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Interannual Variations of the Yearly Mean Sea Level around the Japanese Islands

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Abstract

Yearly mean sea level data collected at 24 tidal stations around the Japanese Islands from 1894-1990 were analyzed to study spatial characteristics of interannual variations in the western boundary of the North Pacific Ocean. The time series of mean sea levels displays a long-term trend mainly due to the vertical ground movement and two principal time scales of decadal (about 20 years) and approximately 7 years. Sea level variations with decadal time scale were observed in all areas along the Japanese coast and their phases were almost uniform. A comparison of sea level variations of approximately 7-year time scale with the interannual path variations of the Kuroshio, i.e., meander and straight paths, shows good correlation. The most remarkable sea level rises appeared along the southern coast east of the Kii Peninsula, when the large meander in the Kuroshio was formed. Sea level rise along the coast of northern Japan facing the North Pacific Ocean with small amplitude was just out of phase with that of the southern ones. Of more interest is the precursor sea level rises leading the Kuroshio meander by 3-4 years, which were observed on a large area from the coast of southwestern Japan facing the North Pacific Ocean to the coast facing the Japan Sea.

Key words: Interannual variation, Yearly mean sea level, Japanese Islands, Kuroshio

Introduction

In recent years, numerous articles dealing with observational aspects of the interannual variations of the atmospheric and oceanic systems over the North Pacific Ocean have appeared. Most studies have been based on the sea surface temperature (SST) data (e.g., Iwasaka et al., 1987; Hanawa et al., 1988; Nitta and Yamada, 1989; Tanimoto et al., 1993) or water temperature/dynamic height data from ship observation (e.g., Nitani, 1975; White, 1975; White, 1977; Qiu and Joyce, 1992; Suga and Hanawa, 1995). Our understanding of air-sea interactions has increased during the year. Tanimoto et al. (1993), for instance, showed that the mid-latitude SST anomalies over the North Pacific Ocean exhibits a significant variability with decadal time scale, which is associated with PNA-like anomalies in the troposphere circulation.

The awareness of global warming due to the increase of greenhouse gases and its impact on sea level have made the active research of long-term variations of sea level in the world oceans (e.g., Emery and Aubrey, 1991). Using coastal sea level along the Japanese coast, there are several studies of their long-term variations. Yanagi and Akaki (1994) concentrated on the rising sea level trend during past 97 years (1984-1990), and suggested that the main cause of these long-term trends may be the plate tectonic processes. So, they enhanced that unpredictable vertical ground movements have largely affected coastal sea level. On the other hand, Tsumura (1963) and Nakano and Yamada (1075) carefully analyzed such sea level data for 12 years (1951-1962) and 18 years (1953-1970), respectively, and pointed out the importance of the interannual variations with several years time scale. However, their record lengths were not enough to discuss their periodicities and to regard them as the oceanic phenomena. Kawabe (1987) used sea level difference between Kushimoto and Uragami, which is the most effective index for monitoring the large meander period of the Kuroshio, and revealed that its power spectrum has a small maximum at 6.7 to 8.7-year period. Thus, our present knowledge for the interannual variabilities in sea level around the Japanese Islands is very scarce and has not reached the stage where we can make a comparative study of its offshore hydrographic variations.

Unoki and Isozaki (1965) showed that mean sea level is high on the coast located on the right of the Tsushima

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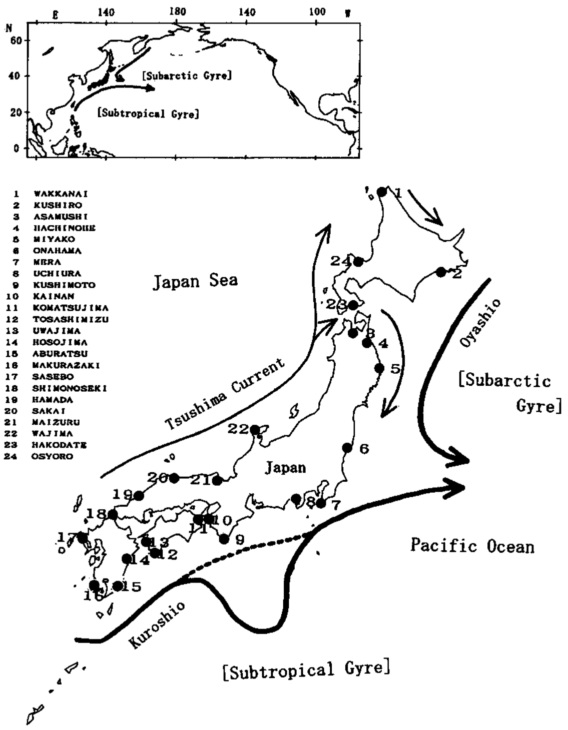

Fig. 1. Locations of 24 tidal stations used in the present study. The current systems around the Japanese Islands are schematically shown. Two types of the Kuroshio path in the region east of the Kii Peninsula, i.e., the straight and meander paths.

Current/the Oyashio and low on the coast located on the left of the Kuroshio, considering the current systems with a geostrophic balance. That is , coastal sea level elevations will be caused not only by the change of the volume of the ocean due to the accumulation and melting of glaciers or the thermal expansion of sea water, but also by the dynamical processes of ocean currents. The typical paths of main currents in the vicinity of Japan, i.e., the Tsushima Current, the Oyashio and the Kuroshio, are drawn schematically in Fig. 1. The subtropical (Kuroshio) and subarctic (Oyashio) gyre meet together just off ten east coast of Japan, and the Tsushima Current flows clockwise mainly along the west coast of Japan. Therefore, we expect that long-term sea level analysis along the Japanese coast will help to produce better understanding for establishing the long-term variability in both gyres in the western boundary of the North Pacific Ocean.

In the present study, we have analyzed the accumulated yearly mean sea level data (1894-1990), based on the observed data at the selected 24 tidal stations along the Japanese coast facing to open oceans, and have discussed following two time scales : the decadal (about 20-year) and approximately 7-year period.

Data

Yearly mean sea level data were published in the "Tables and Graphs of Annual Mean Sea Level along the Japanese Coast" by the Coastal Movements Data Center (CMDC, 1991). Since most tidal stations were taken after the 1950's to the present, the recent 41 years (1950-1990) of sea level data were analyzed to discuss the spatial distributions of interannual variabilities in sea level. We selected 24 tidal stations [1-24] from 116 stations listed in this publication and their locations are shown in Fig. 1.

These selections were strictly performed according to the following requirements. First, Nagoya, Kobe, Osaka and Toba, where the rapid rise of mean sea level was obviously caused by the anthropogenic effects such as a large withdrawal of groundwater (e.g., see Tsumura, 1963), were subtracted. Second, tidal stations within the Seto Inland Sea and Tokyo, Ise, Kagoshima and Ariake bays were also subtracted to avoid the coastal oceanographical phenomena due to the effect of bottom friction, centrifugal force by the local geometry, ununiform distributions of sea water density by an extreme discharge from many small rivers and so on. Among the other stations, we selected only 24 tidal stations that have a secular length longer than 35 years and the numbers of year with no values continuing more than 3 months are less than 7 for the period of 1950-1990. Table 1 shows the beginning of collected sea level data and the period with no yearly mean value continuing for more than 3 months. Sea level data only 5 tidal stations of MERA [7], KUSHIMOTO [9], HOSOJIMA [14], HAMADA [19] and OSYORO [24], whose record length has more than 41 years, were analyzed to verify the periodicities of interannual variations, especially as for the decadal variations. When there is a partial lack of yearly mean sea level data at each station, we linearly interpolated its value with use of data before and after the lacking.

The atmospheric pressure data from 1950-1990 were taken from the "Annual Report of the Japan Meteorological Agency". Yearly mean sea level data are adjusted by the inverse barometric effect using yearly mean atmospheric pressure variations obtained at or in proximity to each tidal station. The meteorological stations are also listed in Table 1. In the present study, the adjusted yearly mean sea level is used as the basic data, and hereafter these data are referred to without the term "adjusted yearly mean".

Table 1. Time span of yearly mean sea level data at 24 tidal stations and the meteorological stations at or in proximity of each tidal station, where atmospheric pressure data are used for the inverse barometric correction

Tide-gauge Station No.	Tide-gauge Station Name	Data Period	Meteorological Station
1	Wakkanai	1955-59, 1961-	Wakkanai
2	Kushiro	1950-81, 1983-	Kushiro
3	Asamushi	1955-	Aomori
4	Hachinohe	1950-63, 1965-	Hachinohe
5	Miyako	1950-	Miyako
6	Onahama	1951-	Onahama
7	Mera	1931-47, 1949-66, 1968-74, 1976-	Katsuura (1950-68) Tateyama (1969-90)
8	Uchiura	1950-	Shizuoka (1950-52) Ajiro (1953-90)
9	Kushimoto	1896-1942, 1950-68, 1970-	Shionomisaki
10	Kainan	1954-72, 1974-	Wakayama
11	Komatsujima	1951-67, 1969-78, 1980-	Tokushima
12	Tosashimizu	1951-	Ashizuri
13	Uwajima	1950-	Uwajima
14	Hosojima	1894-1945, 1947-80, 1982-	Miyazaki (1950-61) Nobeoka (1962-90)
15	Aburatsu	1950-	Aburatsu
16	Makurazaki	1956-73, 1975-	Makurazaki
17	Sasebo	1950-53, 1956-	Sasebo
18	Shimonoseki	1951-52, 1954-86, 1989-	Shimonoseki
19	Hamada	1894-1949, 1950-83, 1985-	Hamada
20	Sakai	1950-62, 1964-	Sakai
21	Maizuru	1950-	Maizuru
22	Wajima	1950-51, 1953-78, 1980-	Wajima
23	Hakodate	1956-75, 1977-	Hakodate
24	Osyoro	1906-45, 1947-	Otaru

Temporal and spatial characteristics of interannual variabilities in sea level

Least-square regressed linear trend

As the eustatic change of the ground level and static response of the pole tide and the nodal tide are considered to be changing slowly and have very small amplitude (see e.g. Nakano and Yamada, 1975), we may neglect these effects. Therefore, the interannual variability in sea level can be regarded as the reflection of (i) the regional characteristics of the air-sea interactions, (ii) the major current systems, and (iii) the crustal movement.

To infer the oceanic phenomena due to (i) or (ii), at first, it will be legitimate to detect the vertical ground movements by the least-square regression method. Figure 2 shows the time series of original sea level and the least-square regressed linear trend at each station. The estimated rate can recognize systematic distribution of sea level trend in spite of some faults being found in respective values. The Okhotsk, Pacific, Philippine and Eurasia plates and the borderlines of four subducting plates roughly coincide with the distribution of the sign of long-term sea level trend. Sea levels at the northern stations have risen on the Okhotsk plate, whereas those at the southern stations have fallen on the Eurasia plate. The similar characteristics has been already investigated by many authors, e.g., Emery and Aubrey (1991), Yanagi and Akaki (1993). But, there are several exceptions: ONAHAMA [6] and OSYORO [24] have the negative rate on the Okhotsk plate, and KUSHIMOTO [9], KOMASTUJIMA [11], UWAJIMA [13], ABURATSU [15], MAKURAZAKI [16] and MAIZYRU [21] have the positive rate on the Eurasia plate. The reason is still unclear and out of the scope of the present study. It should be noted that since these linear trends

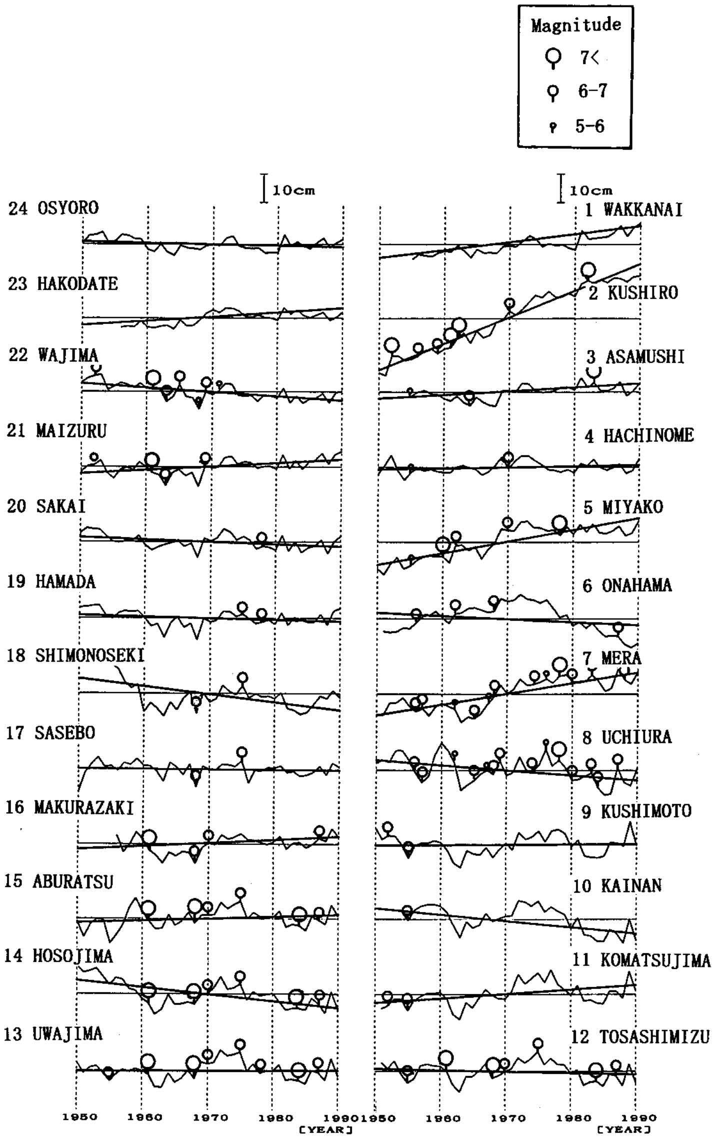

Fig. 2. Variations of yearly mean sea level and the least-squared regression line around the Japanese Islands from 1950–1990. Open circles point to the occurrence year of earthquake more than magnitudes of 5.

also incorporate a climate signal with the time scale more than 41 years, subtraction of the linear trends has been done before the subsequent analysis.

Time scale of interannual variations

It is well known that the activity of earthquake around the Japanese Islands is very high. During an earthquake, the height of the instrument will change abruptly. The earthquake effect is considered to have a limited horizontal scale, supposing their bounds within 400 km diameter in our analysis. The marks of open circle in Fig. 2 indicate the occurrence years of large earthquake more than magnitudes of 5. It is found that the occurrence of large earthquake was irregular with time-intervals from a few years to several ten years, which seem to show that rise and fall of the relative sea level did not always follow the occurrence of the earthquake. Their sea level variations occur rather simultaneously at most stations independent of the earthquake events. We can expect that these simultaneous variations represent the oceanic phenomena of very large horizontal extent. Especially, the decadal variations can be found as a common feature of all the records, i.e., the drop in sea level in the 1960's and 1980's, and the rise in the 1970's. However, there is no denying the fact that the earthquakes occurred on the time scales of 2–4 years at the following tidal stations; KUSHIRO [2], MERA [7], UCHIURA [8], TOSASHIMIZU [12], UWAJIMA [13] and HOSOJIMA [14]. We cannot say that the earthquakes did not influence at all to the relative change of sea level. To take a safety discussion, therefore, we considered having interannual variations

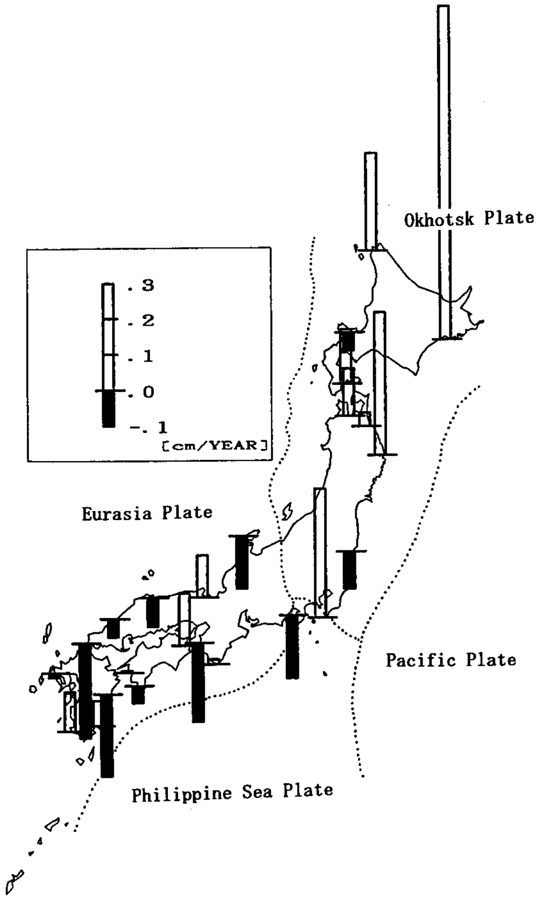

Fig. 3. Estimated mean sea level rise or fall rates for the period 1950–1990 and four plates around the Japanese Islands.

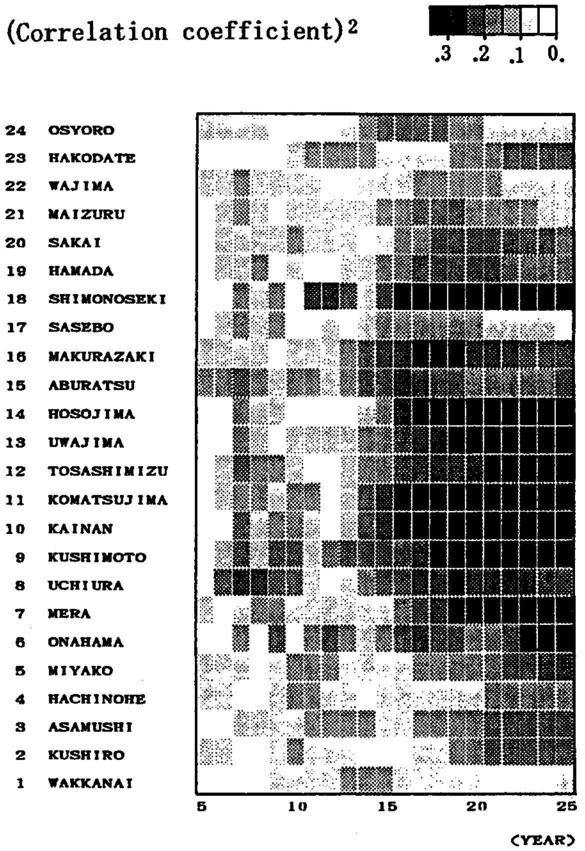

Fig. 4. Squared correlation coefficients among the time series of mean sea level anomaly and the sinusoidal functions from 5 to 25 years period at an interval of one year for each station.

more than 5-year period in the present study.

In order to obtain an outline of the dominant time scales of interannual variations of sea level, we carried out the harmonic analysis and did not use the ordinary spectral analysis because sea level data is not long enough to resolve the decadal variations. At first, the time series of sea level anomalies from the linear trend was corrected for variations of the ground level. Next, the correlation coefficient squared among the sea level anomalies and the sinusoidal function from 5 to 25 years period was calculated at an interval of one year for each station.

The results of correlation for fitting are shown in Fig. 4. Figure 5 is such an example, in which the curves of thin solid lines represent sea level anomalies, and the fitting sinusoidal curves with 20-year period in thick solid lines. From Fig.4, we can detect the relative high correlation peak around 6- to 10-year period and the broader peak more than 15 years. The former peaks at the southern stations [6-22] appear around 7-year period, while those at the northern stations [1-5 and 23] tend to appear as a little shifting to 10-year period. The latter peaks appear at most stations. In the following subsections, we will investigate these two periodicities in detail.

Spatial distributions of variations with 20- and 7-year time scale

The harmonic analysis provides a convenient way to present the spatial characteristics of periodical variations for their information of amplitude and phase derived. In this subsection, the decadal variation more than 15 years was referred to as the 20-year periodicity, and the variations represented by the peak at 6 to 10 years as the 7-year periodicity. The amplitude circles plotted in Figs. 6(a) and 7(a) illustrate the spatial distributions of both variabilities, but except the doubtful results of ONAHAMA [6] and SHIMONOSEKI [18] as discussed later. In phase maps of Figs. 6(b) and 7(b), the stations of [1-17] and [23] are referred to as stations of the North Pacific side, and those of [16-22] and [24] as stations of the Japan Sea side. Then, these two groups distinguished by using the symbols of closed (North Pacific side) and open (Japan Sea side) circles, respectively. Plotting phase value is a lag angle of sea level maxim, measured from the year of 1950.

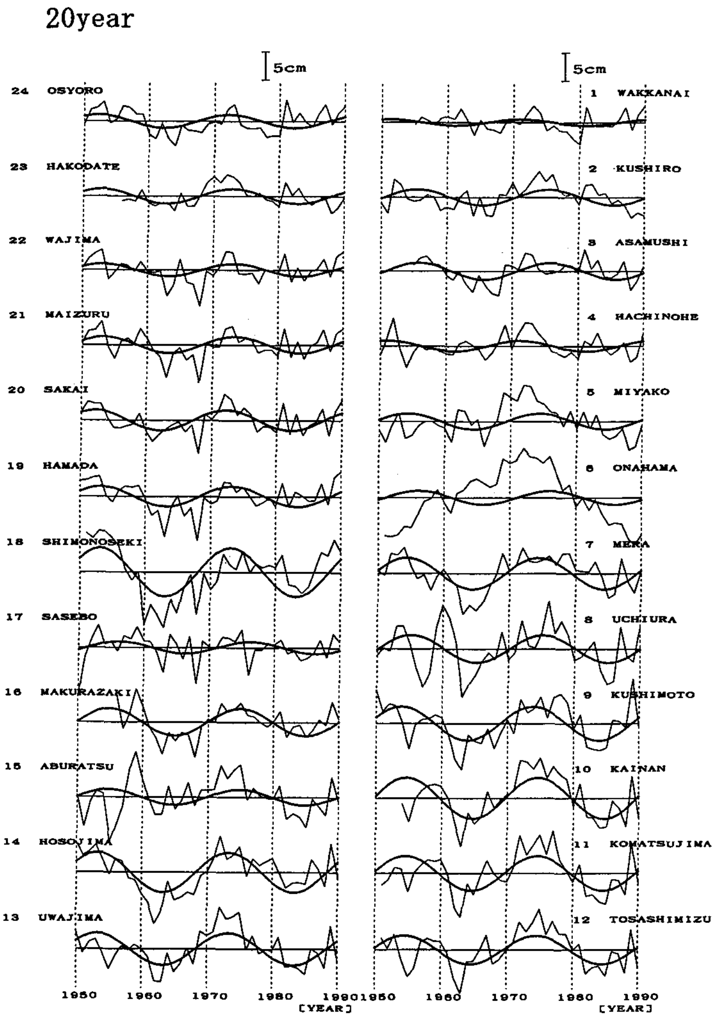

Fig. 5. Variations of yearly mean sea level anomalies from the linear trend corrected for variations of the ground level and the fitting sinusoidal curves with 20-year period.

Before discussing their spatial distributions, the fitting state of a sinusoidal function with 20-year period should be carefully checked in Fig. 5. At ONAHAMA [6], it is evident that the rising sea level trend before 1970 is just canceled by the falling after 1970, and its sinusoidal function is hardly fit for the decadal variations. At SHIMONOSEKI [18], the amplitude of fitting sinusoidal curve is extremely large in comparison with amplitudes at the neighboring stations of SASEBO [17] and HAMADA [19]. Therefore, sea level data at these two stations were out of consideration from the following discussion, because we are concerned to interannual variations of sea level in rather wide area due to the natural ocean phenomena.

Figure 6(a) shows that the amplitude of variations with 20-year period is about 1-2 cm along the coast of northern Japan (Pn, Jn) and the coast facing the Japan Sea (Js), while more than 2-3 cm along the coast of southern Japan facing the North Pacific Ocean (Ps). Figure 6(b) shows that their phases are roughly uniform within about 100° (5.5 years) trough all areas. Indeed, we can readily recognize that the decadal variation seen in Fig. 5 varies in similar manner everywhere. These distributions exhibit well-organized spatial structure on the scale of at least a few thousands of kilometers.

Figure 7(a) shows that the 7-year variability is more energetic in the southern area (Ps-w, Ps-e, Js) with the amplitude of about 1-2 cm, although not as drastically. The amplitude becomes a much smaller along the entire northern coast (Jn, Pn), less than 0.5 cm. Figure 7(b) shows that their phases are largely scattered as compare to those with 20-year period, but there may be somewhat systematic distributions of phase difference. At the eastern area of the Kii Peninsula (Ps-e), the phase most lags behind other stations. At the western (Ps-w) and the Japan Sea (Js, Jn) areas, their phases tend to lead by 60°-100° (1-2 years) from those of Ps-e area. Although the phases of WAKKANAI [1] and KUSHIRO [2] are largely scatted due to a very small fitting amplitude, the variations at another northern stations

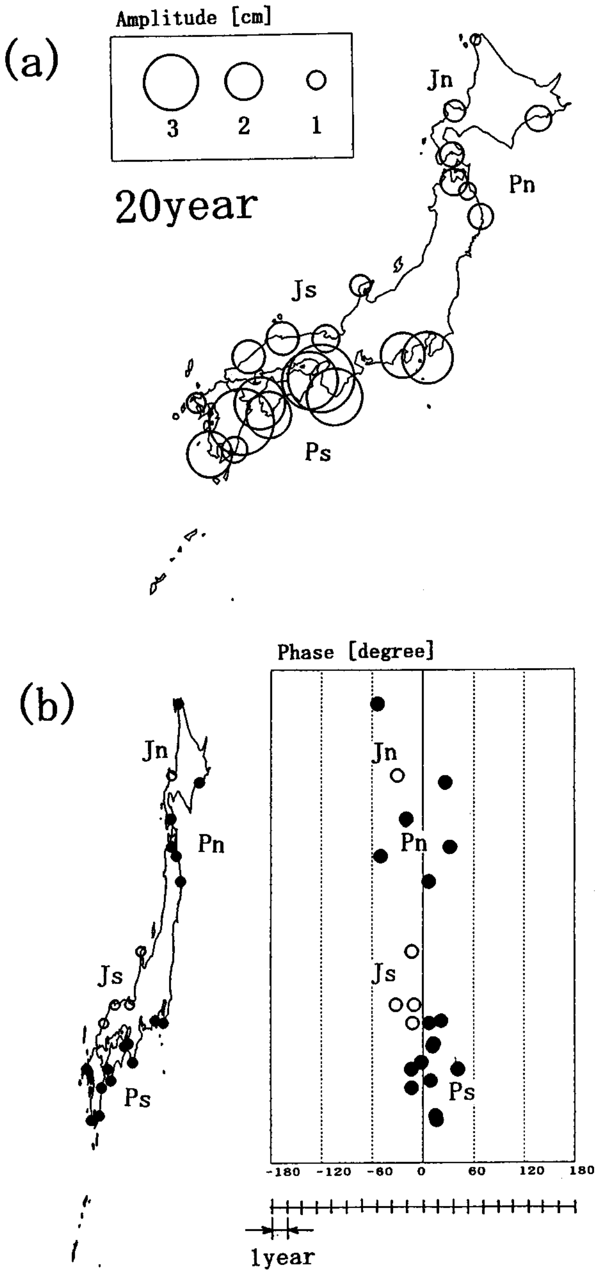

Fig. 6. Spatial distributions of (a) amplitude and (b) phase of the fitting sinusoidal function with 20-year periodicity.

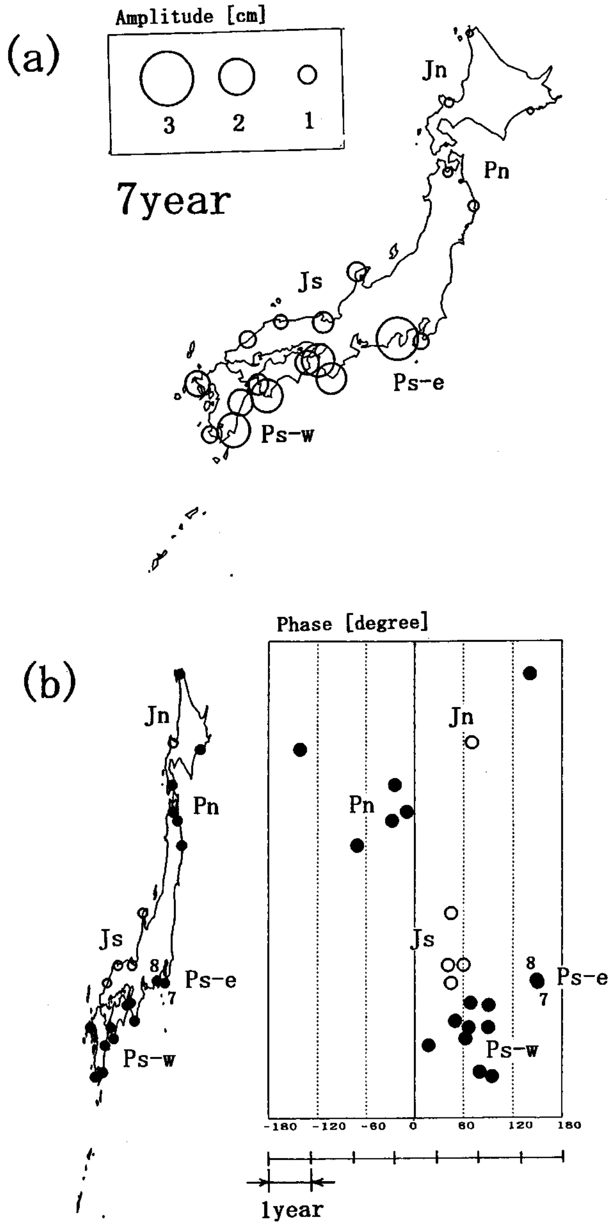

Fig. 7. Same as in Fig. 6, but for with 7-year periodicity.

facing the North Pacific Ocean (Pn) are nearly out of phase with southern ones (Ps-e).

In summary of the harmonic analysis using sea level data from 1950-1990, both interannual variabilities in sea level are systematically too small along the northern coast of Japan, but generally reasonable along the southern coast. From the spatial distributions of phase, the variations with 20-year period are almost uniform, while a large difference among the ambient currents as a control factor. In fact, Kawabe (1987) pointed out that the large meander of the Kuroshio occurs with a primary period of about 20 years and secondary period of 7 to 8.5 years. We will see in the next subsection that the process of such phase difference is a modification of the regional Kuroshio meander.

Temporal and spatial characteristics with 7-year time scale

In the western North Pacific Ocean, the mid-latitude interannual signal is largely represented by the bimodal path variations of the Kuroshio. A straight path denotes the Kuroshio flowing along the south coast of Japan, whereas a meander path denotes that it takes an offshore detour south of the Kii Peninsula (see Fig. 1). In the recent decade, the basic factors in determining

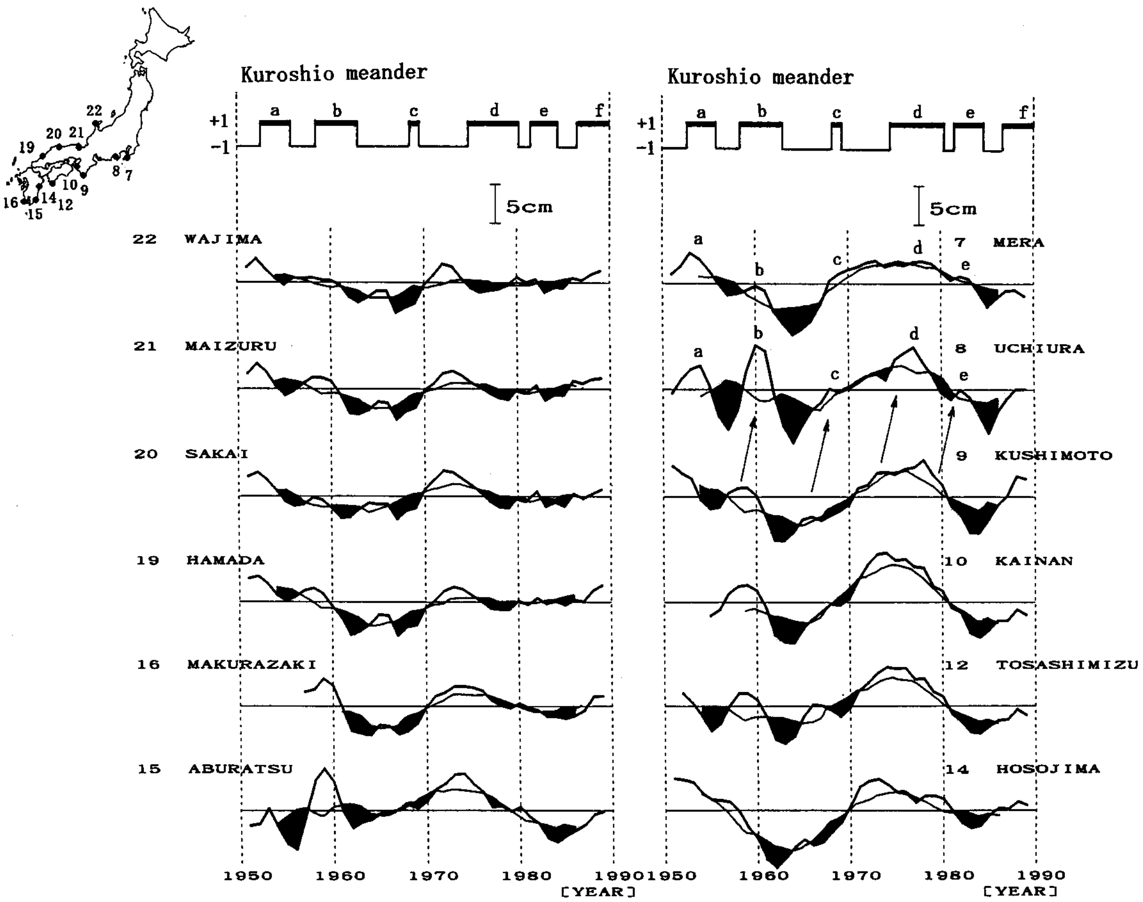

Fig. 8. Two low-passed time series of 3- and 9-year running mean at the southern 12 stations for 41-year period from 1950-1990. The negative 3-year running mean deviation from 9-year running mean is enhanced by the black color at each time series. The periods of Kuroshio meander are marked by black bands and by the numeral (+1) in the top panel, with the small alphabets from [a] to [f].

such a bimodality of the path has been thought to be the interannual fluctuations of the volume transport of the Kuroshio, e.g., Masuda (1982), Yasuda et al. (1985), Yoon and Yasuda (1987). It has been also known that the presence of such Kuroshio meander, which persists for several years, can be detected using coastal sea level data from south coast of Japan, e.g., Moriyasu (1961), Kawabe (1980) and Kawabe (1985).

To examine temporal and spatial variations with 7-year time scale along the southern coast of Japan, sea level anomalies presented in Fig. 8 are two low-passed time series of 3- and 9-year running mean at 12 representative stations, together with the period of Kuroshio meander. That is, sea level difference in the 3-year running mean deviation from the 9-year running mean indicates the temporal variations with 7-year time scale. The negative deviation is enhanced by the black color at each time series. During our analyzed period, a remarkable meander of the Kuroshio occurred 6 times in 1953-1955, 1959-1963, 1968, 1975-1980, 1982-1984, 1987-. These periods are marked by black bands in the top panel, with the small alphabets from [a] to [f].

The prominent feature commonly seen in all records is the sea level rises in 5 or 6 times during the analyzed period, although the variations of this time scale have significant amplitude before 1970, rather than after 1970. A comparison of the occurrence year of these sea level rises with the period of Kuroshio meander suggests roughly positive correlation, especially at MERA [7] and UCHIURA[8]. That is, remarkable sea level rises at both stations well correspond to the time just when the large meander in the Kuroshio was formed. This implies that when the Kuroshio axis moves to onshore (offshore) due to the straight (meander) path, its geostrophic current lowers (heightens) the coastal sea level.

The similar variations with 7-year time scale, however, can be seen at the remained 14 stations including area facing to the Japan Sea. It seems that their sea level rises tend to lead by several years from the period of Kuroshio meander. To study such lag-distributions, the cross-correlation coefficients between the period of Kuroshio meander and the band-passed time series of

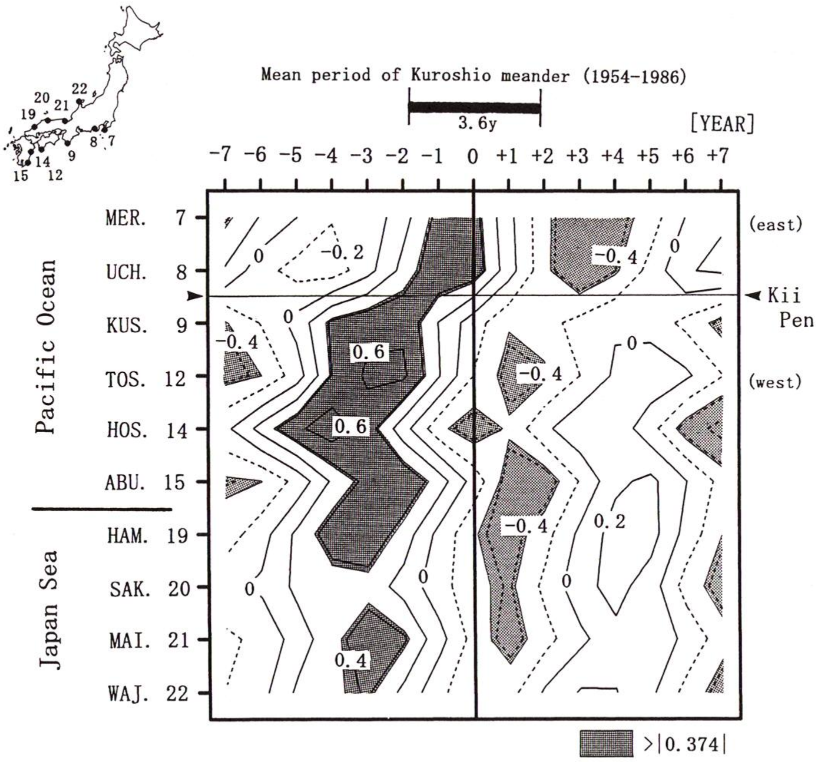

Fig. 9. Cross-correlation coefficients between the period of Kuroshio meander and the band-passed time series of sea level (3-9 years). Shaded regions indicate the coefficient value more than 0.374, which is beyond the 95% confidence level.

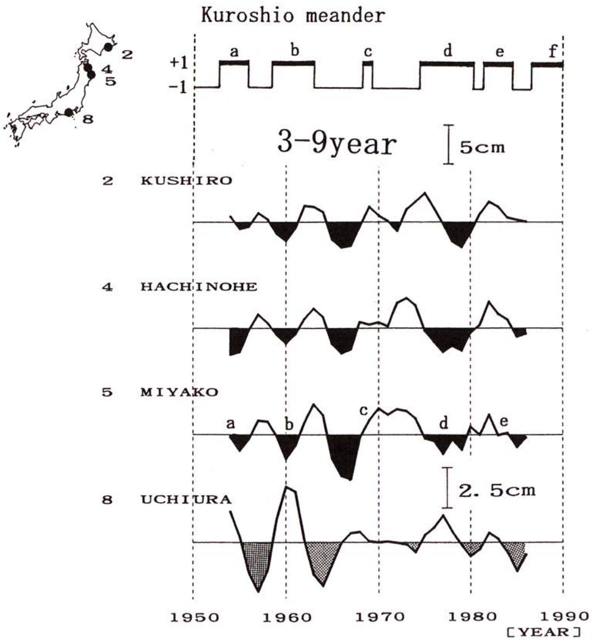

Fig. 10. The band-passed time series of sea level (3-9 years) for 41-year period from 1950-1990 at KUSHIRO [2], HACHINOHE [4], MIYAKO [5] and UCHIURA [8]. The periods of Kuroshio meander are marked by black bands and by the numeral (+1) in the top panel, with the small alphabets from [a] to [f].

sea level (3-9 years) were calculated (Fig. 9). In this calculation, the occurrence year for Kuroshio meander/straight path is counted as numeral of +1/−1, respectively. That is, the interannual path variations of the Kuroshio are represented by the time series of the Walsh (step) function. Mean period of Kuroshio meander during 1984-1986 is about 3.6 year. Figure 9 shows that no significant time lag is found between the sea level rise at MERA [7] and UCHIURA [8] and the Kuroshio meander, whereas sea level rises at another tidal stations simultaneously lead by 3-4 years from the period of Kuroshio meander. Thus, we can recognize a distinct time lag between both sides of the Kii Peninsula.

Figure 10 shows the band-passed time series of sea level (3-9 years) along the northern coast facing to the North Pacific Ocean, i.e., KUSHIRO [2], HACHINOHE [4], MIYAKO [5], for comparison with that at UCHIURA [8]. As is seen in the phase distribution of Fig. 7(b), the variations along the northern area are obviously out of phase with those along the southern area.

The periodicities of variations with decadal and 7-year time scale

Because the analyzed time series (41 years) discussed above are relative short, nothing can be said whether the period of interannual variations of sea level, especially for the decadal time scale, really reflects an oscillatory behavior or not. So, sea level data at the following 5 tidal stations were reexamined to verify the periodicities of both interannual variations. The record lengths of MERA [7], KUSHIMOTO [9], HOSOJIMA [14], HAMADA [19] and OSYORO [24] are 60, 95, 97, 97, and 85 years, respectively (see Table 1 in detail).

Figures 11(a) and (b) show the band-passed time series for the 9-25 and 3-9 years, respectively. These band-passed sea level variations could not be adjusted by atmospheric pressure variations, because atmospheric pressure data before 1950 are not obtained from "Annual Report of the Japan Meteorological Agency". For comparison, yearly mean atmospheric pressure from 1959-1990 is shown together (solid thin line). While the sea level amplitudes of both interannual variations are more than 1-2 cm, yearly mean atmospheric pressure induces the sea level change by less than 1 cm except for OSYORO [24]. At this northern station, the apparent interannual signal of atmospheric pressure seems approximately in phase with the sea level variations. Such atmospheric pressure has the sense to more amplify both interannual variations of sea level. Therefore, we may ignore the effect of atmospheric variations to alter the interannual periodicities in sea level.

The decadal time series for the 9-25 years band-passed data commonly displays positive value in the 1910's, 1930's (1925-1935), 1950's and 1970's (Fig. 11(a)). It is also found that dominant amplitudes along the southern coast facing to the North Pacific Ocean as shown in Fig. 6(a) are not representative, since such feature are limited to the period after 1950 only (see the time series of KUSHIMOTO [9] or HOSOJIMA [14]). Within 80 years from 1906-1985, the remarkable rises in the band-passed sea level for the 3-9 years regularly occurred 11 times (Fig. 11(b)), i.e., we can estimate the periodic time interval to be about 7.3 years.

Summary

Yearly mean sea level data collected at 24 tidal stations around the Japanese Islands from 1894-1990 were analyzed to study spatial characteristics of interannual variations in the western boundary of the North Pacific Ocean. The time series of mean sea levels displays a long-term trend mainly due to the vertical ground movement and two principal time scales of decadal (about 20 years) and approximately 7 years.

Sea level variations with decadal time scale were observed in all areas along the Japanese coast and their

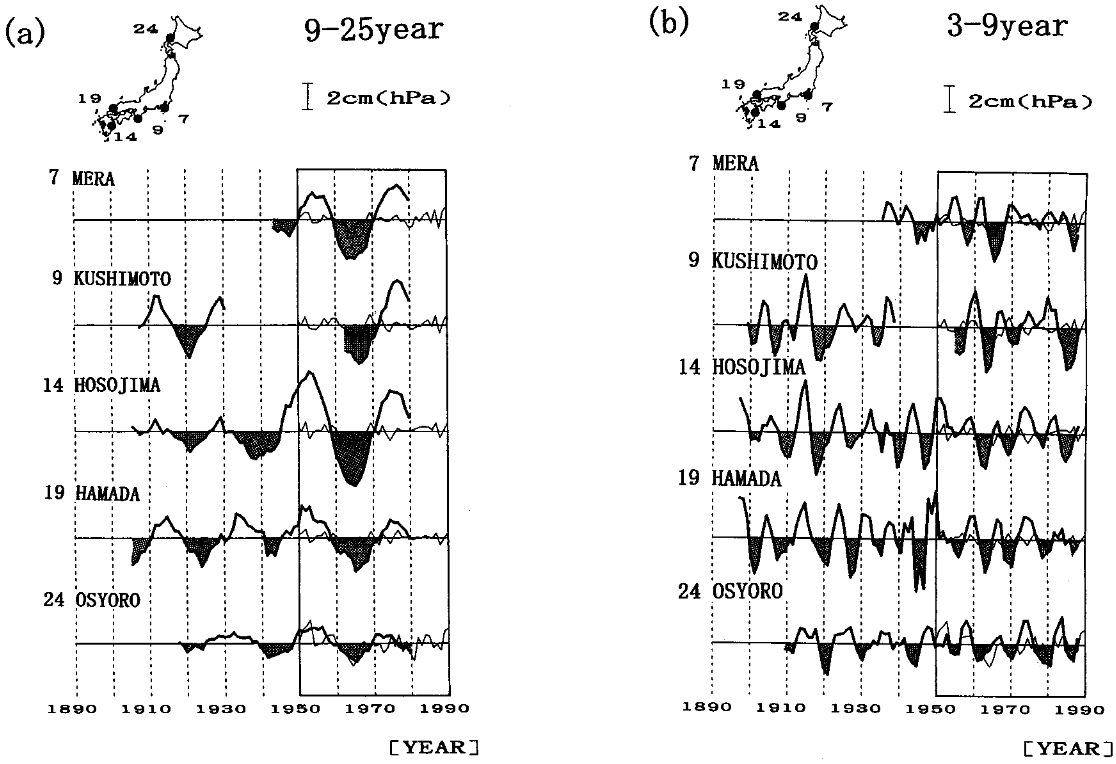

Fig. 11. The band-passed time series of sea level (a) for the 9-25 years and (b) for the 3-9 years at MERA [7] (60 years), KUSHIMOTO [9] (95 years), HOSOJIMA [14] (97 years), HAMADA [19] (97 years) and OSYORO [24] (85 years). These sea level variations are not adjusted by atmospheric pressure variations. For comparison, yearly mean atmospheric pressure from 1950-1990 is shown together as the solid thin line.

phases were almost uniform. That is, this time scale variations exhibit well organized spatial structure on the scale of at least a few thousands of kilometers. After the 1950's to the present, its amplitude along the southern coast facing to the North Pacific Ocean tends to be larger than before.

Sea level variations with about 7-year period were closely related with interannual path variations of the Kuroshio. The remarkable sea level rises were occurred 5 times during the analyzed period from 1950-1990. Their sea level amplitudes are small along the northern coast of Japan, but relatively large along the southern coast. The most remarkable rise seems to appear along the coast east of the Kii Peninsula, when the large meander in the Kuroshio was formed. Along the coast of northern Japan facing the North Pacific Ocean, the similar rises with a small amplitude occurred, but when the Kuroshio had the straight path. From the above relationship for 7-year time scale, we speculate that the coastal sea level facing each subtropical and subarctic gyre tends to have fluctuated out of phase with one another. Of more interest is the precursor sea level rises leading Kuroshio meander by 3-4 years, which were observed on a large area from the coast of southwestern Japan facing the North Pacific Ocean to the coast facing the Japan Sea.

At the present stage, we have no idea of the physical nature of the above interannual variabilities in sea level. We hope that our results will give some useful information to understand the dynamical processes of the interannual variations in the North Pacific Ocean.

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