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Daily Mean Sea Level and Atmospheric Pressure Along the Coasts of the Northwestern Pacific Ocean

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Daily mean sea level variability and its response to atmospheric pressure along the coasts of the northwestern Pacific Ocean are investigated. Daily values of sea level and atmospheric pressure covering the period 1976-1986 from 72 stations are analyzed. The sea level and the air pressure in all the data set have a definite seasonal signal, and higher frequency oscillations at time scales of several days to several weeks are also observed. Among the short-period oscillations of sea level with periods shorter than six months, the period of around 3 or 4 months is dominant in most study stations. According to the statistical analysis of sea level and air pressure, the length scale of sea level variability is smaller than that of air pressure for the present study area. The overall variability of sea level is found to be the smallest around Hokkaido, Japan and the largest in the China coasts. Large short-period (< 6 months) sea level variability is found in the southern coasts of China and Hokkaido, and large long-period (> 6 months) variability in the southern coasts of Japan and Korea along Tsushima Current and Kuroshio. The patterns of air pressure are very similar to those of sea level. The air pressure field is found to account for 31% of the overall sea level variability in the study area. Considering the fact that the results (40%) of Pang and Oh (1995) were obtained through monthly sea level, the present result implies that the short-period sea level variability is less affected by air pressure. Generally the sea level response to air pressure are found to be isostatic, but significantly nonisostatic for the periods around 4 months and for those of 2 to 4 days. In particular, nonisostatic response for higher frequencies seem to be due to the restrictions to water transport necessary for barometric response in the Korea Strait.

INTRODUCTION

The variability of sea level using monthly averaged series of sea levels has been extensively studied for the coasts of the Northwestern Pacific Ocean (Yi, 1967; Won, 1991; Oh *et al.*, 1993; Oh and Park, 1994; Pang and Oh, 1994, 1995). Oh and Park (1994) reported that in sea level fluctuations of the northeastern Asia the dominant period of the first mode is seasonal, and the interannual average for each month shows a typical seasonal variation in which February is the minimum and August is the maximum. Oh *et al.* (1993) also showed that seasonal oscillations are most dominant in the sea level variations of the East Sea, and the semiannual oscillations are also observed. Pang and Oh (1995) found that the sea level variations by oceanic causes are the largest in the coasts along the Tsushima Current, and becomes small in the distant area.

Monthly mean sea levels are suitable and accessible data in investigation of climatic ocean variations. With monthly sea level, however, it is not possible to study the shorter time variations than seasonal scale. It is known that higher frequency oscillations at time scales of several days (synoptic variability) or several weeks are also present in sea level time series, and their amplitudes are comparable to those of seasonal signal (Lascaratos and Gacic, 1990). There have been more studies on the short-period variability of sea level (Garrett and Majaess, 1984; Lascaratos, 1990; Tsimplis and Vlahakis, 1994). For the coasts of the Northwestern Pacific Ocean, however, there is little attempt to study such a short-period variability. It motivates us this study and we will focus on short-period oscillations with the scales ranging from 2 days to several months, but shorter than the seasonal variation.

In addition, it is of some scientific interest to establish how the sea level responds to changing atmospheric pressure. The response of sea level to

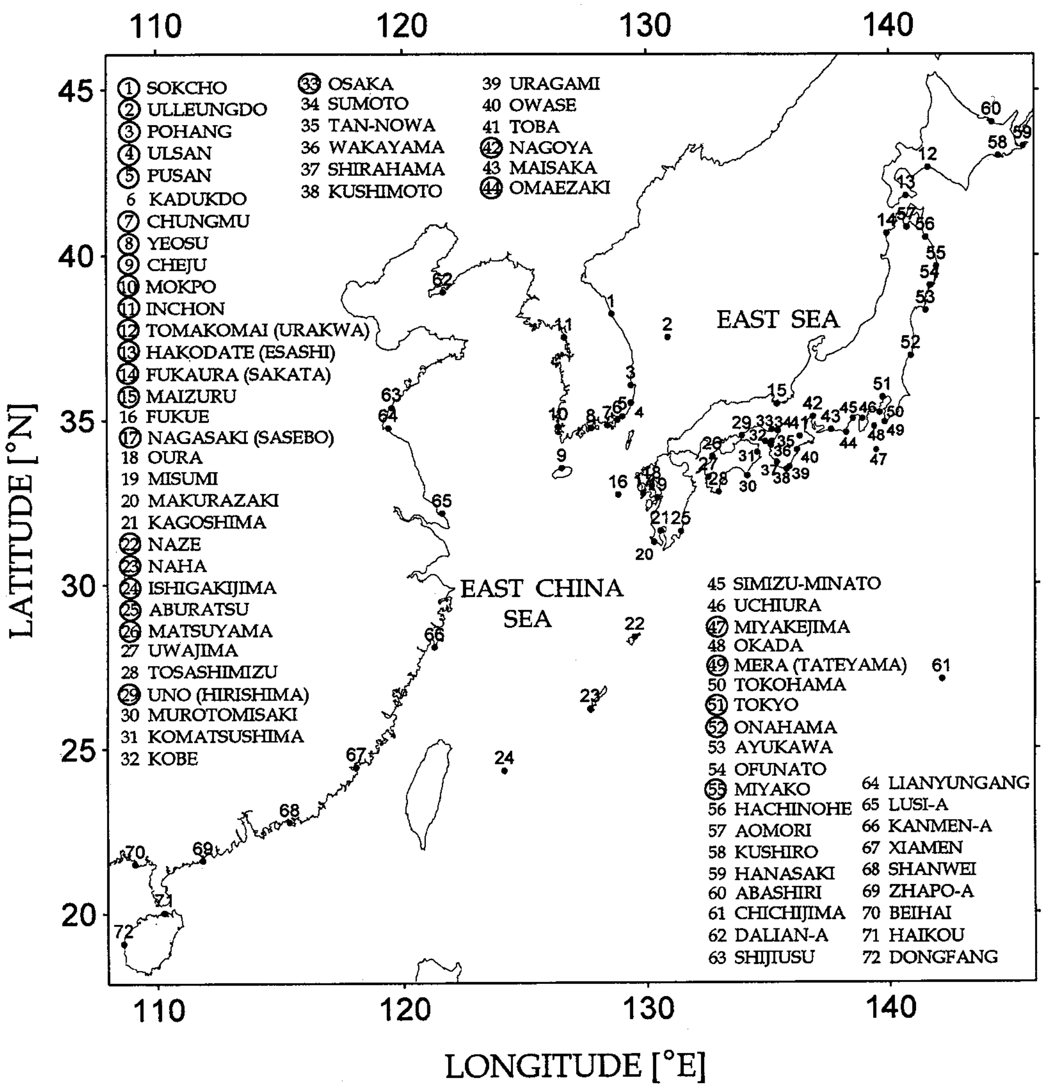

Fig. 1. The locations of sea level and atmospheric pressure sampling points. All stations have tide-gauge. The numbers surrounded by circle represent the positions having both of the tidal and meteorological data. The stations in round bracket means meteorological stations close to tidal stations.

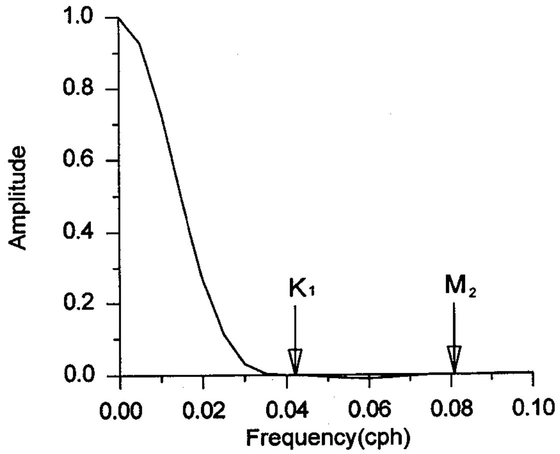

Fig. 2. Amplitude response of the $A_{24}{}^2A_{25}/(24^2 \times 25)$ tide-killing filter (see Godin, 1972).

atmospheric pressure is indicated by inverse barometric effect according to the basis of hydraulic theory (Chelton and Davis, 1982). Papa (1978) pointed out that in the Adriatic and other parts of Mediterranean, sea level variations at time scales from one to ten days were primarily due to atmospheric pressure changes related to synoptic atmospheric disturbances. Orlic (1983) explained that sea level variations at time scale from ten days to several weeks were due to atmospheric planetary waves. In specific area, however, the barometric response of sea level does not happen in all frequencies. Garrett (1983) and Palumbo (1982) discussed nonisostatic response of sea level to atmospheric pressure in the Eastern Mediterranean, and

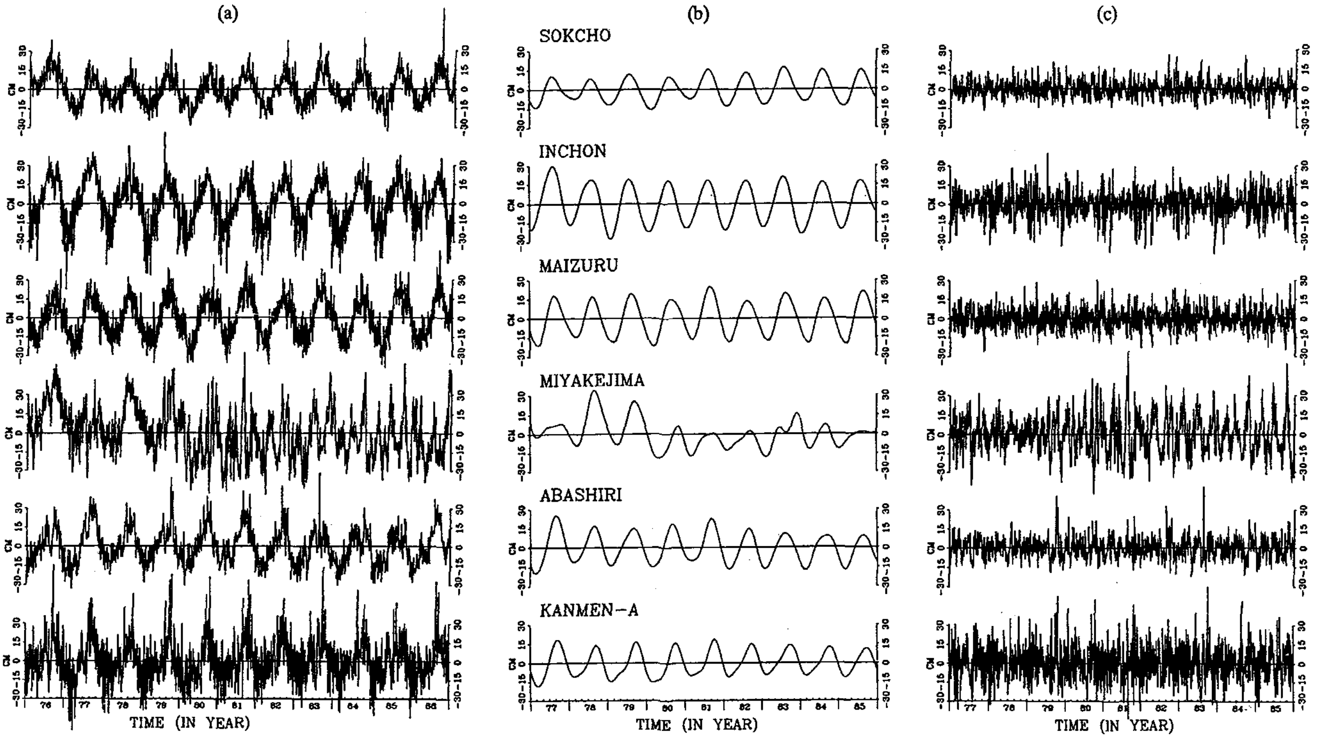

Fig. 3. Time series of daily mean sea level at 12 stations. (a) unfiltered values, (b) 6-month low-pass filtered values, and (c) 6-month high-pass filtered values.

showed that this was due to either local winds or to the restrictions at straits to water transport between basins. On the other hand, along the coasts of the northwestern Pacific Ocean, Pang and Oh (1995) showed that atmospheric pressure field accounts for 40% of monthly mean sea level variation. This was an only attempt for the area to study sea level response to atmospheric pressure.

This study focuses on high-frequency sea level response to atmospheric pressure which can not be explained by the monthly mean data set. The main purposes of this study are to examine the short-period variability of sea level and investigate its response to atmospheric pressure along the coasts of the northwestern Pacific Ocean.

DATA

The sea level data used in this study are hourly values and atmospheric pressure data are daily mean values covering the period 1976-1986. Sea levels have been collected at 72 stations around Korea, Japan and China (see Fig. 1). Unfortunately up to now, we could not get such data from Russian coast. The tidal signals from the hourly sea levels have been removed by use of the low-pass filter $A^2_{24}A_{25}/(24^2\ 25)$, where A_n is a spectrum of the arithmetic summation of n consecutive observations. Amplitude response of this function is shown in Fig. 2.

The atmospheric pressure data come from 30 stations around Korea and Japan, but no data from China. The numbers surrounded by circle in Fig. 1 show the positions having both of the tidal and meteorological data. For the atmospheric pressure of the stations, Urakawa, Sakata, Sasebo, Hiroshima, Tatetama and Mombetsu, we used the nearby stations', Tomakomai, Hakodate, Nagasaki, Uno, Mera, and Abashiri, respectively.

SEA LEVEL VARIABILITY

The typical time series of the sea level for 11 years are shown in Fig. 3(a). Sea levels have a definite seasonal signal in all the time series. It also shows short-period variations at the time scale of several days to several weeks. In order to study long and short period separately, each data set is filtered. Fig. 3(b) and (c) are the sea level oscillations with the periods shorter than six months and longer than ones. Their variance is 36% and 64% of total sea level variance, respectively.

According to the spectral analysis of sea level,

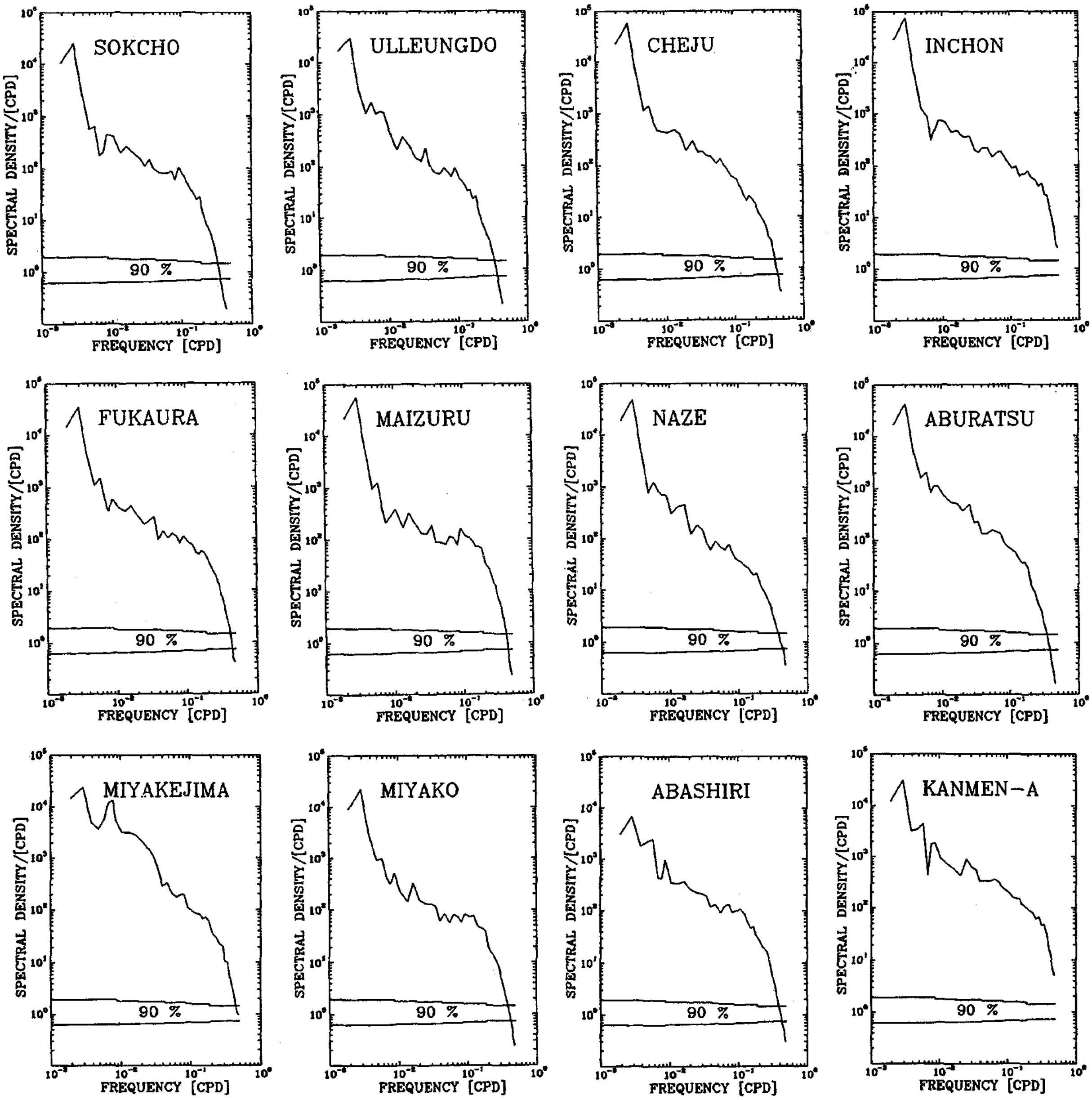

Fig. 4. Spectra of the unfiltered daily mean sea level.

the spectral energy density is large in the frequency range below 0.1 cycles per day (cpd) and the annual peaks are strongly prevailed for all stations (see Fig. 4). Some spectral peaks in a few stations are also observed at frequencis of 2, 3 and 4 cycles per year. After removing the annual and semiannual signals, major peaks are mostly found at the periods around 3 or 4 months as expected. Other spectral peaks such as 2 months, 1 month, and 2 weeks are found, but they are much weaker. Specially, the energy level for Miyakejima at 3 cpy is one order higher than that for the other stations. The known reason is that Miyakejima is an island apart from the mainland coast, and thus it is easy to be affected by the Pacific Ocean (Pang and Oh, 1994).

Some basic statistical analysis such as RMS deviations and variances are done for all tidal stations. RMS deviations of the unfiltered sea level range from 7.7 to 24.9 cm. They are the smallest (<10 cm) around Hokkaido and the largest (>20 cm) in the China coasts (see Fig. 5). The relative portion of the short-period and long-period oscillations in total energy budget of sea level changes were estimated as

$$R_{low} = \frac{\sigma_{low}^2}{\sigma^2} \times 100, \quad R_{high} = \frac{\sigma_{high}^2}{\sigma^2} \times 100 \qquad (1)$$

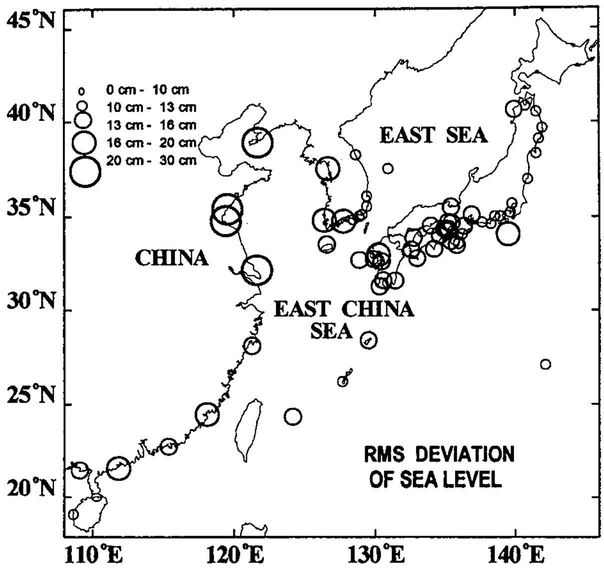

Fig. 5. RMS deviation of daily mean sea level at 72 stations.

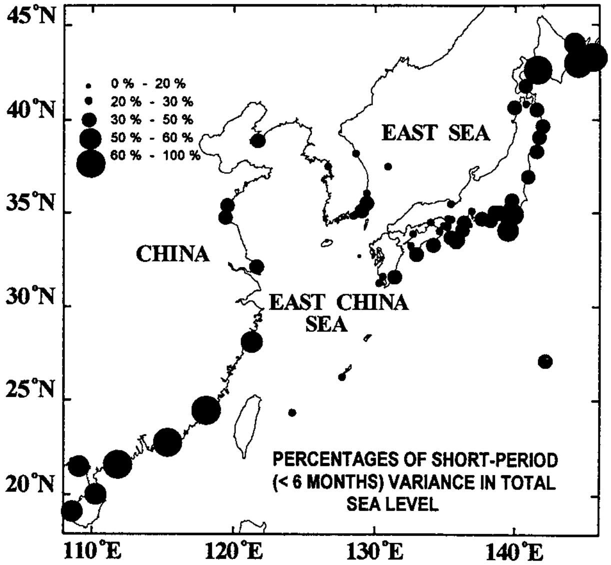

Fig. 6. Percentages of short-period (<6 months) variance in total sea level oscillations.

where σ^2 is the variance of the unfiltered sea level, σ^2_{low} and σ^2_{high} are the variance of the filtered sea level using 6-month low-pass and high-pass filter, respectively. The percentage of short-period variance in total variance of sea level oscillations is large (>60%) in the southern coasts of China and around Hokkaido, and small (<30%) in most of coasts of Korea and in the Japanese coasts along the Kuroshio current (see Fig. 6). In case of the long-period variations, the percentage is large in the southern coasts of Japan and Korea along the Tsushima Current and Kuroshio (see Fig. 7). This distribution suggests that the major long-period variations are related in some way with the Tsushima Current and Kuroshio. The monthly mean RMS deviations of high-pass filtered sea level can be estimated as

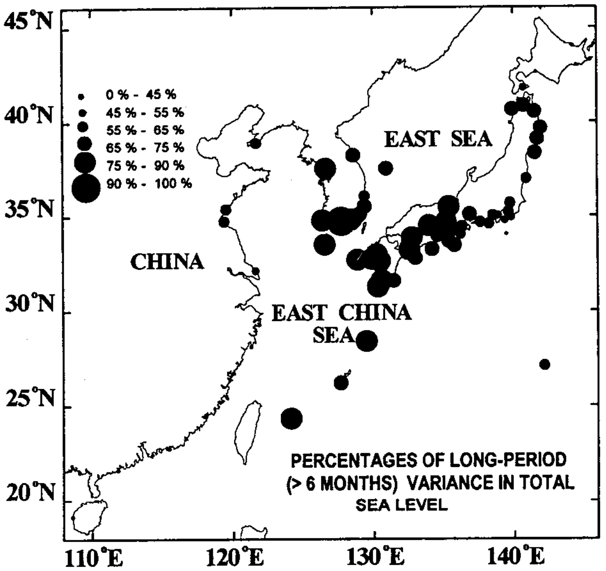

Fig. 7. Percentages of long-period (>6 months) variance in total sea level oscillations.

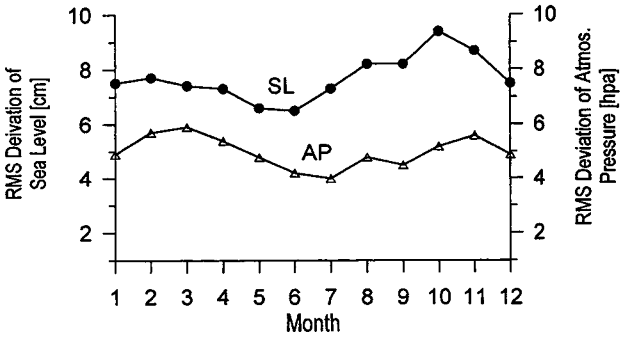

Fig. 8. Monthly mean RMS deviations of high-pass filtered sea level and atmospheric pressure. They are average values of all stations.

$$\sigma_j = \left[\frac{1}{MN} \sum_{k=1}^{N} \sum_{i=1}^{M} (\eta_{ijk} - \overline{\eta_{ijk}})^2 \right]^{1/2} \qquad (2)$$

where j=1, 2, ..., 12 denotes the month, N is the number of years, M is the number of days in each month, η_{ijk} is an individual daily sea level, $\overline{\eta_{ijk}}$ is monthly averaged sea level. They are high in October and November, and low in May and June (see Fig. 8).

ATMOSPHERIC PRESSURE EFFECT

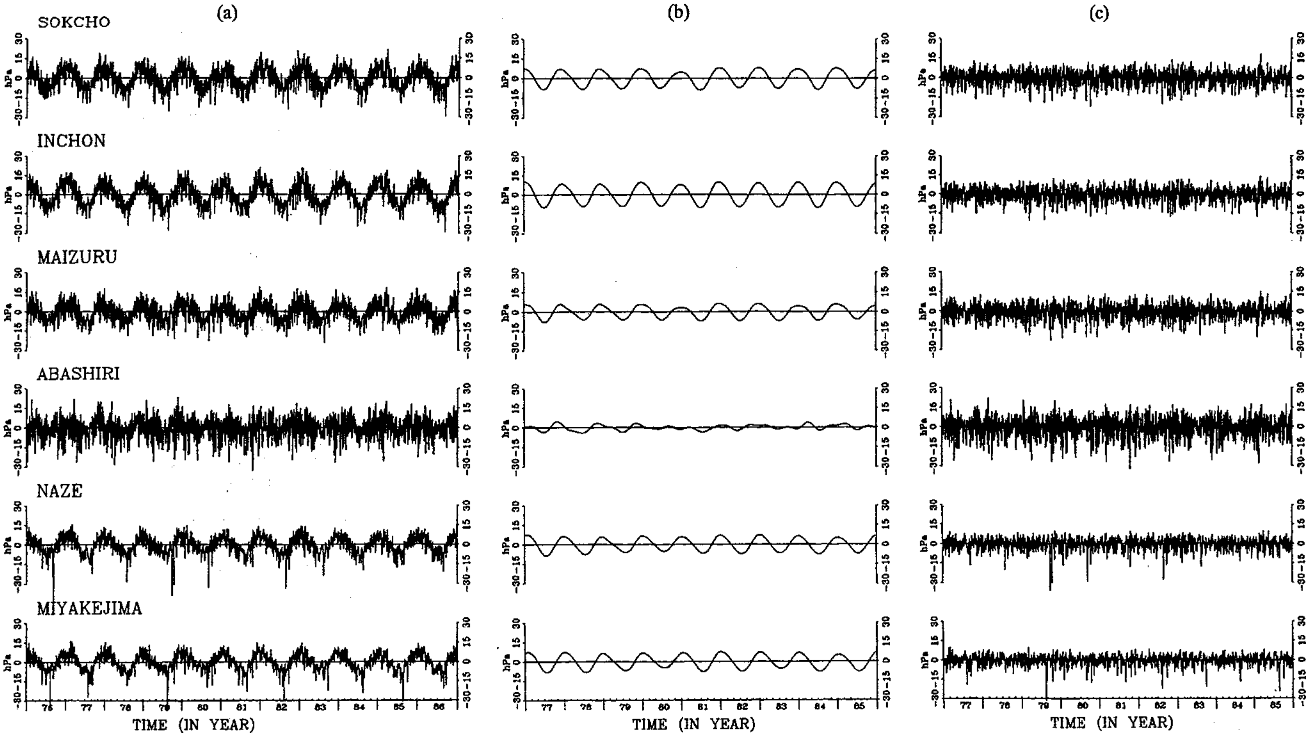

Fig. 9. Time series of daily mean atmospheric pressure at 6 stations. (a) unfiltered, (b) 6-month low-pass filtered, and (c) 6-month high-pass filtered values.

The typical time series of the daily mean atmospheric pressure for the 11 years at 30 stations are shown in Fig. 9. The atmospheric pressure patterns are similar to those of sea levels in a view of having a significant seasonal signal but it has a better regularity than the sea levels. Both high and low frequency variations of air pressure are approximately opposite in phase to the respective sea level variations. Their RMS deviations range from 6.1 to 8.1 *hPa*. It is the smallest in Miyakejima and the largest in Inchon, but the difference between them is not big (see Fig. 10). This means that the length scale of the air pressure variabilities is bigger than that of the sea level variabilities.

In Fig. 11, the percentages of short-period variance in total variance of air pressure oscillations are large (>75%) in the northeastern coasts of Japan and around Hokkaido, and small (<45%) in most of the Korean coasts and in the southern coasts of Japan. Fig. 12 shows the case of the long-period variations. These distributions have very similar patterns with those of sea level. They also suggest that both long and short period sea level variations are highly related in air pressure variations. The monthly mean RMS deviations of high-pass filtered air pressure are high in October and November, and low in June and July. This patterns are similar to those of sea level, but the months of maximum and minimum are not same.

Assuming isostatic response of sea level in all frequencies, we can estimate the barometric response of sea level variations at 30 stations as shown in Table 1. The ratio is large (>0.4) in the eastern coasts of Korea and Japan including around Hokkaido, and its average value is 0.31. This means that

Table 1. Inverse barometric effect in total sea level variation

Stations	Ratio	Stations	Ratio
Sokcho	0.43	Nagasaki	0.26
Ulleungdo	0.32	Naze	0.19
Pohang	0.44	Naha	0.23
Ulsan	0.51	Ishigakijima	0.23
Ousan	0.47	Aburatsu	0.20
Chungmu	0.38	Matsyama	0.21
Yeosu	0.20	Uno	0.19
Cheju	0.26	Osaka	0.30
Mokpo	0.18	Nagoya	0.10
Inchon	0.23	Omaezaki	0.44
Abashiri	0.54	Miyakejima	0.38
Tomakomai	0.26	Mera	0.40
Hakodate	0.20	Tokyo	0.44
Fukaura	0.19	Onahama	0.57
Maizuru	0.21	Miyako	0.60
Average : 0.31			

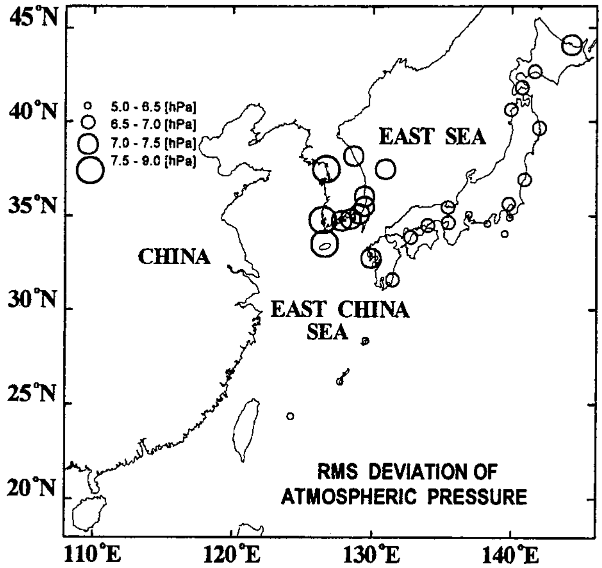

Fig. 10. RMS deviation of daily mean atmospheric pressure at 30 stations.

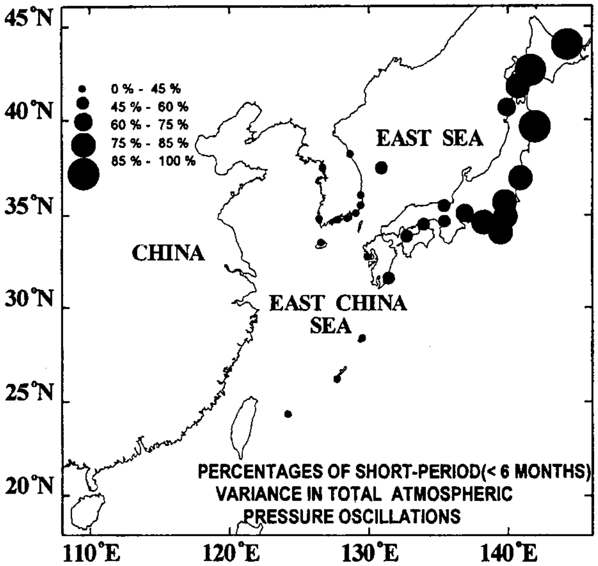

Fig. 11. Percentages of short-period (<6 months) variance in total atmospheric pressure oscillations.

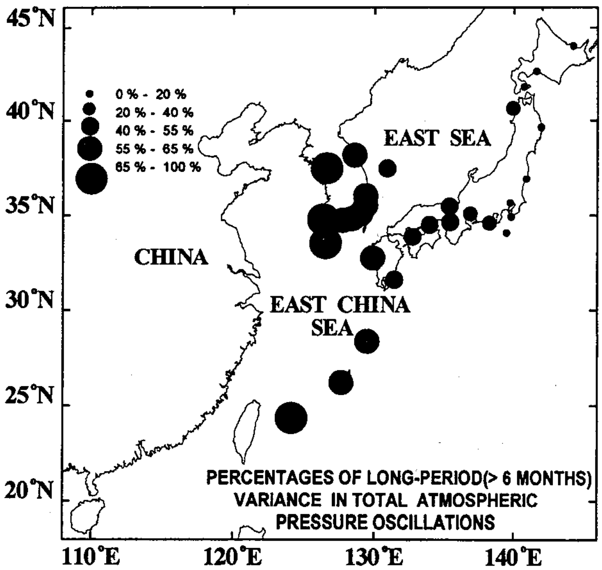

Fig. 12. Percentages of long-period (>6 months) variance in total atmospheric pressure oscillations.

the atmospheric pressure field accounts for 31% of the overall sea level variability in the study area.

NONISOSTATIC RESPONSE TO ATMOSPHERIC PRESSURE

In order to find out coherent signals in sea level and air pressure, we calculated coherence between them. As can be seen in Fig. 13, the sea level response to air pressure is found to be frequency-dependent. It has high coherence in most frequencies, but significantly low (< 0.4) for the periods around 4 months and for those of 2 to 4 days in some stations. This means that the sea level does not barometically respond to air pressure at these specific periods. Generally, nonbarometric response in sea level variations can be attributed to steric effects, to wind influence and to physical restrictions imposed by straits (Garrett, 1983). Nonisostatic response for the periods of 2 to 4 days in the study area is found to be in most coasts along the East Sea and near the Korea Strait as shown in Fig. 14. If the Korea Strait plays a major role in limiting for the response of the East Sea water to atmospheric pressure, quick barometric response of sea level may not be possible in the East Sea. Garrett (1983) showed the response of the Mediterranean to atmospheric pressure is limited by the Strait of Gibraltar and this prevents an isostatic response at some sufficiently high frequency. He defined a critical dimensionless parameter, which shows whether or not the geostrophic control imposes constriction to water flow through a strait. From the expression for the parameter we have defined the order of the time scale which is an estimate of the upper limit above which geostrophic control does not impose flow constriction. In that case, the flow is sufficient to permit an isostatic response of the basin. This time scale is expressed by the following relationship

$$T = \frac{Af}{gH} \tag{3}$$

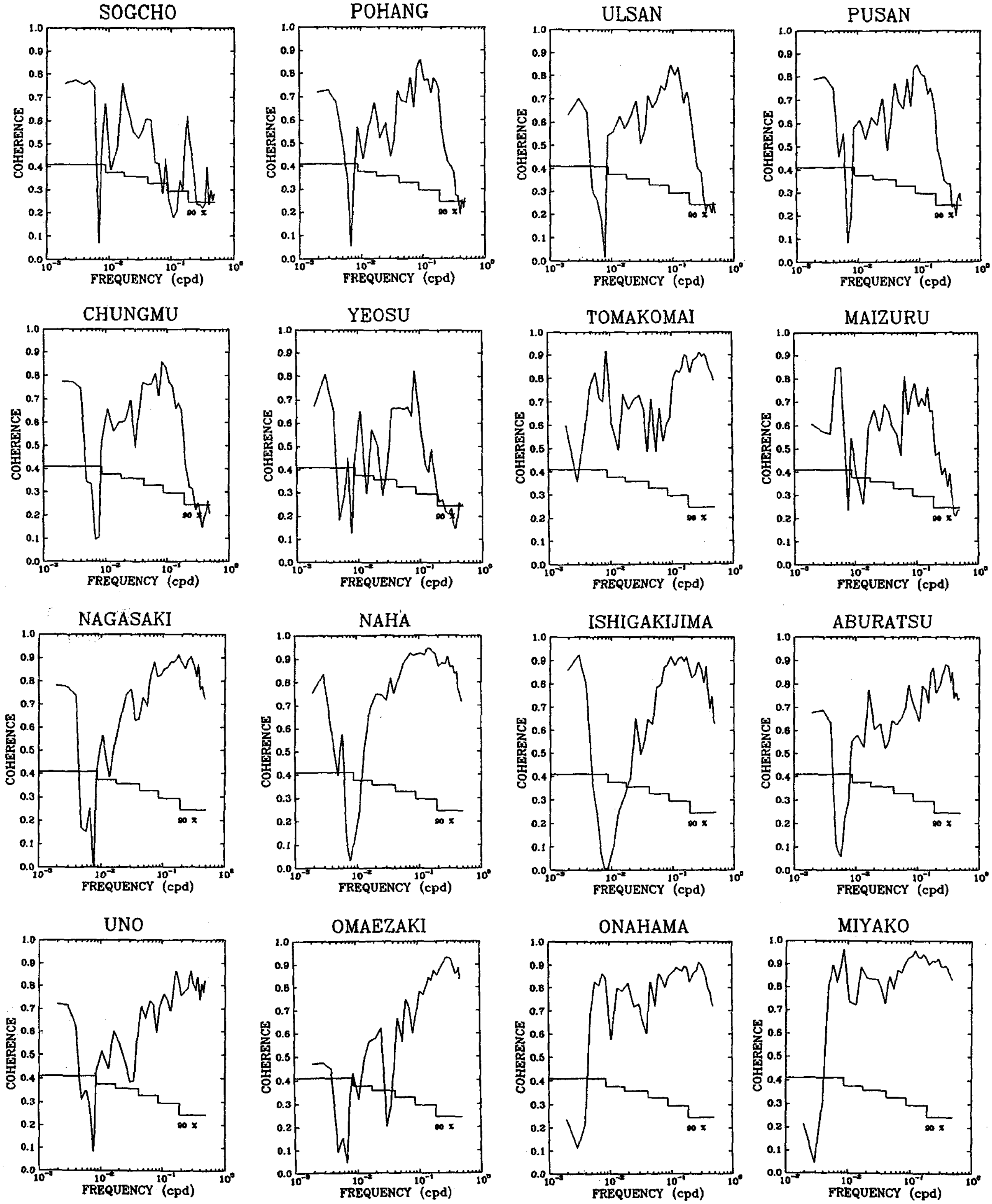

Fig. 13. Coherence between sea level and atmospheric pressure.

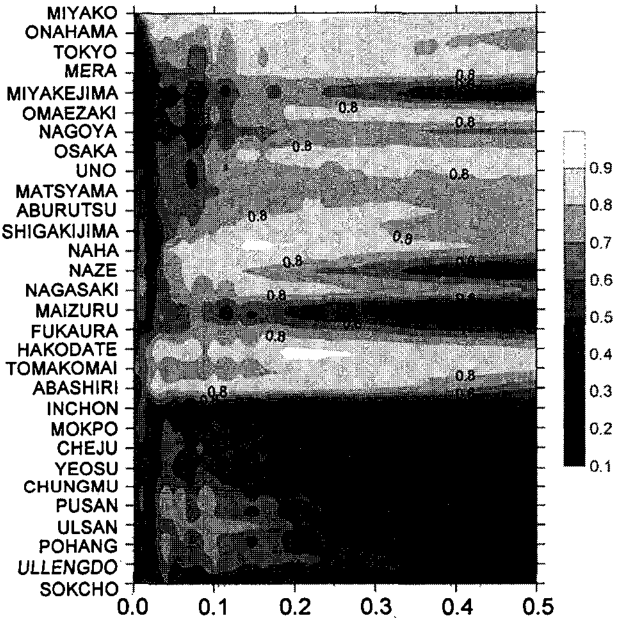

Fig. 14. Coherence between the sea level and atmospheric pressure contoured as a function of frequency and stations. Hachures represent coherence lower than 0.4.

where H is the depth of the strait separating a basin of area A from an ocean, and f and g represent Coriolis parameter ($\sim 10^{-4}\ s^{-1}$) and gravity. In order to apply this to the Korea Strait, we take 73 m as the appropriate value for the depth of the Korea Strait and $1.3 \times 10^{12}\ m^2$ as the area of the East Sea, then the time scale can be estimated to be about 50 hours. Results show that the limiting time scale is the order of two days. Therefore, the flow through the Korea Strait can be controlled geostrophically and the strait prevents the East Sea from having barometric response at the time scale of 2 to 4 days.

SUMMARY AND DISCUSSIONS

Daily mean sea levels reveal a definite seasonal signal, and higher frequency oscillations at time scales of several days or several weeks are also observed in all the time series. In short-period (<6 months) sea level variations, the period of 3 or 4 months is dominant in most of the study stations.

According to the statistical analysis of sea level and air pressure, the length scale of air pressure variability is larger than that of sea level for the present study area. Large short-period sea level variability is found in the southern coasts of China and around Hokkaido Japan, and large long-period ones in the southern coasts of Japan and Korea along the Tsushima Current and Kuroshio. This patterns are similar to those of the air pressure. It shows that the variations of sea level are related not only with air pressure but also with the currents in the area such as the Tsushima Current and Kuroshio. The short-period sea level variability is large in October and November, and small in May and June. Their distributions are similar to those of air pressure, but the months of maximum and minimum are not same.

By the inverse barometric effect, the air pressure field is found to account for 31% of the total sea level variation in the study area. This indicates that isostatic response is not the only mechanism generating sea level variations. Considering the fact that the results (40%) of Pang and Oh (1995) were obtained from the monthly sea level data, the present result implies that the short-period sea level variations are less affected by air pressure.

According to the cross spectral analysis, generally the sea level response to air pressure are found to be isostatic, but significantly nonisostatic for the periods around 4 months and for those of 2 to 4 days. In particular, nonisostatic response for higher frequencies is found to exist in most of the coasts along the East Sea. These results can be explained by the fact that the Korea Strait is limiting the water transport necessary for barometric response at the time scale of 2 to 4 days in the Korea Strait.

Nonisostatic response for periods around 4 months can not be explained in terms of the geostophic control. The other kind of possibility is that the Kuroshio current fluctuation might influence the sea level variation of this period. According to Shioji (1972), there exists a four-month or semiannual component of variation in the current speed of Kuroshio. The current seems to be closely connected with this variation in the sea level. However, we need more study and data to prove the effect of current in sea level variation. This is a subject of the future study.

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