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Seasonal Sea Level Oscillations in the East Sea (Sea of Japan)

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동해 해수면의 계절적인 변동에 대하여

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The monthly mean sea levels at 48 stations located at the East and Yellow Seas coasts of Korea, Russia and Japan are processed to investigate seasonal sea level variations. The strong seasonal variations are found to be at the west coast of Korea (42.1 cm in Kunsan), in the region of the Korea Strait and near the southern part of Primorye (30-33 cm); the weak ones near the southwestern coast of the Sakhalin Island (10-12 cm). Practically for the whole study area except the southwest Sakhalin, the general picture of the seasonal sea level changes is alike: the mean sea level rises in summer-autumn and falls in winter-spring. The spectral analysis of the records also shows that the seasonal oscillations strongly dominate in the sea level variations, more than 80% of total energy in the southern part of the investigated region and 50-70% in the northern part relate to these oscillations. The annual peak significantly prevails in spectra of the monthly sea levels for the majority of stations, the semiannual peak is also well manifested, but the seasonal peaks of higher order (corresponding to the periods of four and three months) reveal only at some records.

The maximal amplitudes of annual component by a least square method are found at the Yellow Sea coast of Korea (20-21 cm) and also near the Japanese coast of the Korea Strait (18-19 cm). The semiannual component has the maximal amplitudes (3-4 cm) near the south and southwestern coasts of the Sakhalin Island. The annual range of the sea levels is much weaker here than in the other regions, the relative investment of the seasonal oscillations in total energetic budget is only 35-40%, annual (A_1) and semiannual (A_2) components have nearly the same amplitude (seasonal factor $F=A_1/A_2=0.9\text{-}1.2$).

On the basis of the present examination on sea level changes together with the results of Tomizawa et al.(1984) the whole investigated area may be divided into 10 subregions, 2 of them are related to the Yellow Sea and western part of the Korea Strait (Y1, Y2), the other ones (E1-E8) to the East Sea.

해수면의 계절적인 변동성을 조사하기 위하여 한국의 황해, 남해 및 동해안의 潮位 관측점과 러시아, 일본의 동해에 연한 총 48개 관측점의 월평균 해수면 자료를 분석하였다. 해수면의 강한 계절적인 변화는 한국 西岸의 군산 (42.1 cm)과 대한 해협, 그리고 Primorye 지역의 남부 가까이(30-33 cm)에서 기록되었으며, 비교적 약한 변화는 사할린 남서해안에서 발견되었다. 남서 사할린을 제외한 전 연구 지역에서 계절적인 해수면 변동 양상이 거의 같다. 즉 여름과 가을에 상승하고 겨울과 봄에 감소하는 양상이다. 이들 해수면자료의 스펙트럼 분석의 결과도 계절적인 진동이 해수면의 변위 중에 가장 우세하며 연구해역의 남부에서는 전체 에너지의 80%에 달하고 북부에서도 50-70%에 달했다. 또, 대부분의 관측점에서 연주기 성분이 현저히 우세하며, 半年周期 성분도 명백히 나타났으나 그 이상의 고주파

성분은 단지 몇몇 관측점에서만 보일 정도이었다.

최소자승법을 사용하여 계산한 年周期 성분(A_1)의 최대 진폭은 한국의 西岸에서 20-21 cm, 대한해협의 일본 연안에서는 18-19 cm에 달하였다. 半年周期 성분은 사할린섬의 南端과 남서 해안에서 최대치 3-4 cm인 것으로 밝혀졌다. 이 지역의 年周期 해수면 변동폭은 여타 지역보다 훨씬 작아서 全 에너지 收支에 대한 계절적 변동의 상대적 크기는 단지 35-40%에 지나지 않으며 年周期와 半年周期의 진폭비 (계절변동 계수 $R=A_1/A_2$)는 0.9-1.2로서 같은 크기 임을 알 수 있다.

이와 같은 해수면 자료의 분석과 Tomizawa et al.(1984)의 연구결과를 근거로하여 본 연구해역을 10개의 해역으로 나눌 수 있다. 즉 황해와 한국의 남해 서부해안을 Y1과 Y2 해역으로, 동해를 E1에서 E8까지 8개의 해역으로 나눌 수 있다.

INTRODUCTION

Sea level is one of the most significant parameters of the ocean dynamics. Various processes in the world ocean such as large-scale ocean circulation, energy exchange with atmosphere, climatic fluctuations, El Nino phenomena, etc. are strongly correlated with sea level changes. Wyrtki (1979) have called them 'breath of the ocean', emphasizing the importance of these changes and the fact that the various hidden phenomena in the ocean may be revealed in the sea levels.

Monthly averaged series of mean sea levels (MSL) are the most suitable and accessible type of information on climatic ocean variations. Usually seasonal cycle (annual and semiannual) is strongly manifested in these variations. Examination of seasonal sea level changes is far from being entirely academic question: in some of the regions (e.g. near the southeastern coast of Asia) annual oscillations over a metre are observed (Woodworth, 1984). Coincidence of high seasonal water level with the other sea level components (tides, tsunamis, surges) may be the reason of catastrophic floods (Rabinovich et al., 1992).

A fundamental investigation of seasonal sea level variations in the world ocean was made by Patullo et al. (1955). Wyrtki and Leslie (1980) executed an additional research on this subject for the Pacific Ocean region. Basing on many new stations and new data Woodworth (1984) made the worldwide inspection of annual and semiannual MSL periodicity and completed their results. Detailed reviews on seasonal MSL changes were made also by Patullo (1963), Galerkin (1968), Lisitzin (1974), Pugh (1987).

The general picture of these variations for the world ocean now is sufficiently well known, but for some marginal seas, like the East Sea and the Yellow Sea our knowledge is only a fragmentary one. Wyrtki and Leslie (1980) did not include these seas in their study at all; Patullo et al.(1955) and Woodworth (1984) used only data of a few Japanese and Korean stations.

Seasonal oscillations near the coasts of Japan and possible mechanism of their generation were studied in the classical papers of Nomitsu and Okomoto (1927), Miyazaki (1955), Tsumura (1963, 1970) as well as in the recent examination made by Tomizawa et al. (1984).

There are some attempts to describe annual variations in the East Sea as a whole (Leonov, 1960; Galerkin, 1960; Lisitzin, 1967; Deyeva, 1978; Won, 1991). But due to the lack of the reliable data all over the sea has limited these efforts. Yi (1966, 1967, 1969) made an examination of seasonal sea level oscillations near the coast of Korea (first of all for the Korea Strait region). Kang and Lee (1985) studied the annual variation of MSL along the coast of South Korea. Near the Russian coasts of the East Sea, the unpublished paper by Deyeva (1975) is apparently the most intensive investigation of the seasonal sea levels. Some essential additional information for the region of North Primorye and Sakhalin Island may be found in the paper by Lyubitsky (1987). The MSL data for the Russian stations in the Primorye region for the whole observational period and for the Sakhalin stations (except Korsakov and Krilyon) for the period up to 1986 were analysed by Firsov (1991). For some stations situated at the East and Yellow Seas coasts of Korea, seasonal oscillations were inspected also by Tomizawa et al. (1984). Some information on seasonal oscillations in this region was published by Ogura (1933).

The main purpose of this paper is to investigate and compare seasonal variations for the Korean, Russian and Japanese coasts of the East Sea and adjacent regions basing on the large quantity of MSL data available in the recent years. The intensive development of coastal and shelf zones and the necessity of proper estimates of extreme sea levels strongly stimulated the actuality of this research. But such study is also of a high scientific significance because of the mentioned correlation between sea levels and other processes in the ocean.

In this work we try to estimate the statistical characteristics of the seasonal sea level oscillations and their interannual variabilities rather than their generation mechanism. The latter question is the subject of a future study.

OBSERVATIONAL DATA

The MSL data of 13 Korean, 21 Russian and 14 Japanese stations were used to analyze annual and semiannual oscillations (Fig. 1; Table 1). Most of the 13 Korean stations are located in the East Sea and the Korea Strait, only 4 stations are in the Yellow Sea. The 19 stations out of the 21 Russian stations are situated in the East Sea (Primorye and Sakhalin coasts), and the stations Korsakov and Krilyon are located in the Sea of Okhotsk. Since they are quite near to the entrance into the East Sea, it is interesting to use these stations for comparison. The 14 Japanese stations are located mainly at the East Sea coasts of Honshu and Hokkaido Islands and on some small islands of the East Sea (Fig. 1). Informations on annual and semiannual amplitudes and phases of some additional Japanese stations and of the station Wonsan (North Korea) of which are taken from the other sources (Deyeva, 1978; Woodworth, 1984; JODC, 1984).

The longest observational series used in this study is in Vladivostok (65 years); time series over 40 years long are at 7 other Russian stations (Nevelsk, Rudnaya Pristan, Kholmsk, Korsakov, Nakhodka, Innokentevka and Posyet). The longest

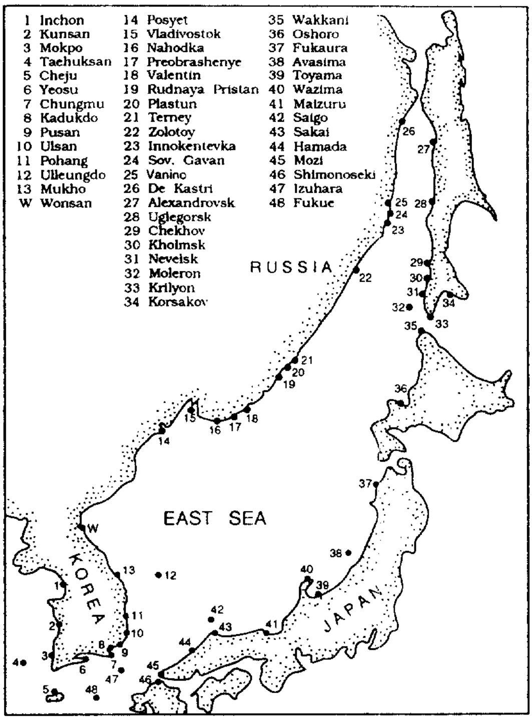


Fig. 1. Location of the stations.

series near the Korean coast is in Pusan (31 years). For most Japanese stations time series are of about 30 years long (Table 1).

Tide gauge measurements are the main source of the mean sea level data all over the world ocean. The sea level data which are used for the present study are no exceptions. But several stations near the coasts of Sakhalin and Primorye with information obtained from the visual sea level observations by means of marine surveyors' rod are included. Later analyses have proved that the quality of the data set is quite satisfactory and that the results for the corresponding stations are in good agreement with those obtained by tide gauges.

For the data treatment, if there are some small gaps in the data (up to 5 points), these missing values are interpolated. One of the longest but best quality series in Nevelsk had 9-year break (1945-1953), for this station the data set are processed separately in two piceses (22 and 37 years).

A special analysis was made to estimate a secu-

Table 1. Harmonic constants of annual and semiannual components

No.	Station	Period	Sa		Ssa		A_1/A_2	Reference
			A_1[cm]	φ_1[°]	A_2[cm]	φ_2[°]		
1	Inchon	1963-1972	20.3	212.1	2.6	120.6	7.8	
		1976-1991	19.2	207.3	1.7	121.0	11.3	
			(20.3)	(213.5)	(1.7)	(139.1)	(12.2)	Yi, 1967
			(21.1)	(208.0)	(5.8)	(13.7)	(3.6)	Ogura, 1933
2	Kunsan(inner port)	1972-1991	20.3	211.0	2.9	113.7	7.0	
	Kunsan(outer port)	1980-1991	19.1	213.1	2.1	116.8	9.5	
3	Mokpo	1960-1991	17.1	217.0	2.9	103.1	5.9	
			(16.1)	(226.1)	(1.5)	(86.2)	(10.7)	Yi, 1967
			(17.2)	(222.0)	(2.8)	(118.2)	(6.2)	Woodworth, 1984
4	Taehuksan	1970-1991	14.7	215.3	2.9	117.3	5.1	
5	Cheju	1964-1990	16.9	224.5	1.8	142.3	9.4	
			(17.1)	(229.3)	(2.5)	(127.7)	(6.8)	Yi, 1967
			(16.6)	(236.2)	(1.3)	(104.1)	(12.8)	Kim, 1965
6	Yeosu	1965-1990	16.7	220.8	1.8	146.5	9.3	
7	Chungmu	1977-1991	14.0	223.6	1.9	110.5	7.4	
8	Kadukdo	1977-1991	13.4	222.8	2.1	107.9	6.4	
9	Pusan	1960-1990	11.5	222.7	1.4	99.3	8.2	
			(10.5)	(227.2)	(1.8)	(91.6)	(5.8)	Yi, 1967
			(12.2)	(223.9)	(3.7)	(98.2)	(3.3)	Ogura, 1933
10	Ulsan	1964-1990	10.9	227.2	1.5	111.6	7.3	
11	Pohang	1972-1991	11.9	224.4	2.8	83.7	4.2	
12	Ulleungdo	1979-1991	12.1	237.6	2.1	5.6	5.8	
13	Mukho	1966-1990	10.6	223.9	1.9	59.1	5.6	
			(13.2)	(226.5)	(1.1)	(109.7)	(12.0)	Yi, 1967
	(Wonsan)	(1932-1944)	(15.2)	(215.3)	(2.4)	(79.5)	(6.3)	Deyeva, 1978
14	Posyet	1950-1990	16.4	205.0	2.5	65.7	6.6	
15	Vladivostok	1926-45,47-75	15.1	206.1	1.8	57.4	8.4	
			(15.8)	(205.3)	(1.8)	(54.5)	(8.8)	Deyeva, 1978
16	Nakhodka	1948-1990	12.3	206.9	2.6	43.2	4.7	
17	Preobrazheniye	1941-1957	10.2	209.9	1.9	47.6	5.4	
18	Valentin	1942-1963	9.4	205.3	2.2	62.8	4.3	
19	Rudnaya Pristan	1940-1974	9.0	206.2	2.2	57.8	4.1	
			(9.3)	(205.3)	(2.7)	(59.5)	(3.4)	Deyeva, 1978
20	Plastun	1942-1957	7.8	205.2	1.1	39.7	7.1	
21	Terney	1948-1965	7.9	205.1	2.1	56.3	3.8	
22	Zolotoy	1949-58,67-85	6.5	213.6	1.7	187.8	3.8	
23	Innokentevka	1947-1985	6.6	223.6	1.0	321.3	6.6	
24	Sovetskaya Gavan	1948-1979	6.7	212.9	1.0	351.4	6.7	
25	Vanino	1951-1966	7.8	220.3	2.6	8.1	2.5	
26	De-Kastri	1974-1990	12.4	205.1	0.4	227.9	31.0	
27	Alexandrovsk	1921-1931	8.7	214.0	1.4	1.6	6.2	
			(8.6)	(213.7)	(1.7)	(346.7)	(5.1)	Lyubitsky, 1987
28	Uglegorsk	1963-1990	8.0	218.0	1.1	322.0	7.3	
			(8.3)	(215.3)	(0.9)	(321.6)	(9.2)	Lyubitsky, 1987
29	Chekhov	1954-1964	3.5	232.0	3.0	4.2	1.2	
			(3.5)	(232.2)	(2.9)	(4.3)	(1.2)	Lyubitsky, 1987
30	Kholmsk	1947-1990	3.9	255.5	3.2	8.4	1.2	
			(3.8)	(251.1)	(3.4)	(9.5)	(1.1)	Lyubitsky, 1987
31	Nevelsk	1922-50,54-74	3.0	279.4	3.2	8.1	0.9	
			(3.0)	(281.3)	(3.5)	(4.5)	(0.9)	Deyeva, 1978

Table 1. Continued

No.	Station	Period	Sa		Ssa		A_1/A_2	Reference
			A_1[cm]	φ_1[°]	A_2[cm]	φ_2[°]		
32	Moneron	1952-1966	7.2	237.2	2.6	351.3	2.8	
33	Krilyon	1963-1990	7.0	342.8	3.9	8.7	1.8	
			(7.1)	(337.8)	(4.4)	(8.7)	(1.6)	Lyubitsky, 1987
34	Korsakov	1948-1990	6.0	327.0	3.8	30.5	1.6	
35	Wakkanai	1960-1989	10.0	243.7	1.3	352.0	7.7	
		(1971-1980)	(10.80)	(237.8)	(0.76)	(15.7)	(14.2)	JODC, No.4, 1984
36	Oshoro	1930-1980	9.6	248.8	2.5	25.5	3.8	
37	Fukaura	1972-1989	13.9	248.0	1.8	5.7	7.7	
38	Awasima	1965-1990	12.8	254.3	2.1	23.6	6.1	
		(1968-1979)	(12.54)	(258.2)	(2.28)	(45.6)	(5.5)	JODC, NO.4, 1984
39	Toyama	1967-1989	16.6	244.8	2.5	12.4	6.6	
		(1971-1980)	(17.19)	(243.1)	(2.91)	(50.0)	(5.9)	JODC, No.4, 1984
40	Wazima	1967-1989	15.4	242.3	1.2	132.0	12.8	
		(?-?)	(16.6)	(244.2)	(3.8)	(17.4)	(4.4)	JODC, No.4, 1984
		(1930-1980)	(15.08)	(248.1)	(3.54)	(29.4)	(4.3)	Woodworth, 1984
41	Maizuru	1968-1989	17.1	238.7	1.9	17.6	9.0	
		(1947-1979)	(17.77)	(242.6)	(2.50)	(39.7)	(7.1)	JODC, No.4, 1984
		(1951-1980)	(17.60)	(243.3)	(2.77)	(40.8)	(6.4)	Woodworth, 1984
42	Saigo	1960-1989	16.8	239.1	1.4	352.8	12.0	
		(1971-1980)	(17.22)	(238.7)	(1.31)	(35.2)	(13.1)	JODC, No.4, 1984
43	Sakai	1960-1989	18.3	234.3	2.4	7.1	7.6	
		(1971-1980)	(18.63)	(233.6)	(2.35)	(51.8)	(7.9)	JODC, No.4, 1984
44	Hamada	1969-1989	18.9	231.4	1.7	28.3	11.1	
		(1971-1980)	(19.35)	(231.8)	(2.06)	(57.6)	(9.4)	JODC, No.4, 1984
		(1958-1979)	(19.09)	(234.0)	(2.38)	(59.4)	(8.0)	Woodworth, 1984
45	Mozi	1960-1988	18.7	227.1	1.4	83.2	13.4	
		(1974-1980)	(19.28)	(228.1)	(1.39)	(131.5)	(13.9)	JODC, No.4, 1984
		(1974-1980)	(18.85)	(230.1)	(1.05)	(100.2)	(18.0)	Woodworth, 1984
46	Shimonoseki	1960-1989	18.7	227.4	0.7	68.9	26.7	
		(1974-1980)	(19.66)	(227.6)	(1.26)	(135.2)	(15.6)	JODC, No.4, 1984
		(1958-1979)	(19.18)	(228.9)	(0.76)	(65.4)	(25.2)	Woodworth, 1984
47	Izuhara	1960-1988	17.4	230.9	1.5	71.8	11.6	
		(1948-1979)	(18.01)	(234.9)	(1.11)	(104.1)	(16.2)	JODC, No.4, 1984
		(952-1980)	(17.59)	(235.8)	(1.32)	(102.0)	(13.3)	Woodworth, 1984
48	Fukue	1964-1989	18.6	229.3	2.0	89.6	9.3	
		(1971-1980)	(19.3)	(229.1)	(2.64)	(115.6)	(7.3)	JODC, No.4, 1984

lar trend of the MSL (related to earth movement or longterm global changes of sea level) but practically for all the stations it proved to be small, that is why the trend was not taken into account in further investigations.

GENERAL DESCRIPTION

Multiyear averaged sea levels, $\bar{\eta}_j$ were computed for each month

$$\bar{\eta}_j = \frac{1}{N}\sum_{i=1}^{N}\eta_{ij} \qquad (1)$$

where j=1, 2, ⋯, 12 denotes the month, N is a number of years of the stations' data set, η_{ij} is an individual monthly sea level value. The average monthly mean sea levels are shown in Fig. 2.

The northwestern Korean stations (Inchon, Kunsan) located in the Yellow Sea have maximal sea level in July-August and minimum in January-

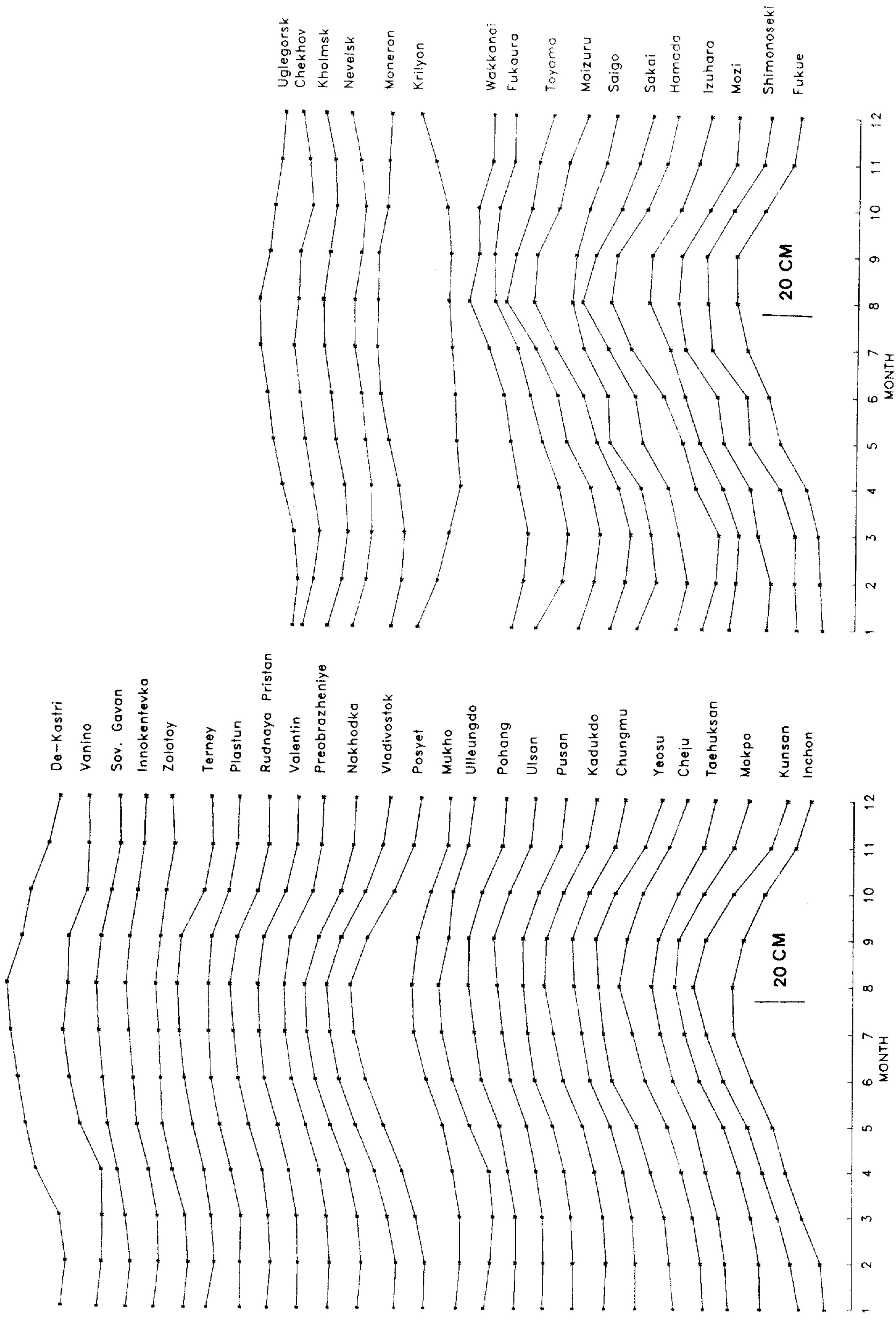


Fig. 2. Average monthly sea levels for all the stations considered.

February. Practically the same picture is for the East Sea Korean stations, Ulleungdo, Mukho and Russian stations situated in the Primorye region (Posyet, Vladivostok, Zolotoy, De Kastri etc.) although minimal sea level for all stations usually is observed in February or March. The Korean stations located in the region of the Korea Strait, as well as most of the Japanese stations, have maximal sea level in August-September and minimal one in January-March. The sea level changes at the southwestern coast of the Sakhalin Island are of anomalous character: there are two maxima (in July-August and in December) and two minima (in March and October) at corresponding stations (Chekhov, Kholmsk, Nevelsk, Moneron).

Except for this anomaly (nature of which is not clear) general pictures of the sea level changes in the investigated area are similar, as it is well seen in Fig. 2: mean sea level in the East Sea rises in summer-autumn and falls in winter-spring(Yi, 1969), demonstrating the universal mechanism of the generation of seasonal oscillations in the basin. Nomitsu, Okomoto (1927) and later Galerkin (1960) and Deyeva (1978) had proved that these sea level oscillations were formed by seasonal changes in sea water density, i.e. that sea level variations were mainly steric. For some regions they may be caused by specific topographic features of the region and by influence of additional factors (ocean currents, atmospheric pressure, etc.). Yi (1969), for instance, showed that MSL in the Korea Strait are strongly correlated with seasonal changes of the Tsushima Warm Current.

The character of sea level changes in Krilyon and Korsakov, belonged to the Sea of Okhotsk, is much different from the described one. High sea level here is observed in December-January and low level occurs in April. Such picture is typical for the whole sea (Leonov, 1960). Likhacheva and Rabinovich (1984) demonstrated that MSL variations in the Sea of Okhotsk are related to the changes of atmospheric pressure with minimum in winter time and maximum in spring and summer. Essential differences between seasonal sea levels in two neighbouring areas (East Sea and Sea of Okhotsk) are to be a subject of great scientific interest.

The average range, $\bar{\eta}_{ra}=\bar{\eta}_{max}-\bar{\eta}_{min}$, i.e. the difference between the highest and lowest values of averaged monthly sea levels in a year is an important characteristic of intensity of seasonal sea level changes. Annual MSL variations in the East Sea have range from 10-12 cm on the southwest coast of Sakhalin to 33-36 cm in the region of the Korea Strait. At the western (the Yellow Sea) coast of Korea (in Kunsan) $\bar{\eta}_{ra}$ comes to 42.1 cm (Table 2). Sufficiently strong seasonal sea level changes (30-33 cm) are observed in the south part such as Posyet and Vladivostok of Primorye region and on the western coast of Honshu and Kyushu Islands; on the other hand, these changes are small near the coast of the central part of Primorye region and on the Hokkaido coast (14-18 cm). They are relatively small also at the southeastern and eastern coasts of Korea (about 22-24 cm at Pusan, Ulsan, Pohang and Mukho). There is a tendency for this region, as well as for the western coasts of Japan, of annual sea level range decrease with increase of latitude (i.e. from south to north).

Extreme monthly sea levels are presented in Fig. 3. In the Figure, we could read that the individual MSL values may differ significantly from the average monthly estimates but the general tendency of the seasonal changes of extreme levels is not very different from the averaged ones.

SPECTRAL ANALYSIS

Usual FFT spectral analysis and MEM (maximal entropy method) were used to estimate spectral characteristics of the sea level records. The results were similar but MEM estimates appeared to be a little more reliable, thus only the latter results are shown in Fig. 4.

It is well seen that seasonal oscillations are dominated in the MSL spectra. Annual maximum is strongly prevailed for all stations except those located at the southwestern coast of the Sakhalin Island (Chekhov, Kholmsk and Nevelsk), i.e. in these stations where some kind of anomaly in sea level changes have been observed. For these stations annual (Sa) and semiannual (Ssa) maxima

Table 2. Averaged sea level and annual range in cm

No.	Station Name	Month												Annual Range
		1	2	3	4	5	6	7	8	9	10	11	12	
1	Inchon	436.4	437.2	444.2	451.7	458.1	466.9	475.0	476.9	471.8	460.5	449.0	441.7	40.4
2	Kunsan(inner port)	322.9	323.9	329.5	335.7	343.5	352.9	360.5	365.1	360.0	347.8	335.0	326.5	42.1
	Kunsan(outer port)	346.5	346.5	352.5	358.8	366.3	374.9	381.9	386.9	380.6	370.3	359.3	351.8	40.4
3	Mokpo	219.8	219.5	221.7	227.0	233.3	242.3	249.4	253.8	252.1	241.3	229.2	222.7	34.4
4	Taehuksan	174.5	173.8	175.7	181.0	186.6	194.6	200.5	204.4	202.2	193.3	182.9	176.7	30.6
5	Cheju	131.1	129.4	132.1	137.6	143.9	152.9	158.9	165.5	161.8	153.9	144.6	136.4	36.1
6	Yeosu	167.2	166.4	168.4	172.9	179.7	189.0	194.4	198.8	198.6	189.1	176.5	169.8	32.5
7	Chungmu	131.9	131.2	132.7	136.1	141.7	150.2	154.1	159.5	158.2	150.7	140.4	136.0	28.3
8	Kadukdo	84.7	83.8	85.7	89.0	93.7	101.8	106.2	111.3	110.0	101.9	92.2	88.3	27.4
9	Pusan	56.0	54.1	55.0	57.3	63.4	70.6	73.4	76.7	76.8	68.7	60.9	57.8	22.7
10	Ulsan	24.1	22.4	22.5	24.6	29.5	36.1	40.2	43.3	44.5	36.4	28.4	25.8	22.1
11	Pohang	5.2	4.0	4.0	7.1	10.4	18.0	24.0	23.6	26.2	17.8	10.2	8.4	22.3
12	Ulleungdo	11.4	7.7	5.9	7.9	15.4	24.2	28.9	31.9	27.2	26.5	21.0	17.3	25.9
13	Mukho	9.4	7.1	6.6	10.0	15.1	22.1	28.1	30.3	27.5	20.2	13.6	12.6	23.7
14	Posyet	132.4	132.0	135.6	141.4	149.9	158.1	163.1	164.4	157.3	145.9	137.6	133.8	32.3
15	Vladivostok	62.1	61.4	65.0	70.6	79.1	86.4	90.3	91.4	85.6	75.4	67.7	64.6	30.0
16	Nakhodka	29.6	28.1	29.4	33.7	41.6	48.5	52.2	52.7	47.1	37.8	32.2	31.1	24.5
17	Preobrazheniye	137.0	136.2	137.6	140.9	146.9	153.0	155.9	156.4	153.9	144.2	140.5	139.8	20.2
18	Valentin	118.6	118.3	118.8	122.2	127.2	133.1	135.3	136.1	133.6	124.2	119.3	119.0	17.8
19	R. Pristan	57.0	55.5	56.5	59.2	65.3	69.8	72.1	73.5	70.5	61.7	57.0	57.1	18.0
20	Plastun	151.2	151.1	150.8	155.2	160.2	163.9	165.1	165.3	163.9	156.6	153.3	152.4	14.4
21	Terney	119.6	116.1	117.6	120.7	125.7	129.3	131.5	132.6	131.1	121.2	117.7	118.3	16.4
22	Zolotoy	144.4	142.6	143.9	149.4	153.8	154.6	155.7	157.0	155.1	152.7	149.1	150.6	14.4
23	Innokentevka	189.6	187.4	188.1	191.9	196.9	198.6	200.5	202.0	200.3	197.1	194.6	193.9	14.6
24	S. Gavan	35.3	33.4	35.7	39.0	43.3	45.5	47.2	48.3	46.3	42.1	38.4	38.9	14.9
25	Vanino	58.5	56.5	56.3	56.8	65.8	70.3	73.0	71.0	70.8	63.3	62.5	62.8	16.8
26	De-Kastri	213.1	211.0	213.6	223.5	227.8	231.0	234.2	235.8	229.5	226.0	218.6	214.2	24.8
27	Alexandrovsk	98.9	97.4	96.5	104.3	107.0	111.7	115.6	115.4	111.4	105.9	105.1	101.4	19.8
28	Uglegorsk	120.1	118.0	120.0	125.1	129.4	132.0	135.3	135.9	131.6	129.5	126.9	125.5	17.8
29	Chehov	164.8	160.1	157.6	161.0	164.4	166.9	169.7	167.8	167.2	162.0	163.7	166.8	12.1
30	Kholmsk	49.7	43.8	41.3	42.9	47.0	49.2	52.4	53.0	50.3	47.6	48.5	52.8	11.7
31	Nevelsk	46.4	40.8	38.4	38.8	41.6	43.6	46.8	47.0	44.2	42.6	45.0	49.0	10.7
32	Moneron	57.4	53.0	52.0	54.8	59.2	63.1	64.9	64.7	64.7	60.9	60.4	59.4	12.9
33	Krilyon	142.3	133.8	128.9	124.1	126.2	126.9	128.6	130.1	129.5	131.2	136.4	142.9	18.8
34	Korsakov	125.7	118.6	113.9	111.0	113.1	113.1	115.2	116.1	115.2	116.3	121.6	129.0	18.0
35	Wakkanai	166.1	160.8	159.9	162.7	167.9	171.5	177.3	182.6	179.8	178.1	173.1	172.0	22.8
36	Oshoro	158.6	153.3	151.1	153.4	159.7	165.3	170.6	173.7	171.3	165.0	162.0	161.3	22.6
37	Fukaura	152.7	146.6	143.8	146.6	152.8	159.7	168.5	174.6	171.2	168.3	163.5	160.1	30.8
38	Awasima	96.8	89.8	87.1	87.7	93.3	100.4	107.9	114.3	112.1	109.3	106.1	103.7	27.1
39	Toyama	119.4	113.2	110.4	112.2	120.3	129.9	139.4	146.2	142.9	137.6	130.8	126.8	35.8
40	Wazima	208.9	207.7	208.4	212.7	219.4	228.1	233.1	237.1	237.2	231.8	221.1	213.8	29.5
41	Maizuru	104.2	98.6	97.0	98.8	107.1	117.5	127.0	133.0	130.1	125.0	118.2	111.4	36.1
42	Saigo	95.9	89.8	88.7	91.8	100.8	109.9	117.4	124.1	121.4	116.5	110.1	103.9	35.3
43	Sakai	118.7	114.3	113.4	117.9	126.6	137.1	147.4	151.6	147.6	141.6	133.7	126.4	38.2
44	Hamada	89.0	85.4	85.2	89.5	98.2	108.9	119.2	123.5	119.6	113.2	104.4	95.9	38.2
45	Mozi	274.5	272.1	273.9	279.5	287.2	297.4	305.0	310.1	307.9	300.6	290.0	280.9	38.0
46	Shimonoseki	239.2	235.9	237.3	243.1	251.8	261.8	268.5	273.8	271.4	264.6	254.7	245.5	37.9
47	Izuhara	156.5	153.7	154.7	158.2	165.8	175.9	182.3	188.6	187.3	179.7	170.1	161.9	34.9
48	Fukue	248.9	247.5	248.5	253.6	261.3	270.2	278.0	284.5	283.3	276.1	263.6	254.6	37.0

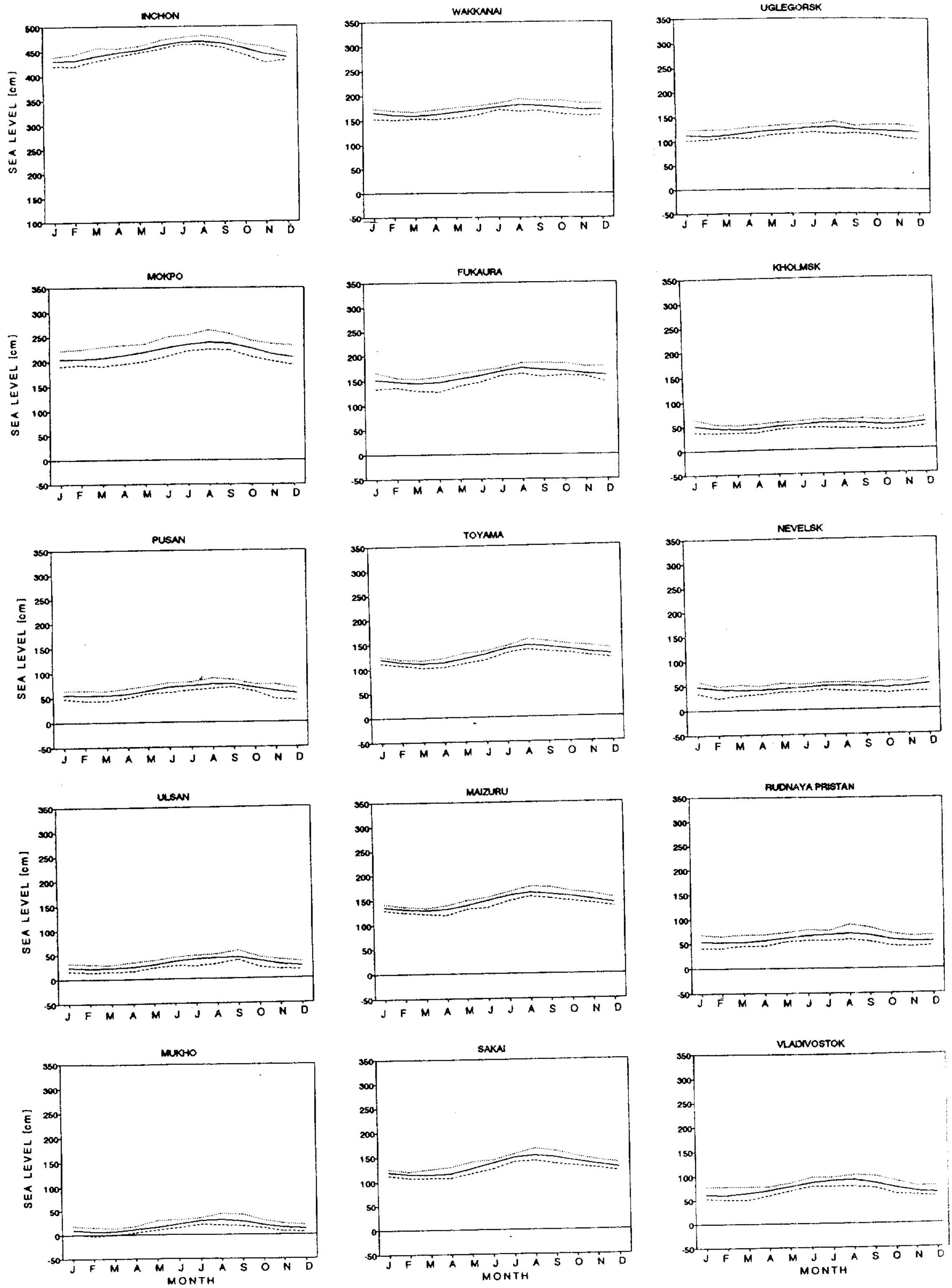
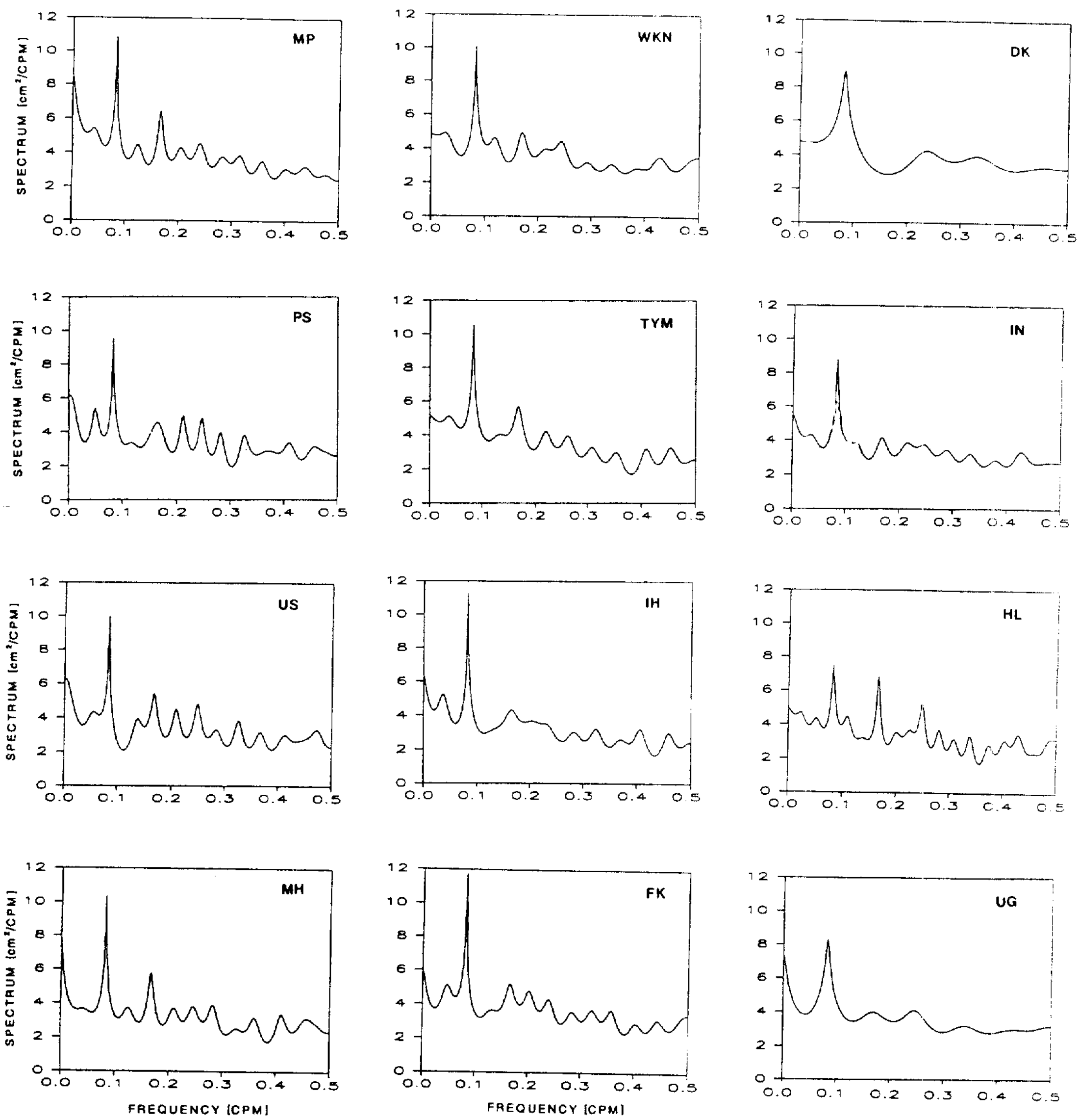


Fig. 3. Mean, maximal, and minimal monthly sea level.



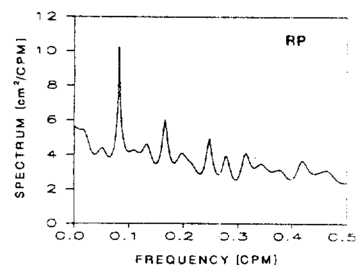


Fig. 4. Spectra of the monthly mean sea level. The symbols denote MP: Mokpo, PS: Pusan, US:Ulsan, MH:Mukho, WKN:Wakkanai, TYM: Toyama, IH: Izuhara, FK: Fukue, DK: De Kastri, IN: Innokentevka, HL: Kholmsk, UG: Uglegorsk, and RP: Rudnaya Pristan.

have about the same value. This peculiarity of seasonal sea level oscillations in the Sea of Japan was emphasized also by other authors (Galerkin, 1960; Deyeva, 1978; Lyubitsky, 1987). The nature of this feature needs to be investigated more accurately.

Also, there are maxima corresponding to seasonal oscillations of higher order (with four or three months periods). In particular, these maxima are clearly seen in spectra of Rudnaya Pristan, Kholmsk, Vladivostok, Pusan. They seem to be caused by interannual variability of the main seasonal components. We need more studies for this phenomenum. The other spectral peaks (e.g. with period of 8 months) are much weaker and do not exceed the confidence level.

HARMONIC ANALYSIS

The amplitudes and phases of annual and semiannual components were obtained from harmonic analysis. The monthly values of the MSL were described as:

$$\eta(t)=A_0+A_1\cos(\omega_0 t-\phi_1)+A_2\cos(2\omega_0 t-\phi_2), \quad (2)$$

where A_0 is a mean level, A_1 and A_2 are amplitudes of annual (Sa) and semiannual (Ssa) harmonics, ϕ_1 and ϕ_2 are their phases, $\omega_0=2\pi/12$ is annual frequency, t is time in months. We chose the 1st January of the first year of observations as a start time, because it is more convenient than the middle of January as it was usually made. We also did not use tidal theory convention for the phase lags of Sa and Ssa to be zero at the mean vernal equinox because in fact these harmonics are related mainly to external meteorological factors with seasonal cycle and not to gravity forces as other tidal harmonics (Lisitzin, 1974; Woodworth, 1984).

The least square method was used to compute amplitudes and phases of seasonal harmonics (Table 1). The results of other authors for the same stations are also given for comparison. In addition, the North Korean station Wonsan and some Japanese stations with known characteristics of seasonal variations are included in this table

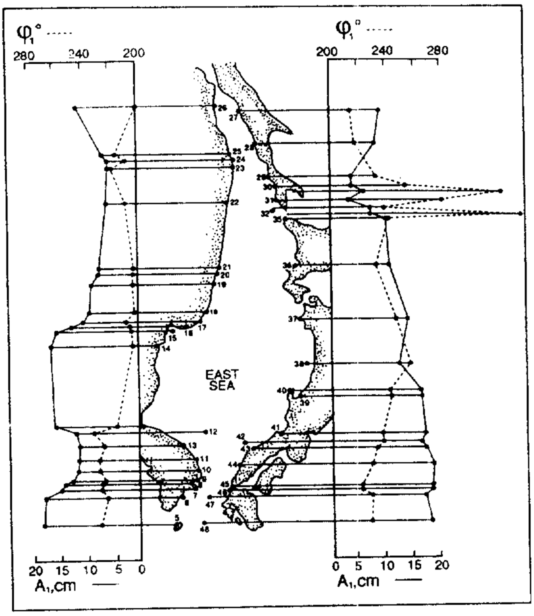


Fig. 5 Variations of amplitude (A_1) and phase (ϕ_1) of the annual sea level component.

to complete the whole picture. All the phases are reduced to the 1st January.

The amplitudes and phases of the annual component are very stable, i.e., no considerable variations are observed by different authors in the estimated values even though the authors use the different period of sea level data. The spatial structure of this harmonic is presented in Fig. 5. It is well seen that the amplitude A_1 is decreasing along the mainland from north to south with minimum at the region of Innokentevka and Zolotoy stations (6.5 cm); by the same way A_1 is reducing also along the western coast of the Sakhalin Island, minimal values of A_1 are in Chekhov, Kholmsk and Nevelsk (3-4 cm), i.e. just at the stations with the strongest semiannual oscillations. Further to the south the annual amplitudes increase both along the continent (15-16 cm in Vladivostok, Posyet and Wonsan) and western coast of Japan (10 cm in Wakkanai on the northernmost point of Hokkaido, 14-16 cm in Fukaura and Niigata on the northwestern coast of Honshu and 18-19 cm in Sakai, Hamada, Shimonoseki, Mozi and the other stations located on the southwestern coasts of Honshu and at Kyushu Islands). There is a local minimum of A_1 component at the southeastern coast of Korea (10-11 cm in Pohang, Ulsan and Pusan), but in the Korea Strait its amplitude increases up to 16-17 cm (Yosu, Cheju, Chungmu) and in the Yellow Sea (Kunsan and Inchon) even up to 20-21 cm.

The semiannual component, Ssa, is not so stable as the annual, Sa, especially inconsistant are phases of this component. The amplitudes A_2 for the most stations are of about 1.5-3 cm; the highest ones are at the southern and southwestern coasts of the Sakhalin Island (3.8-3.9 cm in Krilyon and Korsakov; 3.0-3.2 cm in Chekhov, Kholmsk and Nevelsk) and at the Yellow Sea coast of Korea (3.7 cm in Kunsan). In the latter case the increase of semiannual oscillations corresponds to the general intensification of seasonal sea level changes in the Yellow Sea, in contrary to the region of southwest Sakhalin where total range of seasonal sea level variability is strongly reduced (Table 1).

The character of seasonal oscillations and relative importance of annual and semiannual components may be described by 'seasonal factor' (Pugh, 1987): $F=A_1/A_2$ (8th column in Table 1). For the major part of the investigated area $F>3.0$, i.e. the seasonal sea level changes here are of 'annual type'. The only exception is the region bordering to the southwestern coast of Sakhalin where $F=0.9$-1.2 and sesonal variations are of 'semiannual type'. In fact, as it was mentioned above, there are two sea level maxima and two minima in this region during a year.

The RMS deviation of the individual values from the averaged ones for each month may be estimated as

$$\sigma_i=\left[\frac{1}{N}\sum_{i=1}^{N}(\eta_{ij}-\bar{\eta}_i)^2\right]^{1/2} \quad (3)$$

The relative investment of the seasonal oscillations in total energetic budget of sea level changes was estimated as

$$R=\frac{\sum_{i=1}^{N}\sum_{j=1}^{12}(\eta'_{ij}-A_0)^2}{\sum_{i=1}^{N}\sum_{j=1}^{12}(\eta_{ij}-A_0)^2}=\frac{\sigma_s^2}{\sigma^2} \quad (4)$$

where σ^2 is a variance of the original MSL values and σ_s^2 is a variance of the seasonal oscillations, η'_{ij}, calculated by expression (2). The computed ratio R with the RMS deviation of the individual monthly MSL from the averaged ones are listed in Table 3. Practically for all Korean stations, Japanese and Primorye stations located in south and central part of the East Sea R is bigger than 0.78. In the northern part of the East Sea (northwestern coasts of Honshu, Hokkaido and Sakhalin, northeastern coast of Primorye) $R=0.5$-0.7. In the anomalous region of southwestern coast of Sakhalin $R=0.35$-0.40. It means that except for this region seasonal oscillations are strongly prevailed in mean monthly levels of the East Sea.

DISCUSSION

Based on the longterm observations of mean daily sea levels around Japan, Nakano and Yamada (1975) divided all the area into 5 regions with different values of annual ranges and time of minimal-maximal monthly sea levels. Kurasawa and Toba (1980) analyzed the variations of the thermal structure, dynamic depth anomalies, main current locations and geographical features; combining the results they determined 6 large regions with different characters of seasonal changes, the whole area of the East Sea was related to one of the regions (E), the Yellow and East China Seas (together) to another one (B), etc. Tomizawa et al. (1984) divided these 6 regions (from A to F) into 14 subregions with tidal stations having closer correlations: 6 of these subregions (B1, B2, E1, E2, E3, E4) belonged to the Japanese and Korean coasts of the East Sea and adjusted regions.

Taking the basic classification of Tomizawa et al. (1984) (with small modification for the region of Korea Strait) we made a further division of the remaining part of the East Sea (bordering to the coasts of Russia and Korea) into 5 more subregions (E4-E8); the Yellow Sea subregion adjoining to the west coast of Korea is marked as Y2 (Fig. 6). Certainly, such a division has a conditional character because it is based not on distinc-

Table 3. Monthyl RMS deviation (σ_m) of MSL, variance of the seasonal oscillation, σ_s^2 and variance of the original MSL.

No.	Month / Station	σ_m (cm) 1	2	3	4	5	6	7	8	9	10	11	12	σ_s^2	σ^2	$R(\sigma_s^2/\sigma^2)$
1	Inchon	5.7	6.2	6.0	5.6	6.0	5.1	5.1	5.7	7.3	6.1	6.7	4.9	194.7	229.4	0.849
2	Kunsan (in)	11.8	11.3	12.1	9.9	9.7	10.3	12.5	10.2	10.4	10.2	12.7	12.3	210.7	335.1	0.629
	Kunsan (out)	4.6	5.3	4.1	3.1	3.5	3.9	4.5	3.6	5.1	4.2	3.9	5.2	184.9	203.2	0.910
3	Mokpo	5.7	4.6	4.4	3.7	3.7	3.8	3.8	4.8	4.6	4.0	5.9	5.6	153.5	174.8	0.878
4	Taehuksan	4.5	4.0	4.3	3.6	4.9	4.0	4.0	5.1	4.6	3.3	4.7	5.4	119.1	138.5	0.860
5	Cheju	5.4	5.9	6.6	6.2	6.0	6.0	5.0	7.0	6.0	5.6	5.5	6.2	147.0	182.6	0.805
6	Yeosu	5.1	5.3	4.8	4.4	4.1	5.1	4.7	5.6	5.6	3.4	4.5	6.2	142.8	167.2	0.854
7	Chungmu	3.4	2.8	3.5	3.1	2.6	3.8	3.3	5.0	3.8	2.6	2.8	5.2	100.6	113.5	0.886
8	Kadukdo	3.1	4.1	3.6	3.0	2.5	3.3	3.1	4.4	3.1	2.6	2.7	4.5	92.6	104.1	0.890
9	Pusan	4.0	4.5	4.6	4.7	3.5	4.4	4.0	5.3	4.5	3.8	4.8	5.0	68.0	87.6	0.776
10	Ulsan	4.3	4.1	3.9	4.0	3.5	3.8	3.9	4.4	4.4	3.0	3.7	4.2	61.7	77.3	0.798
11	Pohang	3.4	3.1	2.9	2.9	2.7	3.4	3.5	8.7	3.8	3.8	3.3	4.4	61.5	78.7	0.791
12	Ulleungdo	5.5	5.8	3.7	5.2	4.1	5.0	6.5	6.2	7.4	8.6	9.3	6.2	76.0	116.0	0.655
13	Munho	4.5	4.0	3.5	3.5	4.1	3.7	3.8	5.7	5.4	4.2	4.3	4.4	66.0	84.7	0.780
14	Posyet	5.2	5.2	4.8	4.0	4.8	4.1	3.8	4.5	5.2	4.5	4.2	4.0	137.2	157.8	0.870
15	Vladivostok	4.6	5.1	4.8	3.8	4.0	4.2	4.0	5.2	5.0	5.5	4.6	4.3	116.4	137.8	0.845
16	Nakhodka	4.1	3.8	4.0	4.2	4.0	3.5	3.9	4.7	4.9	5.2	4.0	3.3	79.9	97.2	0.821
17	Preobrazheniye	3.1	3.7	3.7	2.7	2.6	4.1	4.5	4.0	5.6	5.2	4.0	2.5	54.7	70.1	0.781
18	Valentin	4.4	4.3	4.4	4.0	3.6	3.3	4.3	4.3	5.1	5.2	4.3	2.7	47.7	65.4	0.729
19	R. Pristan	5.0	4.6	5.0	4.9	3.8	4.3	4.6	5.5	6.3	5.8	4.8	4./1	43.5	67.7	0.643
20	Plastun	5.4	6.4	5.9	4.6	3.6	5.0	4.7	3.5	5.8	4.3	4.0	4.0	31.8	55.2	0.576
21	Terney	7.2	4.1	6.3	5.1	3.3	2.7	4.0	3.8	5.8	6.2	4.2	2.5	35.1	58.3	0.602
22	Zolotoy	3.7	4.8	3.9	5.0	4.2	3.9	3.6	5.3	4.6	4.9	5.1	5.7	22.3	43.6	0.512
23	Innokentevka	4.1	4.6	3.1	5.5	3.6	3.8	3.8	4.5	4.2	5.0	4.8	4.1	22.8	41.2	0.553
24	S. Gavan	3.6	4.3	3.7	4.1	4.3	4.1	4.0	3.9	4.6	4.6	3.9	3.7	23.4	40.1	0.584
25	Vanino	2.7	5.7	4.3	5.1	2.5	5.0	3.7	4.6	4.0	4.4	2.3	3.3	35.1	51.9	0.676
26	De-Kastri	7.4	6.8	5.6	6.7	5.1	3.7	4.6	5.5	2.6	6.1	6.1	4.3	71.2	101.8	0.699
27	Alsexandrovsk	3.3	4.6	3.4	3.7	3.9	4.8	5.2	4.8	4.2	5.2	4.2	5.1	40.3	59.7	0.675
28	Uglegorsk	5.5	4.8	4.2	6.2	5.4	4.4	4.5	5.8	3.9	5.3	6.3	6.7	32.2	60.5	0.532
29	Chekhov	5.6	4.3	5.0	3.4	3.6	3.0	3.6	2.6	3.4	5.0	5.0	5.5	11.9	30.2	0.393
30	Kholmsk	5.3	4.6	3.8	4.5	3.7	3.4	3.7	3.5	4.0	4.4	4.3	4.0	13.9	31.0	0.448
31	Nevelsk	5.0	4.5	4.4	4.2	3.7	2.5	3.1	3.3	3.2	4.9	4.9	4.6	10.4	27.2	0.382
32	Moneron	3.1	5.1	7.9	5.1	4.1	5.6	6.1	5.0	6.6	5.6	3.8	4.4	18.6	46.9	0.397
33	Krilyon	8.1	4.6	4.7	4.7	3.6	3.8	4.2	3.9	4.0	4.9	4.3	5.5	33.4	56.6	0.590
34	Korsakov	7.9	5.8	5.7	4.8	4.7	4.2	4.0	4.2	4.1	6.1	6.0	6.1	27.0	56.5	0.480
35	Wakkanai	5.6	4.4	3.1	5.7	5.0	3.5	3.8	5.7	4.8	5.0	6.3	5.7	53.2	77.9	0.683
36	Oshoro	6.9	5.8	6.3	5.6	5.4	5.5	5.4	6.5	6.0	7.3	7.7	7.6	49.8	90.9	0.548
37	Fukaura	8.0	5.4	5.6	7.6	6.3	6.5	4.5	5.5	6.9	5.5	6.4	7.4	100.6	141.2	0.712
38	Awasima	5.2	5.0	4.6	5.5	4.5	4.6	4.3	4.8	6.4	5.2	6.5	5.3	84.8	111.8	0.759
39	Toyama	3.8	3.3	3.7	4.3	4.4	4.1	3.9	4.7	5.3	3.7	5.6	4.9	141.4	160.4	0.881
40	Wazima	6.1	6.3	4.0	4.9	5.8	5.9	4.8	7.8	8.1	4.4	4.5	5.5	119.8	153.5	0.780
41	Maizuru	3.6	3.5	3.8	5.3	4.6	4.1	4.1	4.7	5.4	4.4	4.8	5.0	154.1	174.1	0.885
42	Saigo	4.0	4.2	4.5	5.5	5.4	4.5	4.4	4.4	4.6	4.2	4.2	4.4	144.3	165.0	0.874
43	Sakai	4.3	4.2	3.1	4.7	4.3	3.4	4.5	5.8	6.4	3.9	4.7	5.4	173.1	194.6	0.889
44	Hamada	3.7	3.7	2.9	4.4	3.2	2.5	3.8	5.0	5.4	3.3	4.3	4.6	181.2	197.0	0.920
45	Mozi	3.6	4.2	4.5	5.5	4.5	4.9	4.5	5.2	5.3	3.6	4.5	5.4	178.4	200.4	0.890
46	Shimonoseki	4.9	5.2	4.6	5.0	4.9	4.4	4.7	6.0	6.5	4.4	3.9	5.1	175.1	200.2	0.875
47	Izuhara	4.4	4.6	3.9	4.8	4.1	4.9	3.8	4.5	4.6	2.8	4.0	4.7	152.2	170.6	0.892
48	Fukue	4.7	5.0	3.1	4.3	4.4	5.0	4.7	5.3	5.1	3.7	4.4	5.0	176.3	197.5	0.893

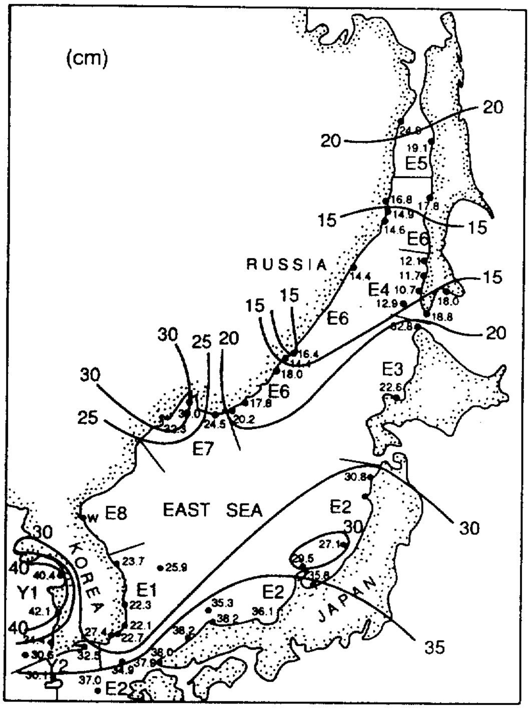


Fig. 6 Contour of the annual ranges of the average monthly sea level, and scheme of the subregions with different characters of seasonal changes.

tions in generation mechanism but on formal manifestations of the seasonal sea level changes. Further investigations may improve this classification.

The unclear problem is a behaviour of seasonal sea levels in the open sea away from the coast of the East Sea. Longterm satellite altimetry measurements may help to clarify this question.

SUMMARY

The monthly mean sea levels at 48 stations located at the East and Yellow Seas coasts of Korea, Russia and Japan were processed to investigate seasonal sea level variations. The statistical characteristics of sea level changes (annual range, deviation, average and extreme monthly levels etc.) were estimated for all the stations. The strong seasonal variations were found at the west coast of Korea (42.1 cm in Kunsan), in the region of the Korea Strait and near the southern part of Primorye (30-33 cm); the weak ones being near the southwestern coast of the Sakhalin Island (10-12 cm). Practically for the whole area of the East Sea, Yellow Sea and Korea Strait except Southwest Sakhalin, the general picture of the seasonal sea level changes is alike: the mean sea level rises in summer-autumn and falls in winter-spring, proving the universal mechanism of its generation in the region. Such a character of the sea level variability is in strong contrast with that in the Sea of Okhotsk where the maximal sea levels are observed in winter time and the minimal levels in spring and summer.

The spectral analysis of the records demonstrated that the seasonal oscillations strongly dominate in the sea level variations, more than 80% of total energy in the southern part of the investigated region and 50-70% in the northern part relate to these oscillations. The annual peak significantly prevails in spectra of the monthly sea levels for the majority of stations, the semiannual peak is also well manifested, seasonal peakes of higher order (corresponding to the periods of four and three months) reveal only at some records.

Least square method was used to compute amplitudes and phases of the annual and semiannual components of the sea level changes. The results of other authors were used also for comparison and to construct the general scheme of seasonal sea level variations in the East Sea. The compound table was completed. The maximal amplitudes of annual component (A_1) were at the Yellow Sea coast of Korea (20-21 cm) and also near the Japanese coast of the Korea Strait (18-19 cm). The semiannual component had the maximal amplitudes (3-4 cm) near the south and southwestern coasts of the Sakhalin Island.

There is an anomaly in the sea level changes at the southwestern coast of Sakhalin. The annual range of the sea levels is much weaker here than in the other regions, the relative investment of the seasonal oscillations in total energetic budget is only 35-40%, annual and semiannual components have nearly the same amplitude (seasonal factor $F=A_1/A_2=0.9\text{-}1.2$), there are two maxima and two minima in monthly sea levels during a year. The nature of this anomaly is not clear and requires

more detailed investigations.

On the basis of the present examination on sea level changes together with the results of Tomizawa et al.(1984) the whole investigated area was divided into 10 subregions, 2 of them were related to the Yellow Sea and western part of the Korea Strait (Y1, Y2), the other ones (E1-E8) to the East Sea; within these subregions almost the same character of seasonal variability is observed in coastal areas.

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