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Seasonal variations of sea level along the Japanese coast

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Abstract: Seasonal variation of sea level was investigated at 68 tidal stations along the Japanese coast by using monthly mean data from 1981 to 1990. The main results mostly agree with TSUMURA's results (1963) by the data from 1951 to 1960, but the details are partly different from his results. The high sea level in winter is found along the Hokkaido coast in the Okhotsk Sea, and even along the southeastern coast of Hokkaido. This high sea level is considered to be closely related to the strength of East Sakhalin Current in this season. The gentle sea level rise occurs from Mera to Uragami along the southeastern coast of Honshu from June to July, i.e., in warming season. The sea level change along Suruga Bay coast mostly agrees with the vertical mean temperature from the sea surface to 200m depth in the center of bay. The vertical mean temperature is not so increased by the surface-temperature rise because of seasonal thermocline ascent in warming season. The seasonal thermocline ascent has been frequently found off the southeast of Honshu from Boso to Kii Peninsulas, and is explained as coastal upwelling induced by the prevailing northward wind in summer. The coastal upwelling is suggested to induce such a unique variation as the gentle sea level rise and secondary minimum of the water temperature. The gentle sea level rise in the Seto Inland Sea and the southwestern coast of Japan also appears from April to May, but the sea level change slightly disagrees with the temperature change in the surface layer.

Key words : *coastal current, coastal upwelling, Japanese coast, sea level, seasonal thermocline, seasonal variations, secondary minimum of temperature*

1. Introduction

Sea level in subtropical region is well known to show a seasonal variation, i.e., a maximum during summer to early fall and a minimum during winter to early spring (e.g., PICKARD and EMERY, 1990). The sea level variations are closely connected to water temperature variations in surface and subsurface layers. But, some observations indicated the unique seasonal variations of sea level. The sea level at the Oregon coast and dynamic height off Oregon are minimum in summer in relation to the coastal upwelling induced by the southward wind (e.g., GILL, 1982). This result is in direct opposition to the usual seasonal variation seen in the subtropical region. Along the Japanese coast, the extraordinary seasonal variations are found in sea level records. The sea level along the Hokkaido coast in the Okhotsk Sea show the peculiar seasonal variations which have two peaks in summer and early winter (TSUMURA, 1963, KONISHI *et al.*, 1987, MATSUYAMA *et al.*, 1999). Such variant phenomena are possible to be found in the seasonal variation of sea level along the Japanese coast.

TSUMURA (1963) analyzed the sea level data at about 58 tidal stations along the Japanese coast during 10 years and investigated the characteristics of annual and interannual variations of the sea level. He showed the seasonal variation of sea level along the Japanese coast and derived the interesting features, but he didn't explain the relations between the sea level variation and oceanographic phenomena. We are very interested in a relation between the seasonal variation and the oceanographic phenomena. Then we grasp the seasonal variations of sea level along the Japanese coast using the monthly mean data during the period from 1981 to 1990. The aim of this paper is to investigate the characteristics of seasonal

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variations of sea level in more detail, and to clarify the relation between the sea level variation and oceanic phenomena, i.e., current and temperature variations, and coastal upwelling.

2. Data and analysis

The monthly mean sea level data registered by the Coastal Movement Data Center (CMDC), Geographical Survey Institute, were used at 68 tidal stations in this study (Table 1). The same data set was already applied to investigate the inter-annual and decadal variations along the Japanese coast (SENJYU *et al.*, 1999). The tidal stations are selected around all over the Japanese coast as shown in Fig.1. Under the inverse barometric assumption with a factor of −1.0 cm/hPa, the original sea level data were corrected by using the atmospheric pressure obtained at a meteorological station near each tidal station. Monthly mean atmospheric pressure was also registered at CMDC.

3. Seasonal variations of sea level along the Japanese coast

Fig. 2 shows typical sea level variations at 9 stations along the Japanese coast for 10 years. These stations are selected as a typical station in each area. The seasonal variations are remarkable at all stations, but the amplitudes are different from each other. The amplitudes are large in the southern region (Kochi (Stn. 37 shown in Fig. 1), Matsuyama (Stn. 48) and Kagoshima (Stn. 51)) of Japan and the Japan Sea (Maizuru (Stn. 62)), and small along the Hokkaido coast (Abashiri (Stn. 3) and Kushiro (Stn. 4)). The maximum and minimum of these variations appear mostly in early autumn and late winter, respectively. But the maximum is found at December at Abashiri (Stn. 3) and Kushiro (Stn. 4), as described by the previous papers (TSUMURA, 1963, KONISHI *et al.*, 1987, MATSUYAMA *et al.*, 1999, ITOH, 2000). The sea level variations are not so decent sinusoidal curve except at Kamaishi (Stn. 13) and Maizuru (Stn. 62), but are frequently disturbed by a few month period fluctuations. These short period fluctuations are especially remarkable between Mera (Stn. 19) to Kagoshima (Stn. 51), i.e. in the coast of facing to the Kuroshio. NOMITSU and OKAMOTO (1927) described the variations of monthly sea level along the Japanese coast to be due to both the variations of density distribution from the sea surface to 200 m depth and of atmospheric pressure. Fig. 2 supports mainly their description, but we are interested in more detailed characteristics and distortion from the sinusoidal curve of seasonal variation.

TSUMURA (1963) analyzed the sea level data at 58 stations along the Japanese coast during the period from 1951 to 1960 and summarized the mean seasonal variations of sea level without correction of atmospheric pressure as

Table 1. Location of the sea level stations

No.	Location	No.	Location
1	Wakkanai	36	Muroto
2	Mombetsu	37	Kochi
3	Abashiri	38	Tosashimizu
4	Kushiro	39	Hosojima
5	Tokachi	40	Oita
6	Urakawa	41	Shirahama
7	Muroran	42	Wakayama
8	Hakodate	43	Kobe
9	Matsumae	44	Uno
10	Oshoro	45	Hiroshima
11	Hachinohe	46	Tokuyama
12	Miyako	47	Uwajima
13	Kamaishi	48	Matsuyama
14	Ofunato	49	Takamatsu
15	Ayukawa	50	Komatsujima
16	Soma	51	Kagoshima
17	Onahama	52	Makurazaki
18	Katsuura	53	Kune
19	Mera	54	Misumi
20	Chiba	55	Nagasaki
21	Tokyo	56	Sasebo
22	Yokotsuka	57	Izuhara
23	Aburatsubo	58	Shimon oseki
24	Ito	59	Hagi
25	Minami Izu	60	Hamada
26	Uchiura	61	Sakai
27	Shimizu	62	Maizuru
28	Yaizu	63	Mikuni
29	Omaezaki	64	Wajima
30	Maisaka	65	Toyama
31	Nagoya	66	Kashiwazaki
32	Toba	67	Oga
33	Owase	68	Fukaura
34	Uragami		
35	Kushimoto		

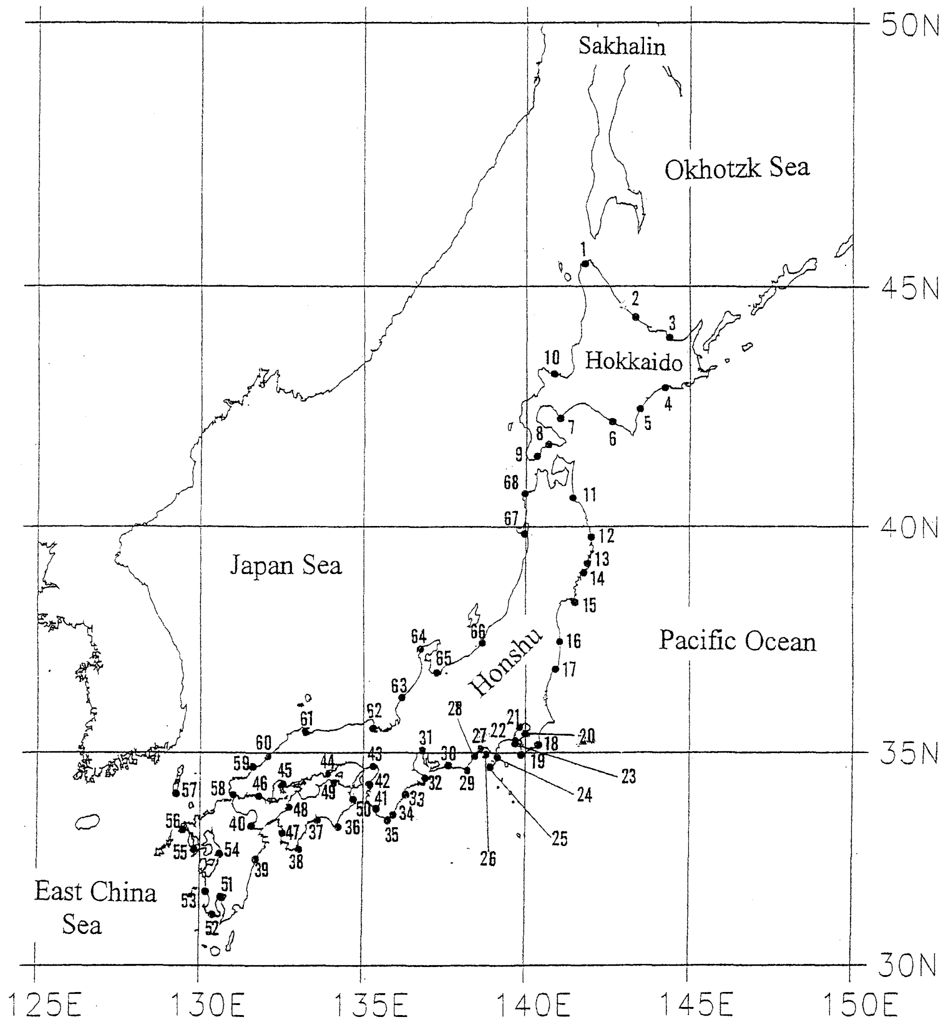

Fig. 1. Location of tide stations used in this study.

follows. (1) The maximum and minimum appear on September to October and March to May, respectively, in most stations. (2) The amplitude is the largest in the western part of the Japanese coast and the smallest in the northern part. (3) The two maximum appear along the eastern coast of Hokkaido. (4) The sea level gently rises along the southern coast of Japan from Mera (Stn. 19) to Megami (near Stn. 55) during the period from July to August. (5) In the northern part of the Japan Sea coast, north of Wajima (Stn. 64), the steep and gentle descents are seen from October to November, and from November to December, respectively.

These results are interesting features in relation to the coastal phenomena, that is, heating and cooling, wind effect and ocean currents. Fig. 3 shows the seasonal variations at all stations using the sea level data at 68 tidal stations from 1981 to 1990. These showed the similar characteristics of the seasonal variations indicated by TSUMURA (1963). Then we will try to verify the above five points by the recent tidal records, and we investigate the features of the seasonal variations in more detail.

The maximum is seen on September and October except the east coast of Hokkaido and Hamada (Stn. 60) and Sakai (Stn. 61) along the

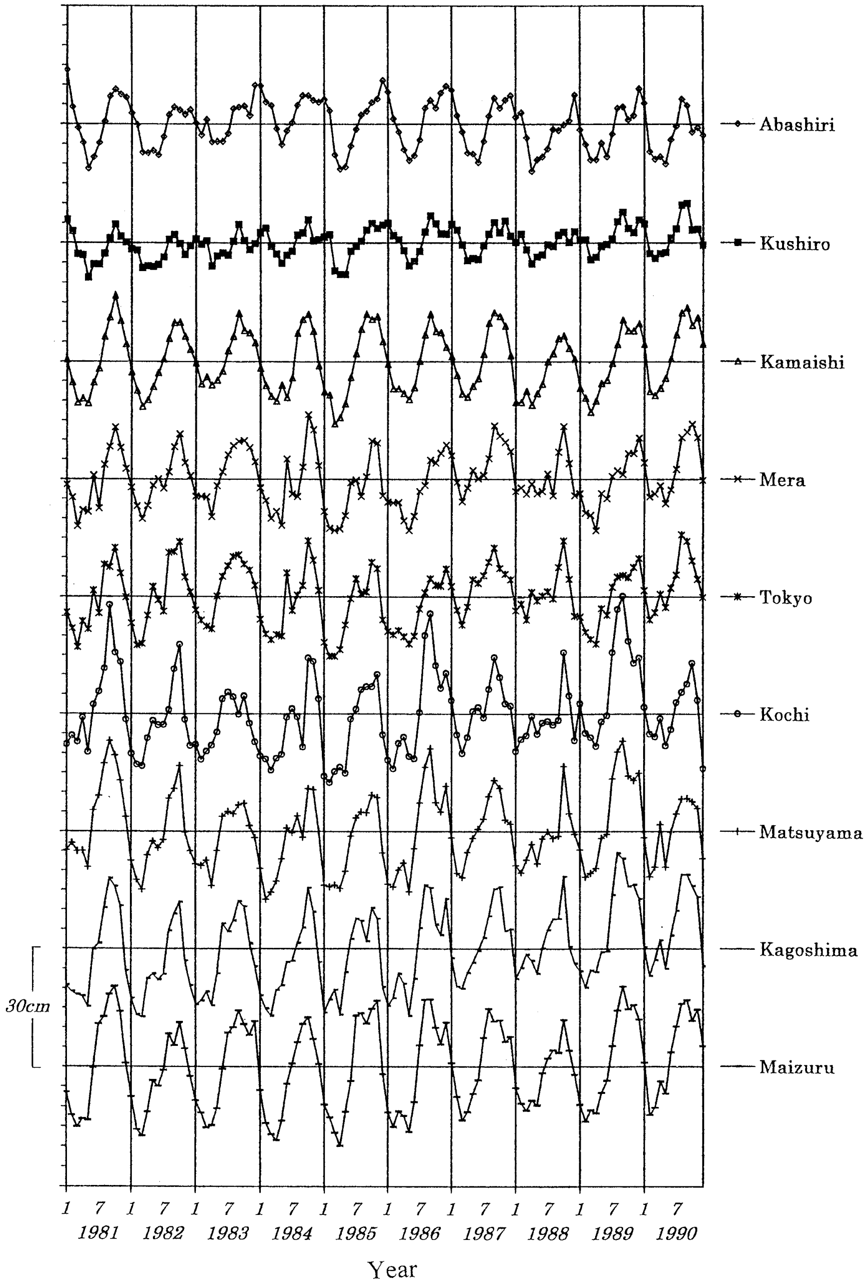

Fig. 2. Sea level variations corrected for the atmospheric pressure at nine tidal stations.

western coast in the Japan Sea. In the Japan Sea coast from Izuhara (Stn. 57) to Wakkanai (Stn. 1), the high sea level continues from August to October. The variations from Akune (Stn. 53) to Sasebo (Stn. 56) of the East China Sea coast resemble to these of the Japan Sea coast region. Along the Pacific coast, the maximum is seen on September from Hachinohe (Stn. 11) to Onahama (Stn. 17), i.e., northern part of Honshu, while it is on October from Katsuura (Stn. 18) to Makurazaki (Stn. 52), i.e., southern part of Japan. The maximum in the

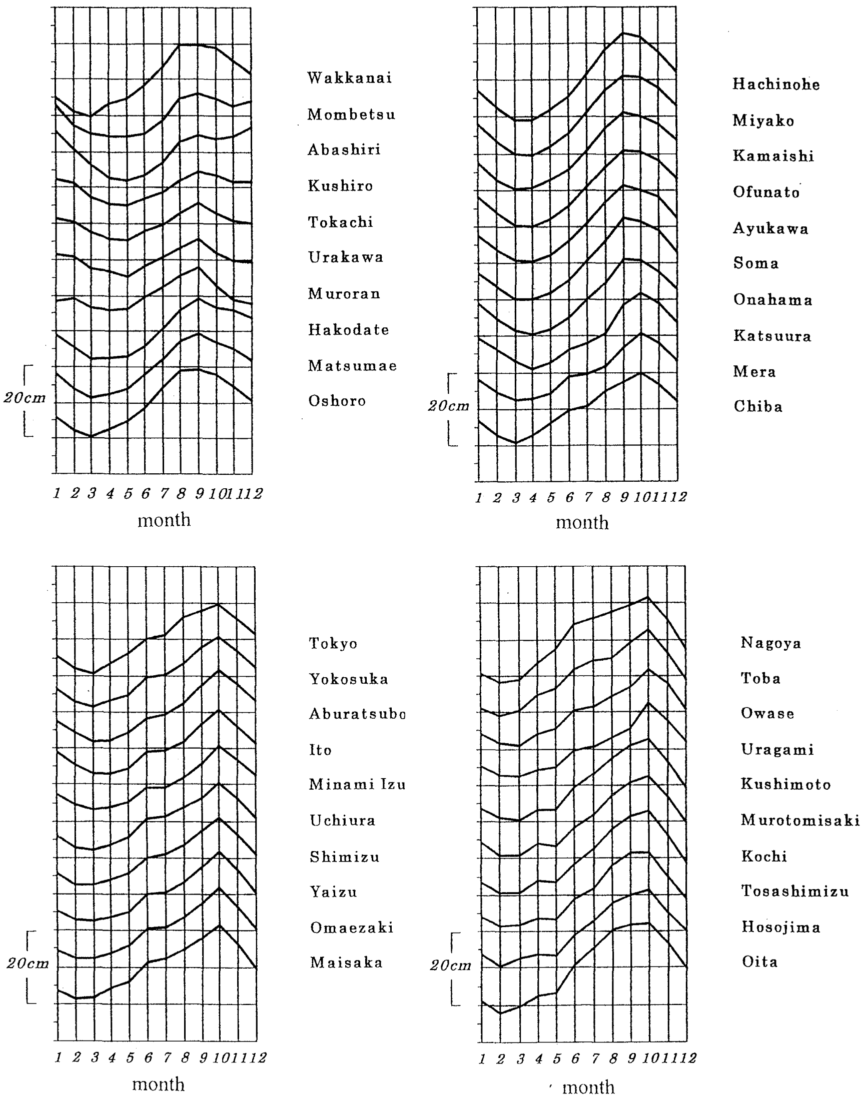

Fig. 3. Annual sea level variations at 68 tidal stations averaged from 1981 to 1990.

region from Katsuura (Stn. 18) to Makurazaki (Stn. 52) has a sharp peak, while it is a flat shape from Shirahama (Stn. 41) to Oita (Stn. 40) along the coast of the Seto Inland Sea. The minimum of the seasonal variation mostly appears between February and April, and the southern part leads the northern and eastern part by one or two month. The time difference between maximum and minimum of the seasonal variations displays the gentle ascent and steep descent along the Pacific coast.

The seasonal variations along the eastern and southern coast of Hokkaido, i.e., Mombetsu (Stn. 2) to Muroran (Stn. 7), as shown in Fig.1, are significantly different from the other stations in the Japanese coast, as indicated by TSUMURA (1963). Fig. 3 shows the variations of the Hokkaido coast and interesting feature with two maximum along the eastern coast from Mombetsu (Stn. 2) to Muroran (Stn. 7). The two peaks appear on September and December or January at Abashiri (Stn. 3) and Mombetsu (Stn. 2), and the peak in winter is higher than in early autumn at Abashiri (Stn.

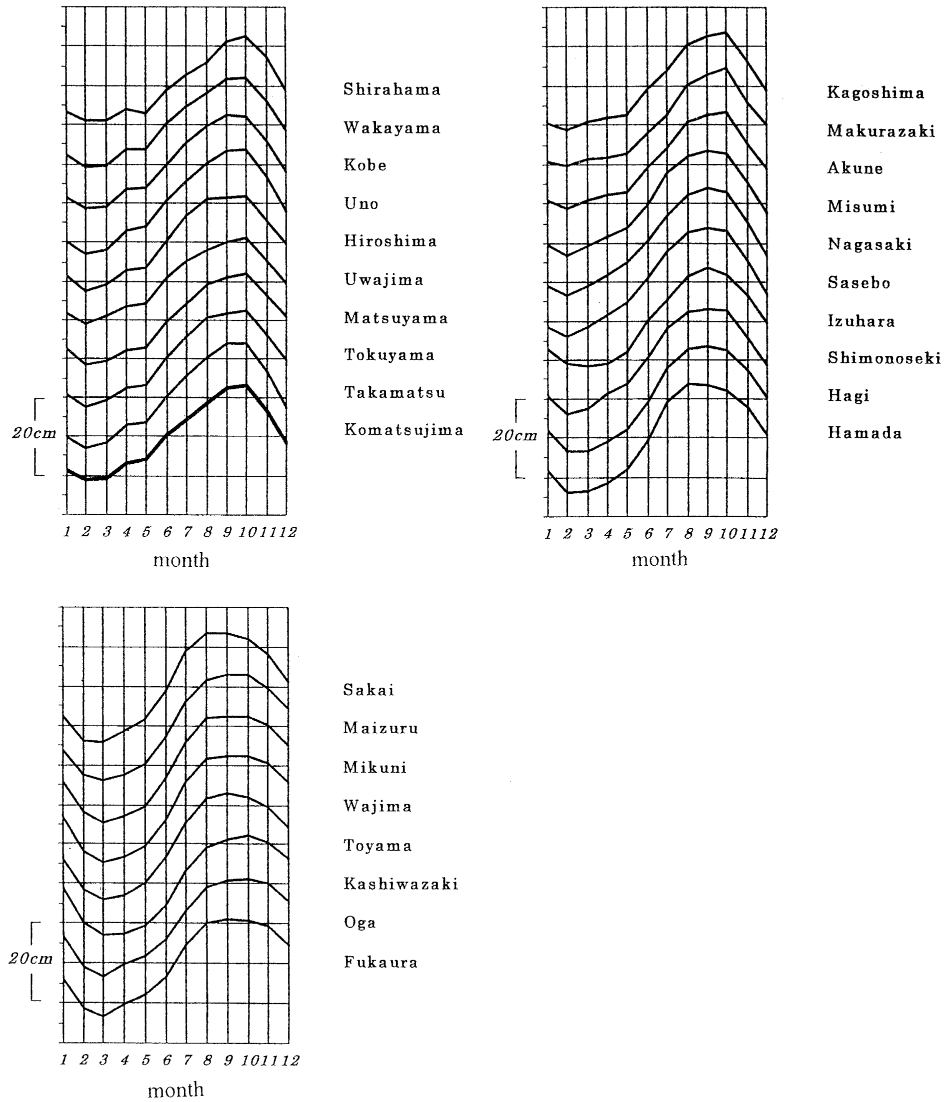

Fig. 3. (Continued)

3).

TSUMURA (1963) indicated that the sea level gently rises along the coast from Mera (Stn. 19) to Megami (Stn. 55) during June to July. We can clearly find this phenomenon along the coast from Mera (Stn. 19) to Uragami (Stn. 34) during this period. In the southwestern coast from Kushimoto (Stn. 35) to Hosojima (Stn. 39), including the Seto Inland Sea coast, the gentle rise of sea level appears during April to May instead of June-July. The significant difference of two-month lag is found between Uragami (Stn. 34) and Kushimoto (Stn. 35), which is a distance of 16km only. The sea level difference between both stations is very important to detect whether Kuroshio path is meandering or not along the southern coast of Japan as well (e.g., KAWABE, 1985). The westward propagation of several-day period fluctuations of sea level is also interrupted and is discontinued between both stations (NARUMI, 2002).

The other phenomenon indicated by TSUMURA (1963), which the steep descent from September to October and gentle descents from

October to December was seen in the northern part of the Japan Sea coast, couldn't be clearly found in this analysis.

4. Discussion

TSUMURA (1963) showed the seasonal variation of sea level along the Japanese coast and derived some interesting features. But, he didn't explain the relations between such the sea level variation as the above results and oceanographic phenomena. We will examine to explain these relations.

4-1 Two maximum along the eastern and southern coast of Hokkaido

The high sea level in winter is found along the coast from Mombetsu (Stn. 2) to Muroran (Stn. 7), and it is especially significant at Abashiri (Stn. 3) and Mombetsu (Stn. 2) along the Hokkaido coast in the Okhotsk Sea. The high sea level in winter in this region is related to the strength of East Sakhalin Current (WATANABE, 1963, OHSHIMA *et al.*, 2002). The southward current along the East Sakhalin coast turns eastward after arriving near the Hokkaido coast (Fig.4), so the sea level rise occur at this region by piling up of the low temperature and low salinity water (ITOH 2000). The sea level difference between Wakkanai (Stn. 1) and Abashiri (Stn. 3) induces the Soya Warm Current (AOTA, 1975, MATSUYAMA *et al.*, 1999), so that the remarkable difference of seasonal variations between both stations directly

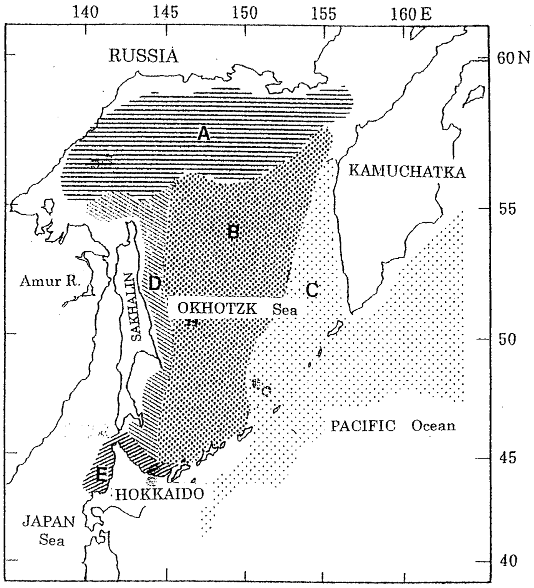

Fig. 4. Distribution of typical water mass and current in Okhotsk Sea. D is the East Sakhalin Current and E the Soya Warm Current. (After AOTA, 1987)

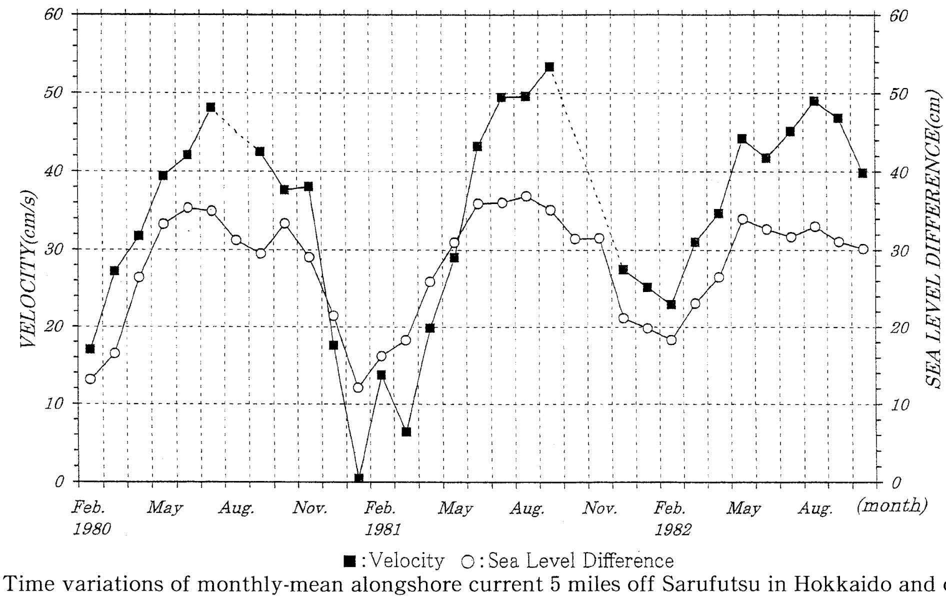

Fig. 5. Time variations of monthly-mean alongshore current 5 miles off Sarufutsu in Hokkaido and of adjusted sea level difference between Wakkanai and Abashiri (after MATSUYAMA *et al.*, 1999).

reflects the variations of the Soya Warm Current, that is, the small difference in winter indicates the weakness of the current (Fig. 5). The minimum of the sea level difference along the Hokkaido coast in the Okhotsk Sea appears on March at Wakkanai (Stn. 1) and on May at Abashiri (Stn. 3), so the Soya Warm Current indicates to be intensified from April.

The maximum of sea level in winter is also found from Kushiro to Muroran along the southeastern coast facing to the Pacific Ocean (Fig. 3). These are seen to be related to the sea level rise along the Okhotsk Sea coast from December to January. But we do not have much data to describe the relation between both phenomena in the Okhotsk Sea and the Pacific Ocean. We will investigate these phenomena in both seas, including the seasonal variation of the Oyashio.

4-2 Gentle rise of sea level along the southeastern coast of Honshu from June to July

The sea level rise is gently sloping from June to July from Mera (Stn. 19) to Uragami (Stn. 34) as seen in Fig. 3. In general, the sea level shows a sinusoidal curve as seasonal variation, and connects closely with the sea surface and subsurface temperature. Then, the small rising of sea level during June-July along the southern coast of Honshu from Boso Peninsula to Kii Peninsula is expected to connect to the low temperature in the surface and subsurface layers, as described by NOMITSU and OKAMOTO (1927).

NAKAMURA (1977) showed the seasonal variations of the temperature and salinity from the sea surface to 200m depth in and around Suruga Bay. Fig. 6 shows observation stations and the temperature distribution from the sea surface to 200 m depth at Stn. A estimated by the observational data from 1964 to 1974. From May to August, the isotherms descend near the sea surface, but they ascend in the subsurface layer. NAKAMURA (1977) called the temperature descending in the subsurface layer in this period a secondary minimum of water temperature. He presented the secondary minimum of the temperature together with the salinity maximum. T-S relation suggested the phenomena to be related to the upwelling. The secondary minimum of the water temperature in the subsurface layer was found at the Boso coast, Sagami Bay and eastern side of the Kii Peninsula (NAKAMURA 1977). UNOKI and UNNO (1983) analyzed the distributions of secondary minimum of the subsurface water temperature from the Boso peninsula to the Kii peninsula from 1965 to 1976, and found the following three cases of appearance of the water, (1) almost the whole area, (2) limited within a partial region and (3) scarcely and scattered distribution.

The gentle rise of sea level is possible to relate on the secondary minimum indicated by NAKAMURA (1977) and UNOKI and UNNO (1983). Then we compare the sea level at Suruga Bay coast with the temperature at Stn. A in Suruga Bay and at Stn. B located at out of the bay from 1964 to 1974. Fig. 7 shows the time series of the temperature distributions at Stns. A and B shown by NAKAMURA (1977). Both stations were selected as the typical stations for the inner and outer bay, respectively. The arrows indicate the secondary minimum of the temperature in the subsurface layer, i.e., ascending of the seasonal thermocline in both stations. The temperature and salinity observations were made at every month by Shizuoka Prefectural Experimental Fishery Station. The arrows are mostly found at both stations in summer, especially August, so that the phenomena can be considered to usually exist in summer, i.e., the ascending of seasonal thermocline in August. On the other hand, Fig. 8 shows the monthly mean sea level at four tidal stations at the Suruga Bay coast from 1965 to 1974. The sea level variations resemble among four stations and show the complicated seasonal variation. The low sea level in August is found on 1965, 1967, 1969, 1970, 1973, and 1974. These years mostly agree with the years of secondary minimum in Fig. 6, but strict comparison is difficult for the difference of the sampling interval between the monthly mean data and one-time data in every month.

Then, we compare the long-term mean data between temperature and sea level. NOMITU and OKAMOTO (1927) described the monthly mean sea level to be closely related to the density distribution from the sea surface to 200m

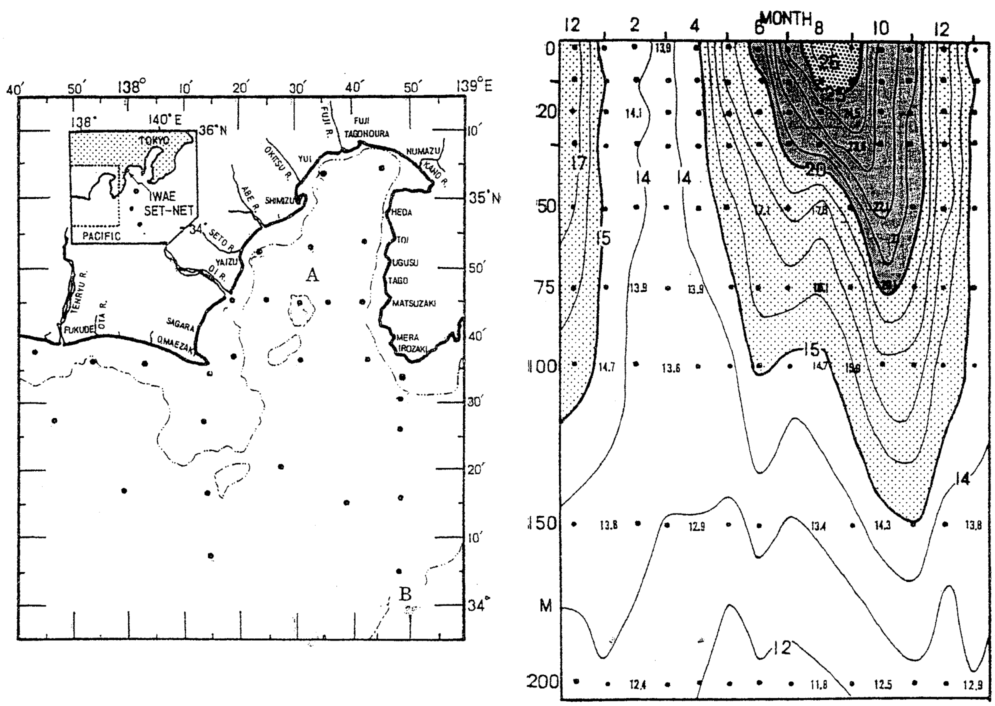

Fig. 6. Observation stations of temperature and salinity in and around Suruga Bay (left) and annual variations of temperature distribution at Stn. A averaged from 1964 to 1974 (right) (after NAKAMURA, 1977).

depth and Atmospheric pressure. The latter effect was already removed from Fig. 3 by the data handling. Then, We compare the monthly mean sea level with the vertical mean temperature from the sea surface to 200m depth at Stn. A as the mean of each month used from 1964 to 1974 calculated by NAKAMURA (1977). Fig. 9 shows the seasonal variations of the vertical mean temperature and sea level at four stations from 1964 to 1974. The vertical mean temperature is less variable from June to August because the temperature rise in the surface layer is canceled by the ascent of the seasonal thermocline. This variation is similar to the sea level variation along the coast. The secondary minimum of the temperature in the subsurface layer is considered to be closely related to the seasonal variations of sea level. The upwelling induces the gentle rise of the sea level from June to July and August.

NAKAMURA (1977) suggested the secondary minimum of temperature to relate to the fluctuation of the Kuroshio without a sufficient explanation. This is difficult to understand the above reason because the seasonal variation of the Kuroshio fluctuation, i.e., path, velocity and volume transport, is not remarkable (IMAWAKI *et al.*, 1997). We suppose that the upwelling in relation to the northward wind is predominant in summer. The southward wind off the Oregon coast induces an upwelling with the descent of temperature and sea level in summer (e.g. GILL, 1982). As the same manner, the coastal upwelling in Sagami Bay was induced by the northward wind in summer along the eastern coast of the Izu Peninsula (KISHI, 1976, 1977). UNOKI and UNNO (1983) speculated the secondary minimum to be associated with the coastal upwelling by the local wind, i.e., westerly wind along the southern coast of Japan. But they could not find the clear relations between the local wind and coastal upwelling, i.e., secondary minimum of the water temperature.

Recently KITADE and MATSUYAMA (2000) investigated the coastal trapped waves along the southeastern coast of Honshu by the data analysis and numerical experiments. They indicated the sea level variations with several-

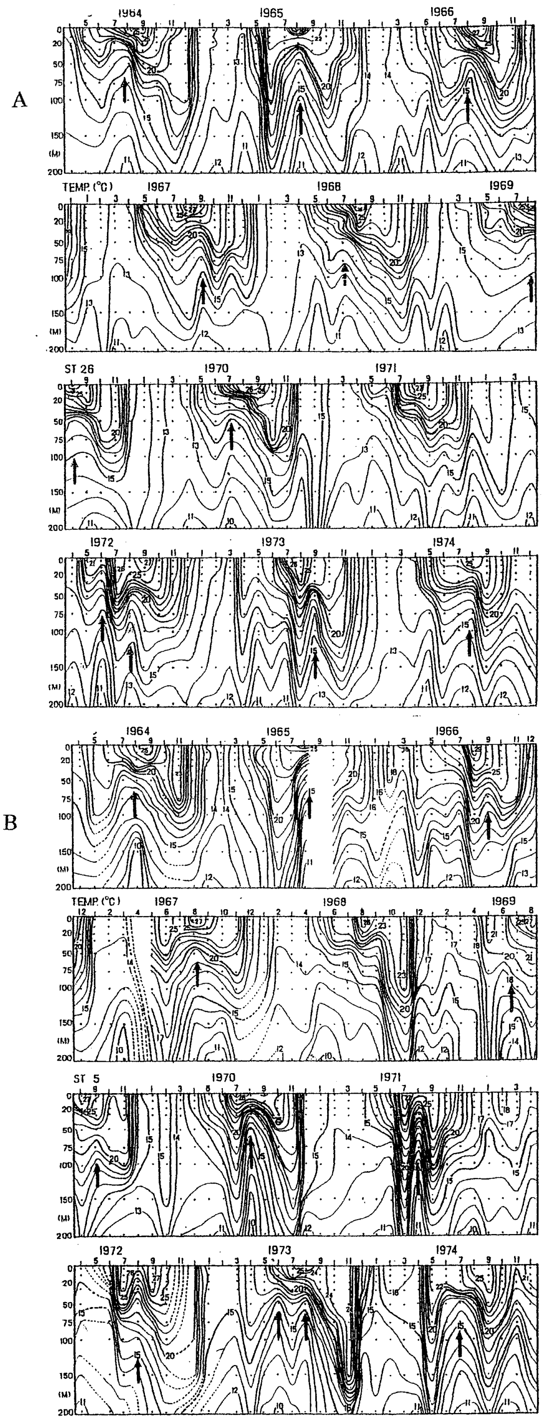

Fig. 7. Time variations of the temperature distribution at Stn. A (upper) and Stn. B (lower) from April 1964 to December 1974. Arrows show the upwelling in summer (After NAKAMURA, 1977).

days period along the southeast coast of Honshu, Japan induced by the wind. From July to August, the northward wind continues over 10 days and induces the upwelling along the Boso and Kashima coast (Fig. 10). The upwelling region propagates westward along the coast from the south of Boso Peninsula, having the characteristic of internal Kelvin waves, so that the low temperature water occupies the subsurface layer in the coastal region as such as the western coast of North America (HUYER 1977). The numerical experiments suggest the coastal upwelling due to the northward wind to be related to both gentle sloping rise of sea level at the coast and the secondary minimum of the water temperature indicated by NAKAMURA (1977).

4.3 Small sea level rise the southwestern coast of Japan in April to May

The seasonal variations of sea level also shows gentle rise in and around the Seto Inland Sea from April to May as seen in Fig. 3. Firstly the temperature variations are considered to relate to the sea level change near the coast. YANAGI (1984) investigated the seasonal variation of the temperature in this area from 1971 to 1975. He calculated the vertical mean temperature from the sea surface to bottom and for station of water depth over 50m, from the surface to 50m depth. His results show the uniform ascent of mean temperature from March to September, that is, a significant sinusoidal curve as a seasonal variation. The temperature change is different from the sea level change from April to May. As seen in Fig. 3, this anomalous seasonal change is seen at Kushimoto (Stn. 35), Murotomisaki (Stn. 36), Kochi (Stn. 37), Tosashimizu (Stn. 38) and Hosojima (Stn. 39), i.e., the southwestern coast of Japan facing to the Pacific Ocean. The reason why the gentle rise of sea level appears along the southwestern coast of Japan from April to May is not sufficiently explained in this study.

5. Summary

The seasonal change of sea level is investigated at 68 tidal stations along the Japanese coast by using the monthly mean data from

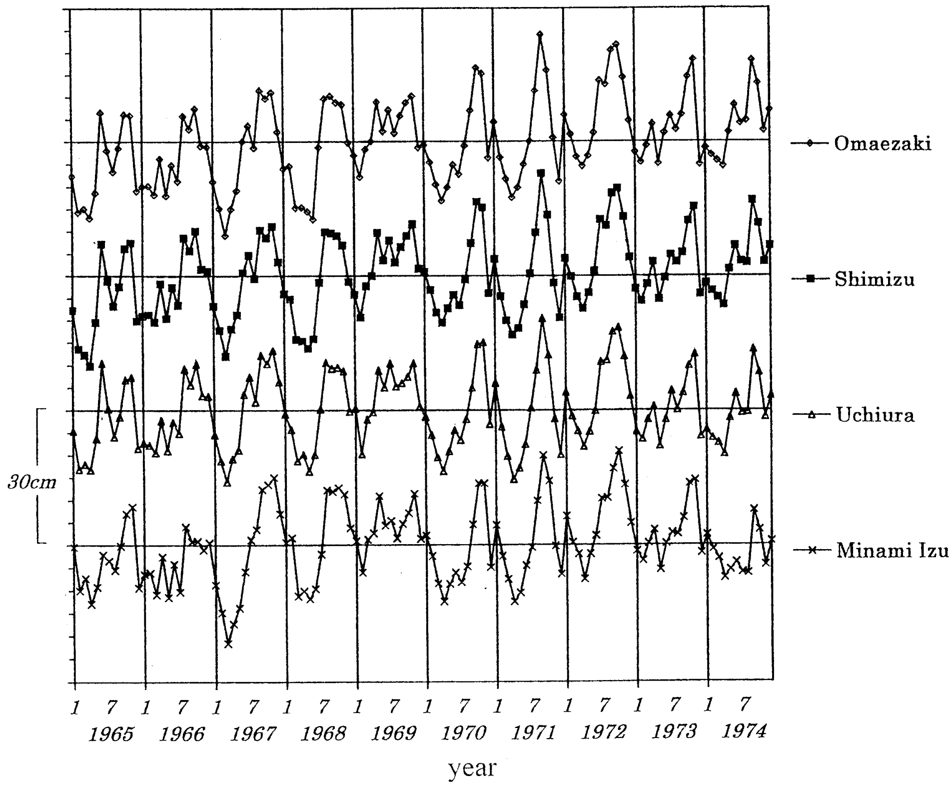

Fig. 8. Sea level Variations at Omaezaki (Stn.29), Shimizu (Stn.27), Uchiura (Stn.26) and Minami-Izu (Stn.25) from 1965 to 1974.

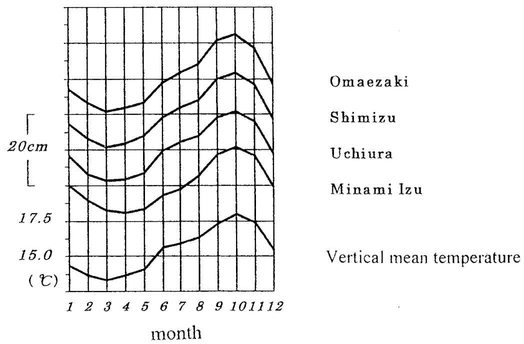

Fig. 9. Annual variations of sea level at Omaezaki, Shimizu, Uchiura and Minami-Izu, and of vertical mean temperature from the sea surface to 200m depth at Stn.26 averaged from 1964 to 1974.

1981 to 1990. The main results mostly agree with TSUMURA's results (1963) by the data during 1951 to1960. We analyzed the seasonal change in detail and discussed the sea level change in relation to the oceanographic phenomenon such as coastal current and coastal upwelling.

The high sea level in winter is found from Mombetsu (Stn. 2) to Muroran (Stn. 7) along the Hokkaido Coast, and it is significant at Abashiri (Stn. 3) and Mombetsu (Stn. 2) along the Hokkaido coast in the Okhotsk Sea. The strength of East Sakhalin Current is considered to induce the sea level rise along the Hokkaido Coast in winter. In addition, the high sea level near Abashiri (Stn. 3) in winter significantly depresses the Soya Warm Current.

The gentle sloping rise of sea level occurs from Mera (Stn. 19) to Uragami (Stn. 34) along the southeastern coast of Honshu from June to July. The sea level change along Suruga Bay coast agrees with the vertical mean temperature from the sea surface to 200m depth in the center of the bay. The vertical mean temperature is depressed by the seasonal thermocline

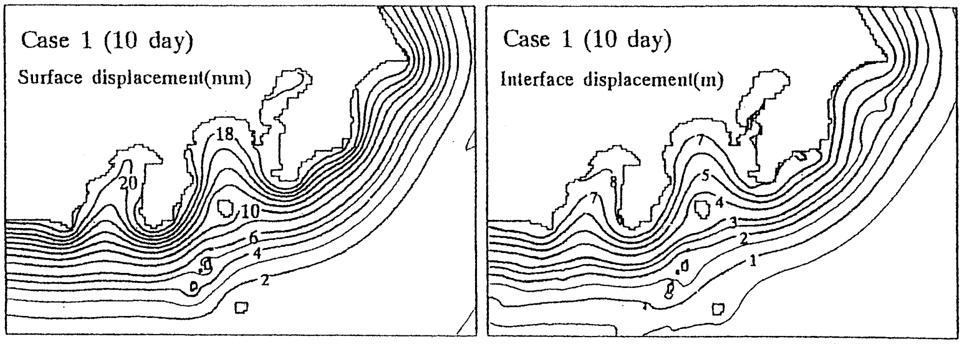

Fig. 10. Amplitude distribution of the sea level (left) and interface (right) displacement after 10 days blowing of $7ms^{-1}$ northward wind calculated by the two layer numerical model (After KITADE and MATSUYAMA, 2000).

ascending in spite of the surface temperature rising in this period. The phenomenon of the seasonal thermocline ascending is called as "secondary minimum of water temperature" by NAKAMURA (1977) and was frequently found in the region from the Boso Peninsula to Kii Peninsula (UNOKI and UNNO, 1983). The coastal upwelling by the northward wind in summer is suggested to induce both the gentle sea level rise and secondary minimum of the water temperature along the southeastern coast of Honshu, Japan.

The gentle sea level rise in the Seto Inland Sea and the southwestern coast of Japan also appears from April to May, but the sea level change slightly disagrees with the temperature change in the surface layer.

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