SEA LEVEL VARIATION IN THE SEA OF JAPAN

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1. — INTRODUCTION

The problem of the seasonal variation in sea level in oceans and seas can at the present time be solved only approximately. Although practically all recent research indicates that variation in atmospheric pressure and changes in water density — and correspondingly in water volume — greatly contribute to sea level fluctuations and that these two factors are of decisive signficance for the seasonal cycle in sea level, there remain a considerable number of questions which are so far unsolved. This is especially so in the type of sea where the water balance is marked enough to be an important factor, or where the piling-up effect of wind is very pronounced, showing in addition seasonal changes. The contribution of these supplementary factors should therefore not be underestimated. It must also be remembered in this connection that the results can never be generalized. Every sea must be studied separately and special attention has to be paid to the features characterizing each particular basin.

Moreover the problem of mean sea level in the world ocean requires additional study. In spite of the fact that significant preliminary work has already been done, a more or less final result can be reached only by means of the numerical evaluation of a large number of observed data on water temperature and salinity, of intensified hydrographic work at sea, and continuous water level recording along the coasts and on oceanic islands on an expanded scale.

2. — SEA LEVEL RECORDS IN THE SEA OF JAPAN

The Sea of Japan is an interesting basin for the study of mean sea level and of its seasonal fluctuations. In addition to a number of Japanese oceanographers (NOMITSU and OKIMOTO [4], MIYAZAKI [3]) this sea basin has been investigated by GALERKIN [1]. This author was able to confirm the significance of the combined effect of water density and atmospheric pressure upon the sea level and he determined the relative contributions

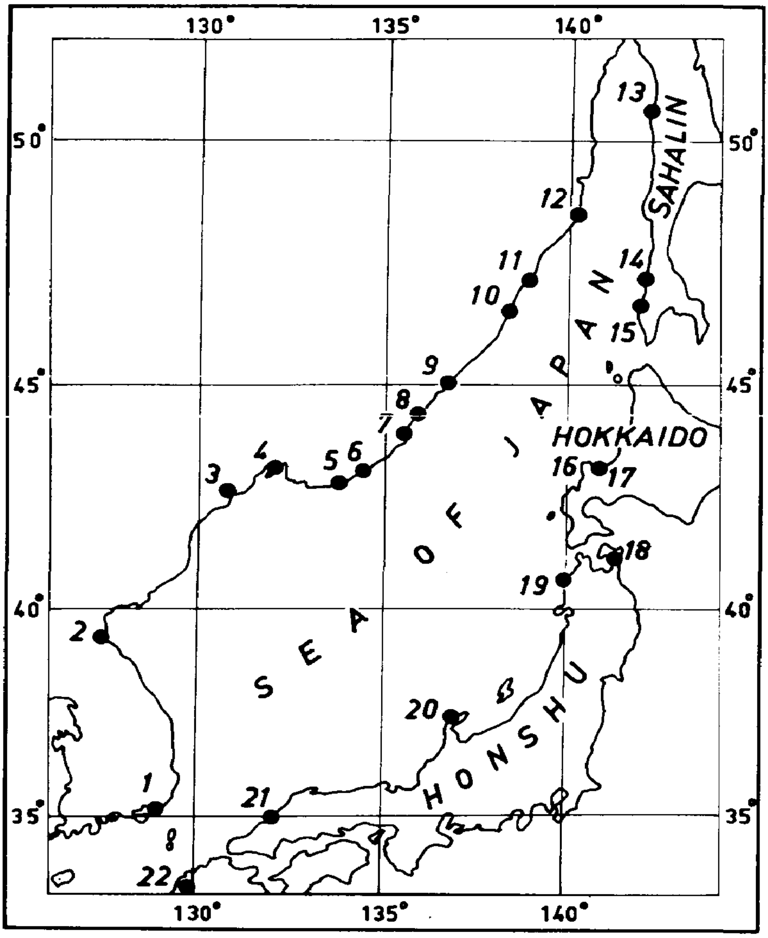

FIG. 1

of the two factors in the different parts of the basin. Reference will also be made in this article to some of the other results achieved by GALERKIN who, for his part, based his studies to some extent on previous research work.

The first step is to study more closely the recorded sea level data and the particular features revealed by these data. Making use of the records collected by GALERKIN, we have at our disposal 22 tidal stations relatively evenly distributed along the continental and Japanese shores of the Sea of Japan and the adjacent waters. The positions of the individual stations are shown in figure 1. The numbers in this figure relate to table 1. The southernmost stations are situated on the coasts of Korea and in the Tsushima Straits, the northernmost stations along the shores of the Tartarian Sound. The Ominato sea level station lies in a bay adjoining the Tsugaru Strait.

Already a rapid glance at table 1 shows that there are very pronounced deviations betwen the amplitudes of the monthly averages in the different parts of the sea basin. The highest amplitudes are noted in the southern

TABLE 1

The monthly means of sea level records in the Sea of Japan (in cm)

No.	Station	Month												Ampl. in cm
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1.	Pusan	—9	—9	—8	—8	—4	4	12	16	13	5	—4	—8	25
2.	Wonsan	—13	—13	—11	—7	1	9	14	18	14	2	—5	—8	31
3.	Posjet	—17	—16	—11	—2	6	13	18	20	14	1	—9	—15	37
4.	Vladivostok	—14	—14	—10	—4	5	11	15	16	11	1	—7	—11	30
5.	Preobrashenie	—7	—9	—7	—4	2	7	10	12	9	—2	—6	—6	21
6.	Valentin	—8	—9	—5	—2	2	8	10	10	9	—1	—7	—9	19
7.	Tetuhe (1)	—9	—9	—7	—2	4	7	9	11	9	—2	—7	—8	20
8.	Plastun	—8	—9	—8	—2	3	8	9	9	9	0	—6	—8	18
9.	Ternej	—9	—8	—3	—1	4	7	8	9	10	—1	—5	—7	19
10.	Cape Sosunov (1)	—11	—9	—5	—5	5	3	5	6	9	5	—1	—5	20
11.	Cape Zolotoj	—5	—8	—6	—4	4	1	6	8	9	2	—1	—3	17
12.	Innokentjevka (1)	—8	—8	—7	—4	4	4	6	9	9	2	—1	—3	17
13.	Alexandrowsk	—9	—8	—1	—1	2	5	7	8	2	—1	—1	—7	17
14.	Holmsk	1	—7	—7	—5	1	2	4	7	8	0	—3	0	15
15.	Nevelsk	2	—3	—5	—5	—2	0	3	3	0	—1	2	5	10
16.	Otary	—6	—10	—10	—9	—2	3	8	12	8	4	2	—1	22
17.	Osyoro	—5	—9	—11	—8	—2	2	8	11	8	3	2	—1	22
18.	Ominato	—3	—5	—10	—13	—9	0	10	15	12	5	—1	—2	28
19.	Iwasaki	—6	—11	—15	—12	—5	2	9	15	11	6	5	2	30
20.	Wajima	—5	—12	—15	—15	—6	3	10	15	13	7	5	0	30
21.	Hamada	—13	—17	—17	—14	—4	7	15	22	16	9	2	—6	39
22.	Sasebo	—18	—16	—13	—9	2	7	17	22	19	9	—4	—14	40

(1) These values differ somewhat from the data given by GALERKIN as here they have been reduced to the yearly mean sea level.

part of the basin, reaching there heights of 30 - 40 cm. The amplitudes decrease gradually towards the north and in the Tartarian Sound they are of the magnitude of 10 - 20 cm. There are relatively slight differences between the amplitudes for the same latitudes on the eastern and on the western shores of the Sea of Japan. The phases of the seasonal cycle of sea level are on the whole similar for the entire basin. The maximum sea level is as a rule noted late in summer, chiefly in August, the minimum generally in January and February and along the eastern coast, however also in March and sometimes in April.

As a consequence of the differences in the amplitudes there occurs in the Sea of Japan a continuous change in the predominant direction of the slope of the water surface, as compared with the average surface for the whole year. At the beginning of the year the highest sea level is observed along the western coast of the island Sahalin, the lowest in the region around the Korea and Tsushima Straits. The maximum and the minimum heights of sea level thereafter move slowly counter-clockwise in such a way that in April the highest sea level appears along the western shore of the Sea of Japan opposite to the island Hokkaido and the lowest off the middle of the island Honshu. In July the maximum sea level has

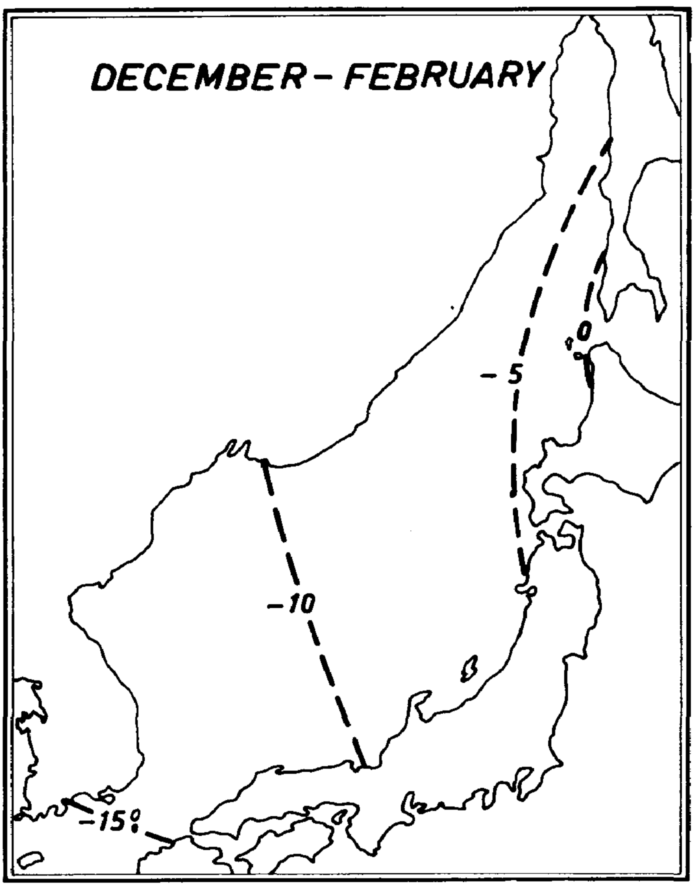

FIG. 2

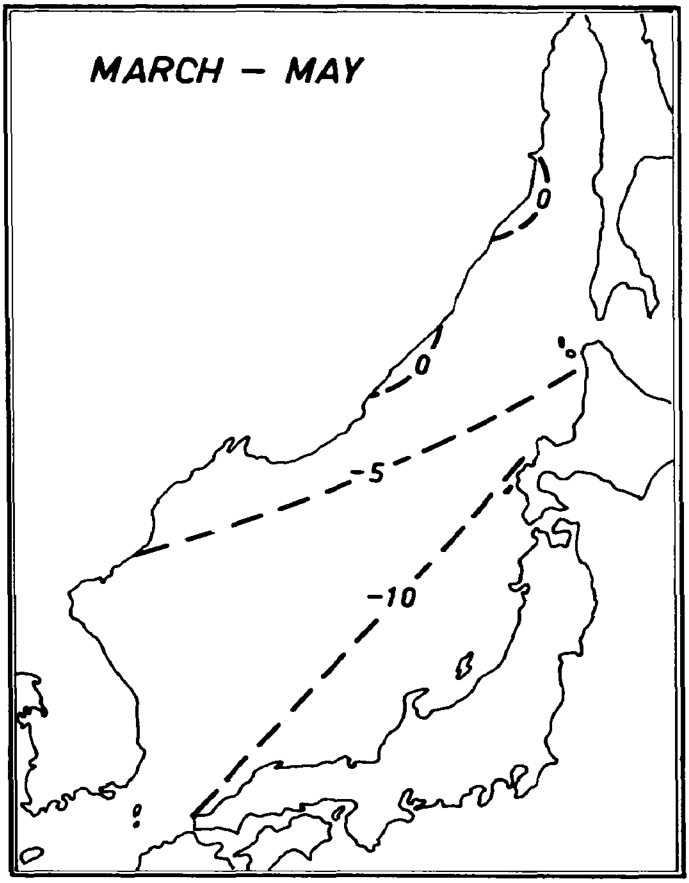

Fig. 3

reached the region south of Vladivostock, whilst the minimum has now replaced the winter maximum along the western coast of Sahalin. In October the sea level is at its highest along the eastern shore of Tsushima Strait, and at its lowest in the north-western parts of the sea basin. It may be mentioned that, generally speaking, the water surface in the Sea of Japan in winter time slopes upwards towards the north-east, in spring towards the north-west, during the summer months towards the south-west and, finally, in autumn towards the south-east. These features are illustrated on the maps in the figures 2 - 5 which refer to the different seasons.

The average scheme described above presumes, however, that the coastal regions are also representative of the open sea, and that there are no noteworthy differences in the average annual sea level in the different parts the Sea of Japan. This assumption is, however, at variance with the actual conditions. According to Unoki and Isozaki [6] the mean sea level increases gradually northwards along the Sea of Japan shores of the islands Kyushu and Honshu, the extreme deviations in height being of the magnitude of 15 - 20 cm. Along the western coast of the island Hokkaido the mean sea level is of a similar height to that in the south.

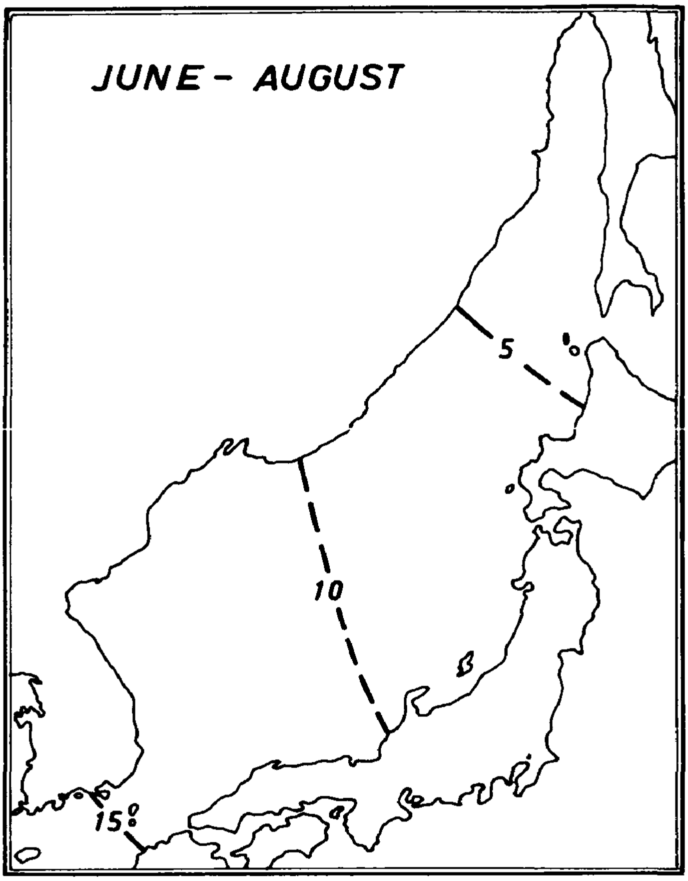

FIG. 4

The primary cause for the differences in mean sea level is, without doubt, the effect of the Coriolis force due to the rotation of the Earth. Taking the direction of the predominant currents into account it may be noted that the mean sea level is always high along the coast located to the right of the current direction and low along the coast lying to the left of it. Although information concerning the mean sea level along the continental shore of the Sea of Japan is so far lacking, approximate conclusions about the height variations may easily be drawn on the basis of a general knowledge of the direction of the current along the coast. This coast being situated to the right of the prevailing current, the mean sea level will be expected to be of the same magnitude as in the region off the Japanese Islands. The velocity of the current, however, indicates that the height rate is probably closer to the rate characteristic of Kyushu and Hokkaido than that off the north-western coast of Honshu. The lowest mean sea level within the basin of the Sea of Japan and adjacent regions probably occurs along the coast of Sahalin in the Tartarian Sound, since this coast is located to the left of the current. Due to the same factor the mean sea level along the Pacific coast of the Japanese Islands is considerably lower than along the shores of the Sea of Japan, the differences reaching in some cases as much as 40 cm.

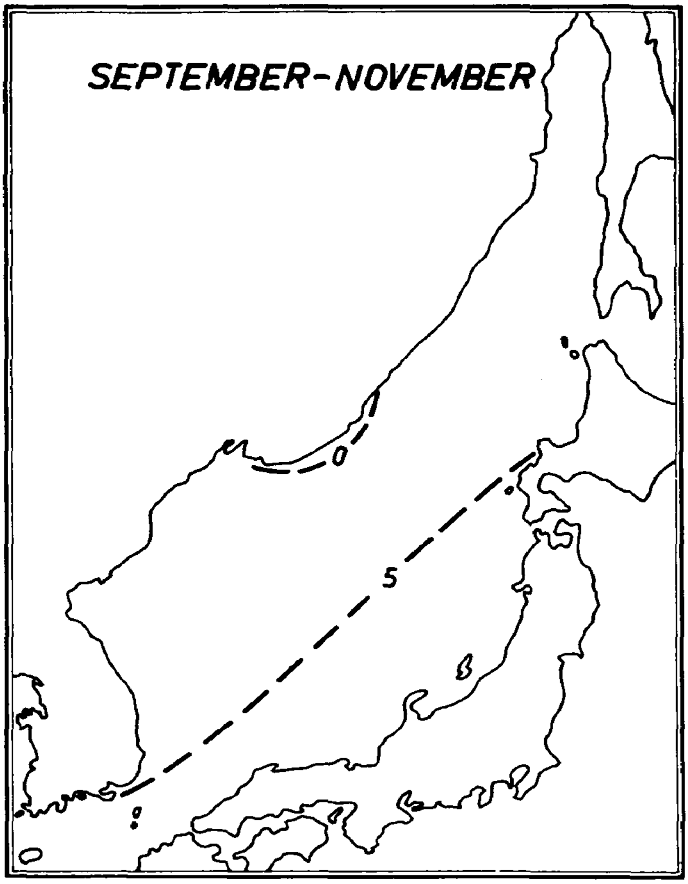

Fig. 5

3. — THE FACTORS INFLUENCING SEA LEVEL VARIATION

It has already been mentioned above that the principal factors influencing the seasonal cycle in sea level are changes in water density and atmospheric pressure. It may therefore be expected that these factors will show a seasonal variation characterized by features similar to those for the sea level cycle. The number of places where measurements of water temperature and salinity were made is, nevertheless, considerably less than the number of sea level stations. In addition, the hydrographic observations are as a rule of a more or less sporadic character, lacking the continuity of sea level records. The gradual travel of the maxima and minima, such as they appear from the density data (transformed into water heights) is therefore not as regular as that concerning the sea level records. The general trend, however, is also evident in this case. The fluctuation in water density or in water volume brings about a counter-clockwise-moving slope of the water surface. The same also holds good for the contribution of atmospheric pressure to the seasonal cycle in sea level. The data concerned are assembled in tables 2 and 3. The magnitude of the relative contribution of the two elements to the sea level is, however, quite different in the various parts of the sea basin. GALERKIN [1] has already shown that along the eastern, and more especially the southeastern, shores of the Sea of Japan the effect of water density is predominant, whilst along the western or continental shore the contribution of the two factors is of practically the same magnitude. In addition, in the latter region the contribution of atmospheric pressure is approximately 100 per cent higher than for corresponding latitudes in the east. These features result in the following differences in sea level between the west and the east shores of the Sea of Japan. During the first half of the year, the contribution to sea level brought about by the density effect as a rule causes a sea level higher in the west than in the east. If all other influences could be eliminated the water surface would thus slope downwards from the west to the east. During the latter part of the year the situation is reversed, with an upward-directed slope from the west to the east.

Passing on to the air pressure effect it may be noted that in this case the differences in the winter season on the one hand and the summer season on the other hand are the most pronounced. As would be expected the sea level affected by air pressure stands higher along the continental coast than off the Japanese Islands during the period from April to September, and lower during the months October through March. The added effect of density and atmospheric pressure results in a sea level higher in the west than in the east from February until July, while the eastern area of the sea is characterized by a higher sea level during the remaining months. This tendency in the distribution of sea level heights is also distinctly reflected in the recorded data, as described in section 2 of the present paper. Table 4 was compiled to obtain a picture of the coincidence of the two series of data.

In the first line of this table are given the monthly averages for the added effect of water density and atmospheric pressure upon the sea level for the seven stations mentioned in tables 2 and 3. In the second line we find the corresponding average sea level records for the same stations. The third line shows the differences between the two series. The most pronounced of these differences, — 3.9 cm, is the one noted for August. This deviation should probably be ascribed to a prevalent inaccuracy in the density data. For five, at least, out of the seven stations presented in table 2 the contribution of water density to the sea level is in August too low, when we compare these values with those for the adjacent months. A correction of the magnitude of 4-5 cm seems therefore to be appropriate for August. If we apply this correction, we note that the data computed by means of water density and air pressure are higher than the recorded data for the months from June to November, and lower for the rest of the year (with the exception of February). This characteristic is so pronounced that it can hardly depend upon occasional factors. The causes for the deviations must rather be sought either in the fact that the locations of the sea level recording stations on the one hand, and on the other the places where the hydrographic observations are made, may not be precisely

TABLE 2

The contribution of water density to sea level (in cm)

No.	Station	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1.	Pusan	—4.9	—6.7	— 6.9	— 7.7	— 4.9	—0.7	6.8	6.0	8.1	5.9	5.3	0.1
2.	Wonsan	—5.6	—2.4	— 6.4	— 6.8	— 3.8	—2.0	2.4	4.8	6.6	10.6	6.2	—3.8
4.	Vladivostok	—4.4	—5.4	— 4.8	— 3.8	— 2.2	2.8	4.4	3.2	10.6	2.4	0.6	—2.8
14.	Holmsk	—1.4	—3.6	— 4.4	— 6.2	— 2.2	1.4	2.0	5.6	4.4	6.0	—0.6	—1.0
15.	Nevelsk	—3.6	—4.0	— 7.0	— 4.8	— 1.6	3.2	5.2	3.2	6.0	3.4	—0.1	—0.2
16.	Otary	—4.0	—8.6	—10.8	— 7.8	— 6.4	2.8	7.4	0.1	7.4	9.2	10.2	—0.2
19.	Iwasaki	—3.8	—7.6	—11.0	—18.2	—12.6	—9.8	4.4	3.6	17.4	22.0	11.0	4.6

TABLE 3

The contribution of air pressure to sea level (in cm)

No.	Station	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1.	Pusan	— 6.9	—5.3	—3.1	—0.4	4.1	8.0	7.6	7.8	3.1	—2.3	—5.3	—6.8
2.	Wonsan	—10.0	—7.6	—3.6	1.7	5.4	10.4	10.9	8.7	2.8	—3.3	—6.8	—9.2
4.	Vladivostok	— 2.6	—4.0	—6.1	4.9	6.7	6.6	7.0	5.1	2.2	—4.1	—8.1	—7.8
14.	Holmsk	— 1.7	—2.3	—0.1	—1.3	3.1	2.1	3.4	2.9	1.7	—3.0	—3.1	—1.9
15.	Nevelsk	— 0.9	—2.6	—1.0	0.3	1.1	3.2	3.9	2.3	—0.9	—2.2	—1.8	—1.8
16.	Otary	— 2.3	0.2	—1.5	—0.9	1.9	4.6	5.0	2.4	—1.2	—3.3	—2.8	—2.2
19.	Iwasaki	— 1.6	—2.5	—2.1	— 0.3	2.0	5.4	5.7	3.8	1.8	—3.9	—5.3	—3.2

TABLE 4

The contribution of water density and air pressure to sea level together with sea level records for seven stations (in cm)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Water density + air pressure	—7.7	—8.9	—9.8	—7.3	—1.3	5.4	10.9	8.5	10.0	5.3	—0.1	—5.2
Sea level	—6.6	—9.6	—9.4	—7.2	—0.9	4.4	9.3	12.4	9.3	2.4	—1.4	—3.0
Differences	—1.1	0.7	—0.4	—0.1	—0.4	1.0	1.6	—3.9	0.7	2.9	1.3	—2.2

TABLE 5

The contribution of water density to the sea level at Wonsan (in cm)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tidal station	—2.9	—5.6	—7.1	—8.8	—4.6	—1.3	2.6	8.8	11.5	5.5	1.5	0.9
Offshore region	—5.6	—2.4	—6.4	—6.8	—3.8	—2.0	2.4	4.8	6.6	10.5	6.2	—3.8
Sea farther off	—3.4	—5.0	—5.1	—5.0	—3.3	—0.9	1.4	4.2	5.2	5.5	5.0	1.3

TABLE 6

The contribution of water density to the sea level in the area between Hamada and Iwasaki (in cm)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	IIX
Tidal station	—6.9	—12.4	—12.9	— 9.6	—7.0	—1.8	9.0	10.8	10.4	11.0	8.6	0.5
Offshore region	—8.1	—16.0	—16.0	—11.2	—7.8	—0.3	4.8	13.9	14.8	13.2	9.9	1.9
Sea farther off.....	—6.9	—11.2	—10.8	— 7.4	—6.4	—6.2	—3.3	6.1	13.7	15.4	11.0	5.9

the same, or else in some additional factors influencing the sea level variation.

As the disturbing effects may be different in the various parts of the research region it has seemed appropriate to study the question not for the Sea of Japan as a whole but rather for separate stations. Tables 5 and 6 give respectively water density contributions for the station Wonsan on the west coast and the mean values in the area between Hamada and Iwasaki on the east coast. The seasonal cycle in sea level corrected for the effect of atmospheric pressure is shown, as well as the corresponding contribution to sea level caused by changes in water density for the adjacent sea area, and also for a region situated at a somewhat greater distance from the coast. All the data concerned thus refer primarily to sea level variations caused by water density changes, and also possibly to some additional factors so far not yet considered in this paper. The data themselves are all to be found in the paper by GALERKIN mentioned above.

Tables 5 and 6 show the following general picture. During the colder season — for the west coast, in December and from March to June : for the east coast from October until May — the highest sea level is to be found in the region situated farther off the coast. During the warm season — July to September for Wonsan, and July for the area between Hamada and Iwasaki — the highest sea level appears at the site of the tide gauge station. These features are without doubt connected with the decrease of the degree of water-warming and the corresponding water-cooling from the coast outwards to the sea. There may, however, be an additional factor which should be taken into consideration in this connection. The work of SOK-U [5] concerning the seasonal variation of water transport across the Strait of Korea has shown that this transport reaches its largest increase during the months May to July, a fact that may be reflected in the sea level records by an increase (in tables 5 and 6 the records are corrected for the effect of atmospheric pressure). The most pronounced decrease in water transport through the Korea Strait is, according to SOK-U, reached between November and January, that is exactly when the near-shore data, based on sea level records, are very low. The absolute value of the balance indicates, however, that the observed sea level variation constitutes only a slight fraction of the balance value, which supports the point of view of MIYAZAKI [2] that the quantity of water entering the Sea of Japan from the north is of the same magnitude as the outflow of water through the straits in the north part of the sea. MIYAZAKI assumed that the amount of sea level variation due to the changes in water volume in the Sea of Japan is solely the consequence of the balance of fresh water which shows seasonal features similar to those for the inflow of water through the Korea Strait. The problem, however, cannot be solved in detail at the present time. Moreover, on the basis of available data it is hardly possible to decide to what degree and in which areas the intensified or diminishing water transport has an influence on the velocity of the current system in the Sea of Japan, and consequently on the slope of the water surface and the sea level variation. However, the fact that the seasonal changes in sea level along the western shores are not as marked as along the eastern shores indicates that the sea level variations depend only weakly upon the hydrographical conditions corresponding to the different phases of the water balance, while according to SOK-U the water inflow constitutes in the west approximately 70 per cent, and in the east only 30 per cent, of the total water transport to the Sea of Japan.

Continued and fairly intensified studies are thus needed for the Sea of Japan region, and also for the adjacent areas, in order to solve the problem of the seasonal variation in sea level in this already largely investigated basin.

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