (from 3 to 11 %). The coherent energy estimated by MISA always exceeds that calculated by MRA technique because of limitations of regressional model. There is systematic reduction in the corresponding difference as additional weights are added to the analysis. But excessive increase of the number of weights causes instability of their values and worsens application of the regressional equations for forecast purposes. The special inspection is required to determine the optimum number of weights and appropriate time lags (Zetler and Munk, 1975).

Response weights for time lag $\tau_{ij}=0$ are presented in Table 4. The regression coefficient between atmospheric pressure and sea level ('barometric factor') is a problem of special interest. The corresponding values are relatively small in comparison with theoretical values −1.01 cm/mbar for the southernmost stations Sogwipo and Cheju (−0.67 and −0.79), and close to theoretical ones for the stations at the southeastern coast of Korea and Ullungdo Island (from −0.89 to −1.15) and large for the northern Korean and the Russian stations (from −1.22 to −1.50). A tendency of northward increasing barometric factor is well seen. The corresponding values estimated by Isozaki (1969) all over the coasts of Japanese Islands were more stable (from −0.69 to −1.13). It was shown by Likhacheva and Rabinovich (1986b) that reaction of sea level to variations of atmospheric pressure depends significanly on the direction of atmospheric disturbances in regard to continental shelf waves: when these systems are propagating in the same direction as free shelf waves as it takes place at the Okhotsk Sea coast of Kuril Islands, they produce considerably greater sea level response than when they are moving in opposite directions as at the Pacific coasts. The latter is the case of the Korean and Russian coasts where cyclones and typhoons are moving to the northeast and shelf waves to the southwest. This is the reason why it is necessary to look for another explanation of barometric factor increase. It is quite possible to explain that this peculiarity is connected with 'encloseness' of the Sea of Japan with only one wide entrance–the Korean Strait to its south. The stations Sogwipo and Cheju with minimal barometric factors are situated just in the Strait. De Kastri with maximum is the remotest one.

It is neccesary to note that these estimates of barometric factors have been obtained from 3-month observational series (July-September, 1986). Seasonal and year-to-year variations of these factors are quite possible. From the other side the appropriate values are in good agreement with the results of ISOZAKI (1969) for the southern and western coasts of Japan.

Regression coefficients for wind stress components were used to calculate 'effective wind direction', i. e. the direction of the strongest wind influence upon sea level raising (PUGH, 1987) given by

$$\theta = \tan^{-1} (w_Z / w_M), \qquad (6)$$

where w_Z and w_M are regression coefficients for zonal and meridional components. Wind directions are measured clockwise from the north.

The southeast and east winds were obtained as effective for the majority of the Korean and Russian stations except Muko and Sokcho. There were no significant winds at the Muko (Kangnung) station during the examined period probably because of peculiarities of local observational conditions. This is the reason why determination of the effective wind direction is difficult to estimate for this station.

8. Storm surge caused by typhoon Vera, August 1986

The severe typhoon "VERA" was passing through the Korean Peninsula during 28 – 29 August, 1986 (Fig. 8). Atmospheric pressure in the center reached 950 mb. Maximal wind speed of 70 m/s was observed. This typhoon brought heavy damages on both human beings and properties at the Korean coasts.

Remarkable storm surges were caused by this typhoon at the all inspected stations except De Kastri (Fig. 3). According to RABINOVICH and SOKOLOVA (1992) main surge parameters were determined and presented in Table 5. The surge and total heights were accounted from mean monthly level; the total height is the sum of surge and tide. Time difference between them is shown in brackets. Duration of surge, its half-height, surge steepness (relation of surge height to half-height duration) and surge energy are shown. There were two surge maxima at the Ullungdo station, both of which are given in Table.

OH *et al.* (1988) had adduced similar height values of this storm surge for the southern Korean stations. The significant surge was observed at stations Sogwipo, Cheju, Komundo, Yosu and Chungmu as well as at stations Muko, Sokcho located at the eastern coast of Korea and in Primorye region of Russia (Posyet, Vladivostok and Nakhodka). Much less surge elevations took place at southeastern Korean stations Kadukdo, Pusan, Ulsan and Pohang (Table 5). These features of sea level reaction to atmospheric depression are closely related with the characteristics of typhoon, its track and transition speed. The typhoon "VERA" reached Korean Peninsula near its southwesternmost part (Cheomranam-do region) (Fig. 8); center pressure was about 960 mb, and the maximum wind speed was 70 m/s (OH and KIM, 1990). Wind set-up caused by strong on-shore winds and reinforced by the pressure fall generated destructive storm surge at the stations located in the Korean Strait. Numerical model of OH and KIM (1990) simulates this process quite convincingly. Propagating northeastward, the typhoon "VERA" crossed the eastern coast south of Muko station. On-shore winds forced wind set-up at the stations situated to the left of the typhoon track (Muko, Sokcho and others), while off-shore winds caused wind set-down at the southeastern stations. Apparently the strongest surges were observed at the eastern coasts of North Korea, where there were maximum on-shore winds (see Fig. 5, Kang *et al.*, 1988). The observed surge heights in North Korea were 105 cm in Wonsan, 106 cm in Chongjin, 68 cm in Sinpho and 55 cm in Senbong (KANG, 1988).

HWANG (1971) had collected data on the remarkable storm surges for southern and southeastern coasts of Korea for 1959–1970. The most powerful surge during this period was on 22–24 August, 1966 (102 cm in Cheju, 110 cm in Yosu). But for further northern stations no one had been as strong as the surge caused by typhoon "VERA".

It is well seen that height, character and duration of the storm surge varied significantly for

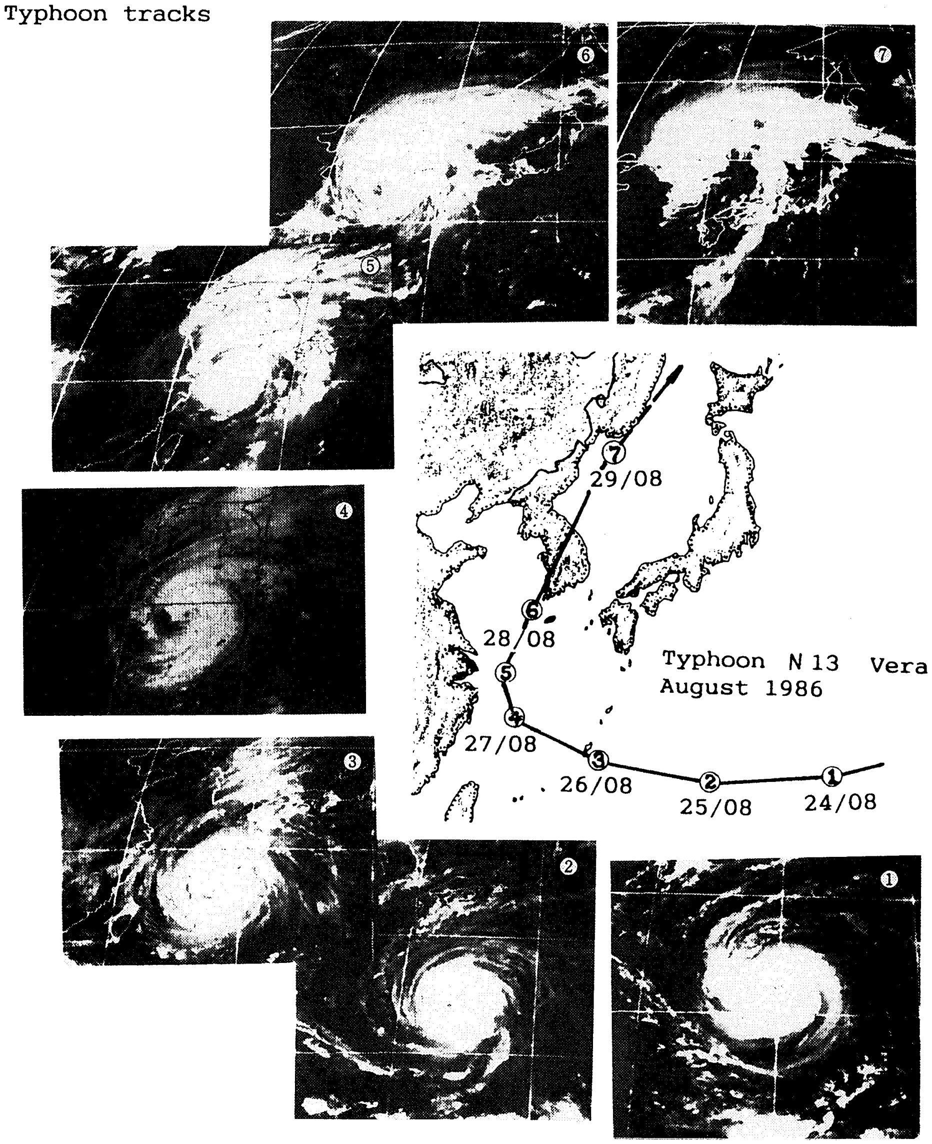

Fig. 8. Track of typhoon No 8613 "VERA" and its satellte images.

different regions. For the stations at the southern coast of Korea and in the Korea Strait it had character of relatively short (55–81 hours) and high (52–66 cm) sea level elevations with well manifested negative displacement behind the surge (Fig. 3, Table 5). The main features of the storm surge behaviour in this region were explained by numerical modelling (OH and KIM, 1990).

The surge height became smaller (37–49 cm) and more prolonged (118–138 hours) at the southeastern Korean coast. For the northern stations the situation changed to the opposite (Fig. 3, Table 5).

Table 6 shows the atmospheric parameters at the stations during this surge. 'Pressure fall' means the difference between the mean monthly value and observed minimal atmospheric pressure. Time difference between maximum of the surge and pressure minimum is given in brackets. It is interesting that for all stations this difference was positive, i. e. surge maxima

Table 5. Parameters of the storm surges caused by typhoon "VERA" (August, 1986) observed on the various coastal stations.

Stations	Time of surge Maximum, date, time	Surge height, cm	Total height($\pm t$) cm (hours)	Surge duration, hours	Duration of half-height, hours	Steepness, cm/hour	Surge variance, cm^2
Sogwipo	Aug. 28, 06	66.3	67.6 (−3)	81	24	2.8	925.9
Cheju	Aug. 28, 05	54.5	70.0 (−1)	77	18	3.0	636.4
Komundo	Aug. 28, 07	52.4	66.8 (−5)	75	21	2.5	600.0
Yosu	Aug. 28, 11	65.0	92.9 (+3)	55	14	4.6	909.1
Chungmu	Aug. 28, 12	58.1	86.6 (+2)	73	15	3.9	575.3
Kadukdo	Aug. 28, 12	40.1	61.4 (+1)	55	20	2.0	418.2
Pusan	Aug. 28, 13	48.6	99.4 (0)	138	19	2.6	340.6
Ulsan	Aug. 28, 14	44.2	52.9 (0)	130	32	1.4	361.5
Pohang	Aug. 28, 14	37.7	38.1 (−1)	118	49	0.8	381.4
Ullungdo	Aug. 28, 19	37.1	39.1 (+10)	120	50	0.8	450.0
	Aug. 29, 15	37.4	39.1 (0)				
Muko	Aug. 28, 18	50.3	45.5 (0)	114	63	0.8	868.4
Sokcho	Aug. 28, 19	63.1	61.9 (+1)	122	48	1.3	1090.2
Posyet	Aug. 29, 13	69.6	77.8 (−2)	125	33	2.1	1040.0
Vladivostok	Aug. 29, 18	60.5	62.5 (−7)	114	40	1.5	1026.3
Nakhodka	Aug. 29, 18	52.5	54.3 (−7)	106	39	1.3	801.9

passed ahead of pressure minima.

Maximal and significant wind wave heights as well as wind speed and direction in the moment of the highest surges are also presented in Table 6. The wind direction corresponds quite well to the direction of effective wind (Table 4).

'Pressure factor' in the last column is defined as ratio of surge height to pressure fall. Actually the 'presure factor' is related not only to pressure fall but also to wind influence; this is why in most cases it is sufficiently bigger than 'barometric factor' obtained from the regression analysis as reaction to atmospheric pressure alone (Table 4).

Storm surge records were analysed separately by MRA method. The short observational series (4-7 days) were processed. For comparison in Table 4 the same parameters calculated for storm surges as for 3-months series are presented. The barometric response is higher for the storm surge than for the longer series but it has the same tendency to increase northward. It was revealed during the storm surge analysis in Yosu that atmospheric pressure and meridional wind stress are closely correlated. Therefore, the reaction to atmospheric pressure and wind stress was calculated independently. The corresponding values are given in brackets. There were relatively good agreements between two sets of computations except at Muko, Sokcho and Ullungdo. These stations were situated just on the track of the typhoon (Fig. 8).

Both sets of regression coefficients computed from 3-month series and from storm surge records were used for surge hindcasting. The results were in good agreement; improvement in storm surge restoring from applied response weights estimated from the same record was insufficient. Some examples of surge hindcasting based on average coefficients set are given in Fig. 9. It is interesting that wind stress insignificantly affected sea level variations in calm weather in comparison with atmospheric pressure, while it did significantly for the storm surge moment.

9. Wave set-up

Positive change of mean sea level in nearshore zone due to the presence of breaking incident waves ('wave set-up') is well-known phenomenon (BOWEN *et al.*, 1968; PUGH, 1987). The effect is physically distinct from 'wind set-up', because it can be present even without local wind, owing to swell from distant storms (THOMPSON and HAMON, 1980). The theoretical basis of wave set-up generation was elaborated by LONGUET-HIGGINS and STEWART (1964) who had shown

Table 6. Meteorological parameters of the storm surges caused by typhoon "VERA".

Stations	Minimal atm. pressure(±t) mb (hours)	Wind Speed, m/s	Wind direction	Wave height,m		Pressure fall, mb	Pressure factor, cm/mb
				$H_{\max}$	$H_{1/3}$		
Sogwipo	976.2 (+ 3)	20.7	SSE	–	5.0	−32.9	−2.0
Cheju	973.3 (+ 4)	14.7	SE	–	1.0	−35.7	−1.5
Yosu	981.4 (+ 3)	16.7	S	7.0	4.5	−28.5	−2.3
Chungmu	986.6 (+ 3)	11.7	S	–	–	−23.9	−2.4
Pusan	987.4 (+ 3)	14.7	ESE	–	4.0	−22.3	−2.2
Ulsan	986.5 (+ 3)	9.0	SE	8.0	5.0	−22.7	−1.9
Pohang	985.8 (+ 4)	10.2	SSE	–	–	−24.9	−1.5
Ullungdo	988.1 (+ 3)	6.7	S	–	–	−21.8	−1.7
	988.1 (−16)	11.7	SSW				
Muko(Kangnung)	977.6 (+ 1)	6.0	ESE	4.5	3.0	−32.2	−1.6
Sokcho	977.7 (+ 1)	15.2	SE	6.0	3.5	−31.9	−2.0
Posyet	986.8 (+ 8)	18.0	NE	–	–	−22.8	−3.1
Vladivostok	986.6 (+ 4)	13.0	SE	–	–	−23.0	−2.6
Nakhodka	986.9 (+10)	12.0	ENE	–	–	−22.7	−2.3

that corresponding sea level changes inside the surf zone are related to the conservation of momentum flux of surface gravity waves entering shallow water.

Wave set-up may sufficiently increase storm surge heights. For example during the 1938 New England hurricane surge elevation was about 1 m greater at the relatively exposed areas where storm wave energy was dissipated as surf than at regions of calmer waters (Guza and Thornton, 1981). Unfortunately we could not investigate this factor in detail because of lack of data. Wave set-up was inspected very briefly only for the stations Ulsan and Muko. Maximal wind wave heights were regarded as additional inputs in MISA and MRA. It was found that wind waves are correlated with onshore wind, i. e. it is not easy to distinguish wave set-up from wind set-up. Nevertheless, supplement of the additional input increased coherent parts of the variances by 5 % for Ulsan and by 2.6 % for Muko. Appropriate values of predicted variance were increased by 9.7 and 4 % (Table 3).

Including wind wave input in the multi-regressional analysis gave the appreciable improvement in hindcasting of the storm surge. Unpredicted variance reduced from 104.8 to 43.1 cm for Muko and from 40.3 to 13.0cm for Ulsan. Contribution of wind waves in addition to atmospheric pressure and wind stress to rise of the storm surge height for Ulsan is well seen in Fig. 9. Maximal wind wave heights ($H_{\max}$) during the storm surge were 8 m at Ulsan and 4.5m at Muko. Significant heights ($H_{1/3}$) were 5 and 3 m respectively (Table 6).

There are some empirical relations between the height of wave set-up η_m and $H_{1/3}$. Specifically, Guza and Thornton (1981) found that change of mean sea level η_m owing to waves satisfies to the ratio

$$0.14<\frac{\eta_m}{H^{\infty}_{1/3}}<0.21 \qquad (7)$$

where $H^{\infty}_{1/3}$ is significant wind wave height in deep water.

We had only fragmentary data of significant wave heights, too scanty to apply MRA analysis. All these data were used to define empirical regression relations between $H_{1/3}$ and $H_{\max}$. We found that

$$\begin{aligned} H_{1/3}&=5.5+0.66\,H_{\max} \text{ for Ulsan} \\ H_{1/3}&=0.3+0.65\,H_{\max} \text{ for Muko.} \end{aligned} \qquad (8)$$

Relations (8) were applied to get significant wave heights for 3-month series and to use them for further computations.

Residual sea level series were used after subtraction of the parts correlated with atmospheric pressure and wind stress. The following regression coefficients between $H_{1/3}$ and sea level were obtained:

Ulsan: $w_s=0.039$; Muko: $w_s=0.026$.

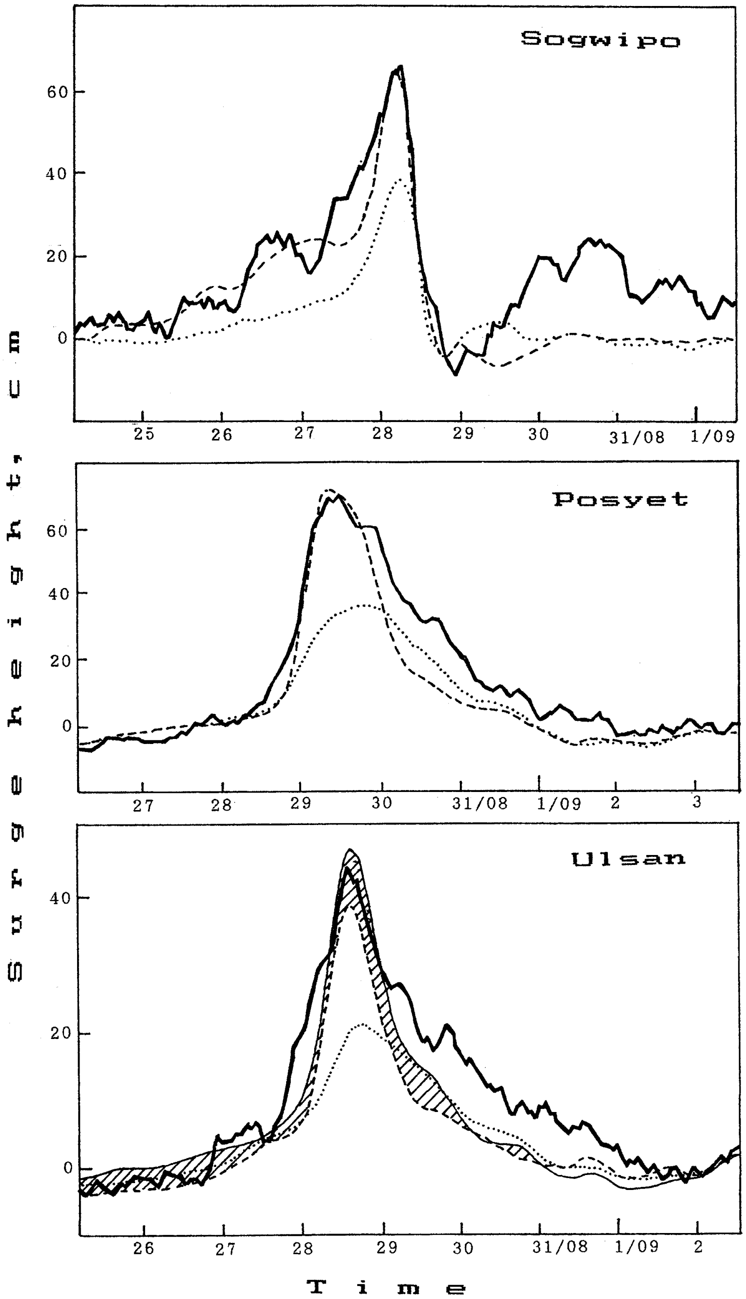

Fig. 9. Time series of recorded storm surges (solid line) and predicted by atmospheric pressure (dotted line) and by pressure and two wind stress components (dashed line). For the Ulsan station aditional part related to wave set-up is hatched.

Wind waves with significant wave height of 3 m cause sea level rise of 12 cm in Ulsan and 8 cm in Muko.

These values are less than those given in relation (7). One of the possible reasons of this difference is that part of wave set-up 'went away' from residual series together with wind coherent part. Another reason is that estimates obtained by GUZA and THORNTON (1981) are related to smooth beach slope and may be inapplicable to measurements in bays and harbours. THOMPSON and HAMON (1980) found wave set-up in harbour may be represented as

$$\eta_m=\frac{3}{16}\frac{H^2_{1/3}}{h}, \qquad (9)$$

where h is the depth at the entrance of harbour.

To estimate suitableness of this formula to our situation we have made special computations of wave set-up with square of significant wave height as input function and obtained following regression coefficients:

Ulsan: $w_{ss}=0.80$; Muko: $w_{ss}=0.95$.

These values correspond to expression (9) if $h=23.5$ m for Ulsan and $h=20$ m for Muko; the depths are quite reasonable.

10. Influence of non-linear interaction of storm surges with tides.

Sea level variations described by expression (5) show linear response of the sea to external meteorological forces. It is possible to explain that residual background variations $\varepsilon(t)$ unpredicted by (5) are partly related to non-linear interaction of storm surges and tides. In this case non-tidal sea level may be represented as

$$\zeta(t)=\zeta_l(t)+\zeta_{nl}(t)+\varepsilon_r(t), \qquad (10)$$

where ζ_l is the linear sea level component obtained from (5) with regression coefficients, ζ_{nl} is the non-linear component and ε_r is background noise.

In accordance with AMIN (1982) special non-linear input functions were constructed for southern Korean stations which have relatively big amplitudes of tides (Table 2):

$$F_{nl}(t)=\zeta_l(t)\,\zeta_t(t), \qquad (11)$$

where ζ_t is pure predicted tidal series; non-linear sea component was estimated then from the equation

$$\zeta_{nl}(t)=\sum_{j=1}^{N}\mathrm{w}_j(\tau_1)F_{nl}(t-\tau_j)+\varepsilon(t) \qquad (12)$$

by MRA technique. Only one regression coefficient was determined but with different time lags.

It was found that for long 3-month series influence of non-linear input is negligible but a certain non-linear influence is found out for storm surge records. Variances of background residuals have reduced: for Cheju from 48.1 to 35.4 cm (27 %), for Chungmu from 52.9 to 44.3 cm (16 %) and for Ulsan from 21.3 to 19.1 cm (10 %). For all other stations decreases of background variances during the storm surge were less than 4 %. Best results were achieved with time lags $\tau_j=3$–5 hours. The strongest influence of tide-surge interaction was observed just for the same stations (Cheju, Chungmu) with relatively strong shallow water tidal constituents M_4 and MS_4.

The non-linear effects during the storm surge caused by typhoon "VERA" are apparently the result of the interaction between tidal and storm surge currents. More detailed analysis of the phenomenon is a subject of the future study.

11. Summary and discussion.

We processed 3-month data series to study behaviour of non-tidal sea level variations along the Korean and Russian coasts of the Sea of Japan and reaction of sea level to meteorological forces. Two different approaches were used to examine the data: 1) investigation in frequency domain (spectral, cross-spectral analysis, multi-input system spectral analysis); 2) investigation in time domain (multiple regression analysis). Combination of these two approaches allowed us to make comprehensive examination of the subject.

It was found that in synoptical frequency band the atmospheric pressure plays principle role in forming non-tidal variations: 46 to 77 % of total sea level energy are coherent with pressure. These sea level variations move along the coast in the same direction as atmospheric disturbances. The barometric factor is increased northward; it is much less than theoretical value (−1.01 cm/mb) for southernmost stations Sogwipo and Cheju (−0.67 and −0.79) and is much higher for the northernmost station De Kastri (−1.50). The same tendency is remained for individual storm surges but the corresponding values of barometric factor are bigger (from −1.07 to −2.30).

Energy of non-tidal sea level oscillations for the stations situated in the Korean Strait decreases from west to east with a minimal value at Pusan and then increases northward with maximum in De Kastri. Total amount of energy which is coherent with meteorological forces is changed from 59 % (for De Kastri) to 92 % (for Sokcho). Multiple regression analysis (MRA) allows to predict from 47 % (for Cheju) to 78 % (for Posyet) of sea level variance. Improvement of MRA prediction may be apparently achieved by use of additional response coefficients and better choice of corresponding time lags.

The relative importance of wind and wind waves in sea level generation is increased drastically during typhoon passages amplifying surge heights sufficiently.

The storm surge caused by the typhoon "VERA" was studied in detail. Some useful parameters were chosen to compare surge behavior with transformation along the coast. Regression weights computed from 3-month data series were used to hindcast this surge and results were quite satisfactory.

One of the most important questions is an applicability of regression models to disaster forecast. To solve this problem it is necessary to predict sea level changes. To estimate the principal possibility of such prediction a special test was made. The MRA calculations with subsequently increasing time lags were performed for both long series and storm surge segments. It turned out that quality of the forecast was fairly good for periods of 0–12 hours but rapidly became worse one day or more ahead.

An interesting but not well known problem is the influence of the secondary factors on sea level forming. We have studied briefly two of such factors: non-linear intraction of tides, weather-induced oscillations and wind set-up. It was found that in the investigated region the first factor plays a small role in the total budget of sea level energy; only during strong surges in shallow water areas with sufficient tidal variations it is possible to find weak display of such interaction; on the other hand spectral analysis shows certain evidence of non-linear interaction of tides with mean flow.

Influence of wind set-up is appeared in the records at two stations Muko and Ulsan, especially in the periods of storms. It would be interesting to research this question for the other stations with more adequate data.

At last, it would be useful to investigate significance of free waves in sea level variations specifically continental shelf waves propagating along the Korean coast and shelf of the Primorye region of Russia. These waves usually are manifested in currents but may also affect sea level oscillations (Lappo *et al.*, 1978; Likhacheva and Skripnik, 1981). Preliminary investigation of sea level residuals has not revealed these waves in the processed data but it is desirable to explore this question more attentively.

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