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# SPECTRAL ANALYSIS OF DAILY MEAN SEA LEVEL RECORDS ALONG THE COAST OF JAPAN

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## Abstract

Simultaneous daily mean sea level records are analyzed by the method of spectral analysis and cross correlation at 24 tidal stations along the coast of Japan. The relations between adjusted daily mean sea level, reduced daily mean sea level and tide and oceanographic condition are investigated. The feature of power spectra of the adjusted daily mean sea level is that remarkable differences are found on the Pacific Ocean coast and the Japan Sea coast. That is, on the Pacific coast, the power spectra are simple and one prominent peak is seen at the frequency of 0.0666 cycles per day (cpd), the peak may be produced by long-period tides Mf, MSf, lunar tide $M_2$, and the variation of the Kurosio.

On the Japan Sea coast, the feature of power spectra is very complicated and the prominent peak of the adjusted daily mean sea level is in agreement with the spectral peak of atmospheric pressure at the frequency of about 0.1333 cpd.

The cross correlation and the plots of the adjusted daily mean sea level indicate the presence of traveling wave progressing from south to north with velocity of about 320～450 cm/sec, and the frequency of the wave is 0.1333 cpd. Observed wave velocity is in accord with the theoretical values estimated by the theory of continental shelf wave for fundamental mode.

Also the existence of internal standing wave may be expected.

## 1. Introduction

As a method to investigate various oceanographic phenomena, many oceanographers have intersted in analysis of the accurate and successive data of the daily mean sea level records which are taken easily. It is well known that the change of the daily, monthly, and yearly mean sea level is generated by several elements, for example, tide, current, atmospheric pressure, and wind. Recently the effects of these elements on the daily mean sea level were studied by Groves (1965, 1967), Hamon (1962, 1966), and Endo (1965). On the other hand, we get some informations concerning oceanographic conditinos from the mean sea level.

Shoji (1954, 1961) got several informations as to the change of the Kurosio, and internal Kelvin wave from the investigation of the adjusted daily mean sea level along the Japanese coast.

Hamon (1962, 1966) studied the relations between the fluctuation of the daily mean sea level and the movement of axis of current and continental shelf wave on the Australia coast. Moors and Smith (1968) studied for the continental shelf wave of several days' periods on Oregon sea level records.

In the present paper, the effects of tide, wind, and current are examined for the daily mean sea level. On the Pacific coast, the statistical significant periodicity of the power spectra and the effects of variation of transport, axis of the Kurosio for the change of the adjusted daily mean sea level are discussed. On the Japan Sea coast, the daily mean sea level and atmospheric pressure variation are investigated.

The possibility of existence of continental shelf wave and internal standing wave are discussed.

## 2. Data

The tide and atmospheric pressure have been observed and provided by the Japanese Hydrographic Division and the Japanese Meteorological Agency.

The location of tidal stations is shown in Fig. 1. The daily mean sea level is calculated by averaging 24 hourly heights from tide gage records, and daily mean atmospheric pressure is by averaging values of four times a day at six hour intervals at weather stations nearest to each tidal station.

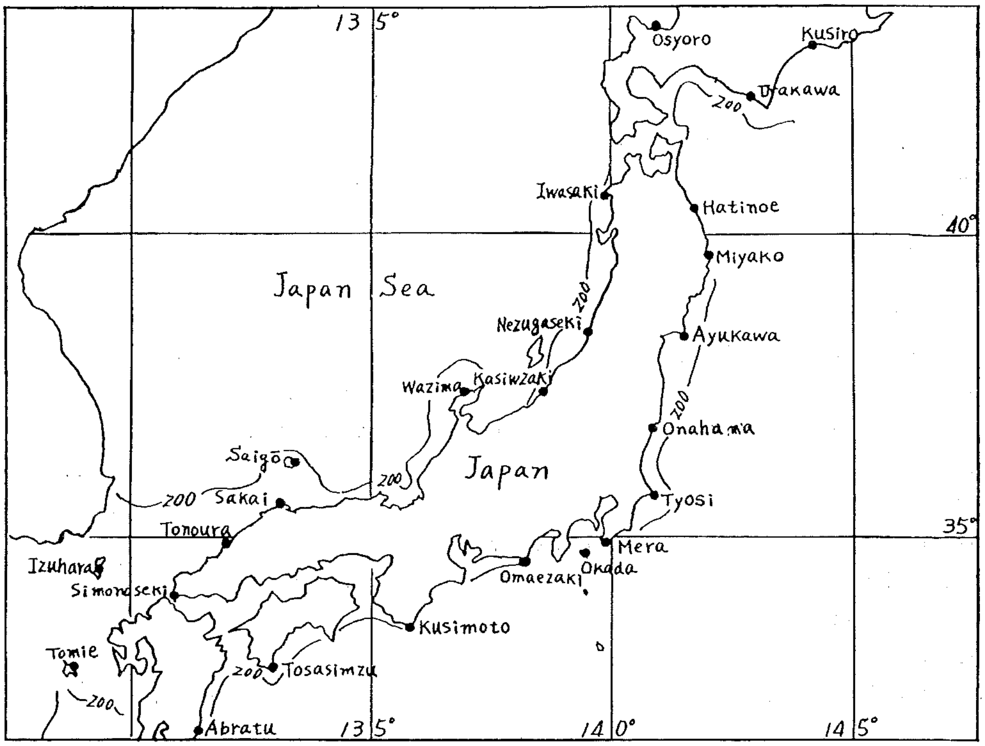

Fig. 1. Map showing the location of tidal stations along the Coast of Japan.

## 3. Adjusted and Reduced daily mean sea level

It is assumed that the adjusted daily mean sea level $Z_i$ and reduced daily mean sea level $Z_i'$ are represented by the expression

TABLE 2.

| Tidal Station | Long. E. | Lat. N. | Barometric Factor | Total power ($cm^2$) | Long-period Tide Amp. (cm) | | N | Note* |
|---|---|---|---|---|---|---|---|---|
| Pacific Ocean Coast | | | | | Mf | MSf | | |
| Kusiro | 144°22′ | 42°58′ | −0.87 | 22.7 | 0.58 | 0.84 | 366 | A |
| Urakawa | 142 46 | 42 10 | −0.96 | 37.9 | 3.77 | 1.10 | 366 | A |
| Hatinoe | 141 31 | 40 32 | −0.87 | 77.4 | 0.53 | 1.66 | 366 | A |
| Miyako | 141 58 | 39 38 | −0.86 | 80.5 | 1.34 | 0.57 | 366 | A |
| Ayukawa | 141 31 | 38 18 | −0.87 | 66.2 | 0.71 | 0.99 | 366 | A |
| Onahama | 140 55 | 36 56 | −0.82 | 72.8 | 1.54 | 0.37 | 366 | A |
| Tyosi | 140 50 | 35 45 | −0.73 | 80.3 | 1.65 | 0.50 | 366 | A |
| Mera | 139 50 | 34 55 | −0.84 | 41.2 | 1.06 | 0.76 | 366 | A |
| Okada | 139 24 | 34 47 | −0.90 | 82.5 | 1.75 | 0.30 | 366 | A |
| Omaezaki | 138 14 | 34 36 | −0.92 | 84.3 | 1.57 | 0.80 | 366 | A |
| Kusimoto | 135 46 | 33 28 | −0.97 | 67.0 | 0.91 | 1.34 | 366 | A |
| Tosasimizu | 132 58 | 32 47 | −0.99 | 68.4 | 1.29 | 1.44 | 366 | A |
| Aburatsu | 131 25 | 32 35 | −0.94 | 77.5 | 1.56 | 0.09 | 366 | A |
| Japan Sea Coast | | | | | | | | |
| Osyoro | 140 52 | 43 13 | 1.10 | 72.0 | 0.30 | 0.10 | 366 | A |
| Iwasaki | 139 54 | 40 35 | −1.13 | 64.8 | 2.80 | 1.20 | 366 | A |
| 〃 | 〃 | 〃 | .... | 40.0 | .... | .... | 366 | P |
| 〃 | 〃 | 〃 | .... | 116.9 | .... | .... | 366 | H |
| Nezugaseki | 139 33 | 38 34 | 1.07 | 82.6 | .... | .... | 366 | A |
| 〃 | 〃 | 〃 | .... | 37.9 | .... | .... | 366 | P |
| 〃 | 〃 | 〃 | .... | 125.8 | .... | .... | 366 | H |
| Kasiwazaki | 136 31 | 37 21 | 0.99 | 95.6 | .... | .... | 366 | A |
| Wazima | 138 54 | 37 24 | 1.12 | 100.1 | 2.40 | 1.20 | 366 | A |
| 〃 | 〃 | 〃 | .... | 42.0 | .... | .... | 366 | P |
| 〃 | 〃 | 〃 | .... | 152.7 | .... | .... | 366 | H |
| Saigo | 133 20 | 36 12 | −1.21 | 108.2 | .... | .... | 366 | A |
| Sakai | 133 14 | 35 33 | −1.45 | 103.0 | 1.95 | 0.66 | 366 | A |
| 〃 | 〃 | 〃 | .... | 42.3 | .... | .... | 366 | P |
| 〃 | 〃 | 〃 | .... | 189.5 | .... | .... | 366 | H |
| Tonoura | 132 04 | 34 54 | −1.56 | 117.6 | 0.21 | 0.43 | 366 | A |
| Izuhara | 129 18 | 34 12 | −1.45 | 108.2 | 1.07 | 0.29 | 275 | A |
| 〃 | 〃 | 〃 | .... | 42.8 | .... | .... | 275 | P |
| 〃 | 〃 | 〃 | .... | 164.7 | .... | .... | 275 | H |
| Simonoseki | 130 57 | 33 58 | −1.50 | 93.8 | 1.29 | 3.30 | 366 | A |
| Tomie | 128 46 | 32 37 | −1.51 | 88.3 | .... | .... | 366 | A |

* A ; Adjusted daily mean sea level. H ; Daily mean sea level.
P ; Daily mean atmospheric pressure.

$$Z_i = -\alpha_j(P_i - 1000) + H_i \qquad (1)$$

$$Z'_i = -\alpha_j(P_i - 1000) + H_i - H'_i \qquad (2)$$

where $H_i$ ia daily mean sec level (in cm), $H_i'$ is the predicted daily mean sea level from harmonic constants, $P_i$ is daily mean atmospheric pressure (in mb), $\alpha_j$ is barometric factor which was estimated by same author (Endo, 1965) for each tidal station. These factors are given in Table 2.

## 4. Analysis of data

The adjusted daily mean sea level (the mean sea level), the reduced daily mean sea level, and the daily mean atmospheric pressure can be regarded as time series, and these are assumed to be approximately stationary Gaussian process. Therefore spectral analysis method applied to these data. The data are not applied prewhitening before analyais.

Auto-correlation function $R(l)$, and cross-correlation $C(l)$ are computed by the formulas

$$R(l) = \frac{1}{N-l}\left(\sum_{i=1}^{N-l} x_{i+l}x_i - \frac{1}{N-l}\sum_{i=1}^{N-l} x_{i+l}\sum_{i=1}^{N-l} x_i\right) \qquad (1)$$

$$C(l) = \frac{1}{N-l}\left(\sum_{i=1}^{N-l} x_{i+l}y_i - \frac{1}{N-l}\sum_{i=1}^{N-l} x_{i+l}\sum_{i=1}^{N-l} y_i\right) \qquad (2)$$

$$l = 0,\ 1,\ 2,\ 3,\ 4,\ ,\ ,\ ,\ ,\ m,$$

where $N$ is number of sampled data, and $l$ is maximum lag used by computation.

Power spctrum density function $E(k)$ is computed by the formula.

$$E(k) = \frac{2\Delta t}{\pi}\left\{\frac{1}{2}R(0) + \sum_{l=0}^{m-1} R(l)\cos\frac{\pi kl}{m} + \frac{1}{2}R(m)\cos\pi k\right\} \qquad (5)$$

$$k = 0,\ 1,\ 2,\ 3,\ 4,\ ,\ ,\ \ m.$$

The final smoothed estimates of the power spectrum density function $P(k)$ is formed by moving weighted average

$$P(k) = a_{-1}E(k-1) + a_0E(k) + a_1E(k+1) \qquad (6)$$

where $a$ is hamming window and $a_0 = 0.54$, $a_{-1} = a_1 = 0.23$ respectively.

The power spectrum density is distributed approximately as chi-squre for each value of $k$. The number of degrees freedom is defined by the expression,

$$F = 2\left(\frac{N}{k} - \frac{1}{2}\right). \qquad (7)$$

Total power is expressed by $R(0)$.

## 5. The power spectra of the Pacific Ocean coast

The power spectra are shown in Figs. 2a and 2b. Remarkable feature is that the spectra are simple structure, consisting of one significant peak at the frquency of 0.0666 cpd, every spectrum is similar, however, by detailed examination of the spectra, the feature of spectra are divided into three types, south of Hokkaido, north of Tyosi, south of Mera.

Similar conclusion was expressed for the change of the daily mean sea level on the Japanese coast by Shoji (1961).

Most of power is concentrated in the frequency range from about 0.02～0.3

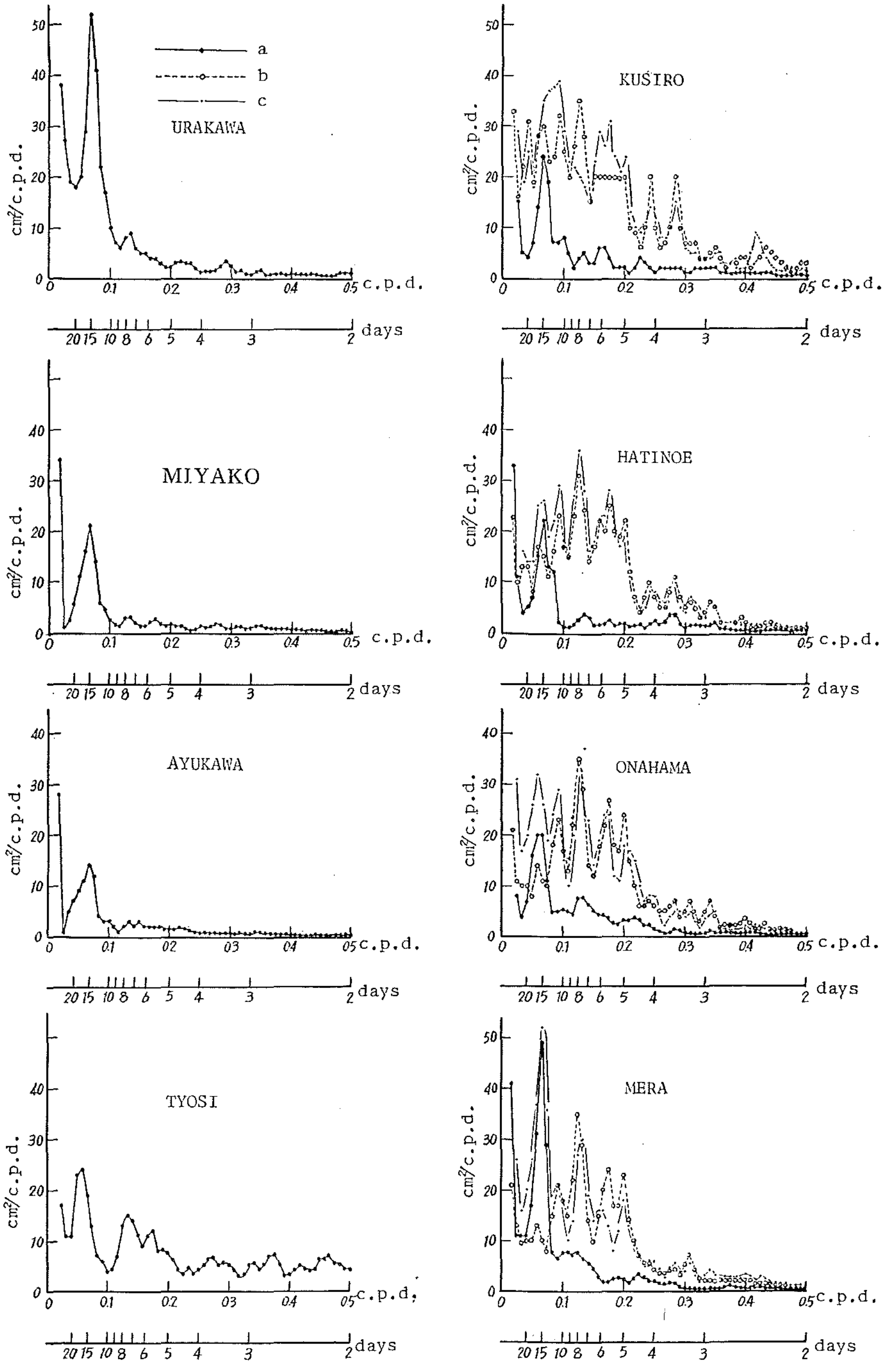

Fig.2a. Power spectra of daily mean sea level, adjusted daily mean sea level and daily mean atomospheric pressure; a) adjusted daily mean sea level; b) daily mean atomospheric pressure; c) daily mean sea level, along the Pacific Ocean coast in 1960.

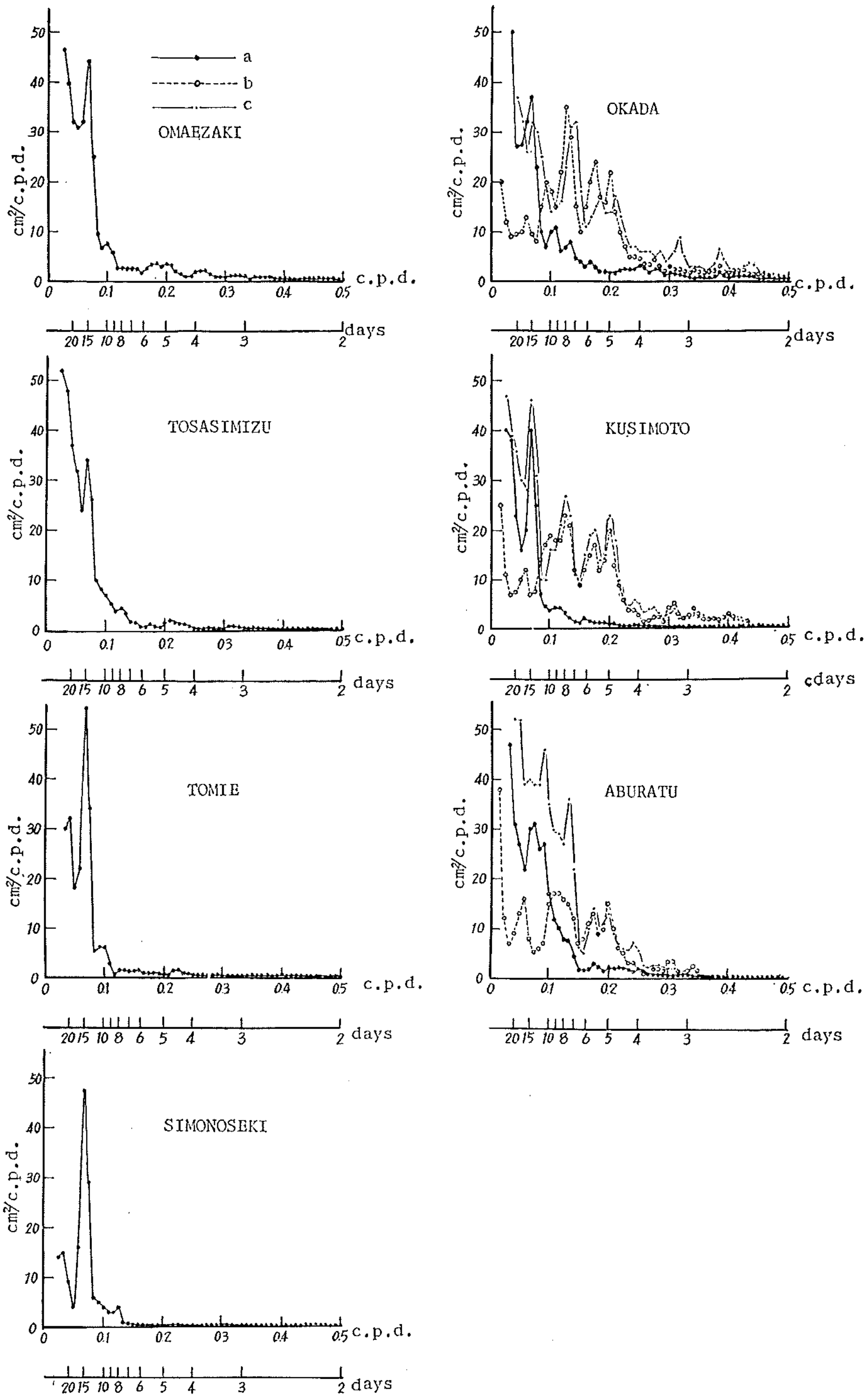

Fig.2b. Power spectra of daily mean sea level, adjusted daily mean sea level and daily mean atomospheric pressure; a) adjusted daily mean sea level; b) daily mean atomospheric pressure; c) daily mean sea level, along the Pacific Ocean and the Japan Sea coast in 1960.

cpd, except for the spectrum of Tyosi which have one prominent peak and tow subpeaks.

The total power is equivalent as to all tidal stations with exception of Kusiro and Urakawa, these values are given in Table 2. The frequency of the significant peak is nearly in agreement with the frequency of the long-period tide constituents of Mf and MSf, whose frequencies are 0.0677 and 0.0723 cpd respectively. The lunar constituent $M_2$ is important in the day to day variation of the mean sea level, the residue of $M_2$ has quasi frequency of about 0.0615 cpd, the quasi frequency is roughly in accord with the frequency of significant peak.

The solar constituent $S_2$ is eliminated perfectly. Then we examine the magnitude of the tidal residues assuming that the speed of a harmonic constituent is $\sigma$ (in hour$^{-1}$) and amplitude is in unity, the daily mean due to the constituent is given in the formula

$$\overline{m}=\left\{\sigma\left(t+\frac{\tau-1}{2}\right)+\varphi\right\}\cdot f \tag{8}$$

$$f=\sin\frac{\sigma\tau}{2}\Big/\tau\sin\frac{\sigma}{2},$$

$f$ is attenuation factor, each of factors is given in Table 1, the attenuation factors of the long-period tide are nearly equal to unity, since the long-period tide components remain mostly in the mean sea level. The component of $M_2$ considerably remain in the mean sea level thinking of the magnitude of actual amplitude for the mean of 24 hourly observations.

TABLE 1.

| constituent | 24 hours | 25 hours |
|---|---|---|
| $M_2$ | 0.035160 | 0.006419 |
| $S_2$ | 0.000000 | 0.040000 |
| Mf | 0.991224 | 0.990478 |
| MSf | 0.992458 | 0.991846 |

Considering above discription and the significant peak appearing at the frequency of 0.0666 cpd in each of spectra except for Tyosi, it is evident that the significant peak is constituted of the components of long-period tide and lunar tide $M_2$, however it is difficult to explain this peak is constructed with only the tide components, because the amplitude of significant peak is comparatively larger than the amplitudes of the tide components; moreover, the significant peak energy of the reduced daily mean sea level is about 35~78% of the energy of the mean sea level in spite of eliminating the tide energy as shown in Fig. 2d.

Then we consider the other effects it is suggested that the variation of the transport, velocity, and main stream position of the Kurosio (the variation of the Kurosio) may produce a periodic variation on the mean sea level, by reason of Japan islands are situated in the field of streams which is called the Kurosio current system and consists of the Kurosio and Tusima current.

Therefore it is obvious fact that the mean sea level are affected by the currents directly or indirectly. This fact is pointed out by several oceanographers. For example, Shoji (1955, 1961) pointed out that the change of the mean sea level closely relates to the variation of the Kurosio along the south coast of Japan.

Hikosaka (1953) reported that the fluctuation of current, and differences of two daily mean sea levels at different tide stations showed a periodicity of a fortnight at Tugaru straits where Tusima current flows.

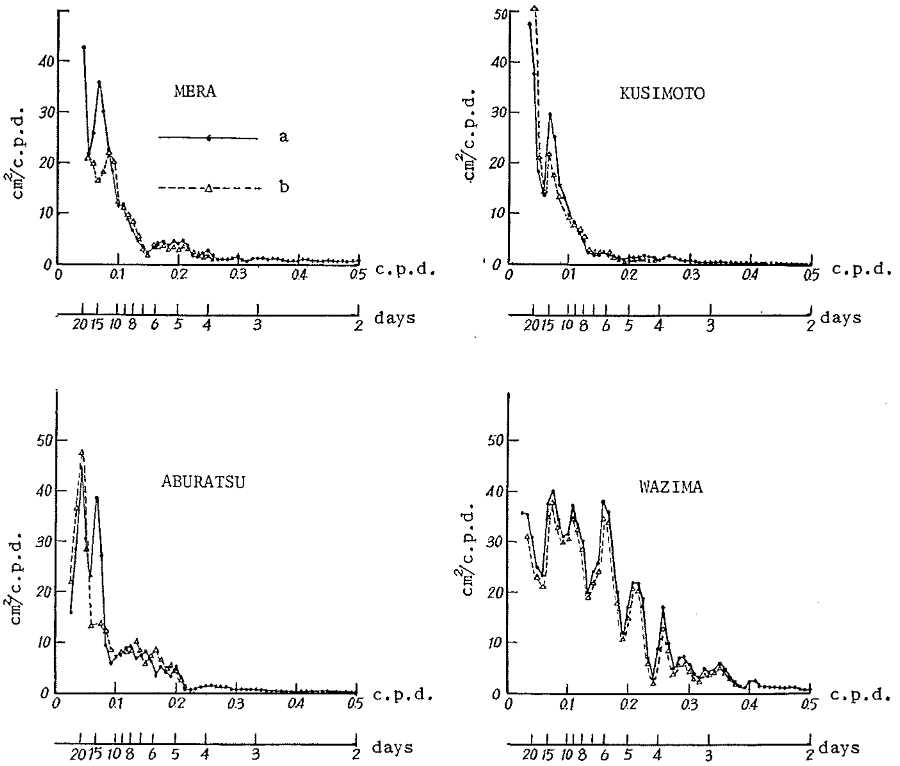

Fig. 2d. Power spectra of adjusted daily mean sea level and reduced daily mean sea level, a) adjusted daily mean sea level, b) reduced daily mean sea level, along the Pacific Ocean coast and Japan Sea coast in 1962.

According to the observations in 1960, the main stream of the Kurosio flowed around the large vortex which appeared off the south coast of Japan.

This vortex moved gradually to north-east. The main stream meandered following the movement of the vortex from May to July, the Kurosio flowed along the east coast of Japan and extended its strong influence off the bay of Miyako. Since August the main stream shifted to north-east off Tyosi. Considering above discription and the Fig. 3. the Kurosio showed large scale variation through the year of 1960. Thus, it is certain that the mean sea level is considerably influenced by the variation of the Kurosio. The power spectra of Mara and Kusimoto have one prominent peak which is narrow and sharp with frequency of 0. 0666 cpd (period; 15 days) as this features are shown in Figs. 2a, 2b, 2d.

This phenomenon is inferred to indicate a periodic variation of the Kurosio, because Mera and Kusimoto tide gages are most sensitive to the variation of the Kurosio and the both stations are situated at coast where the main stream of the Kurosio most approach. Shoji (1954, 1961) suggested that the Kurosio made short period variations with a few days and a few weeks. In particularly this periodic variations are found at Hatizyo Is.

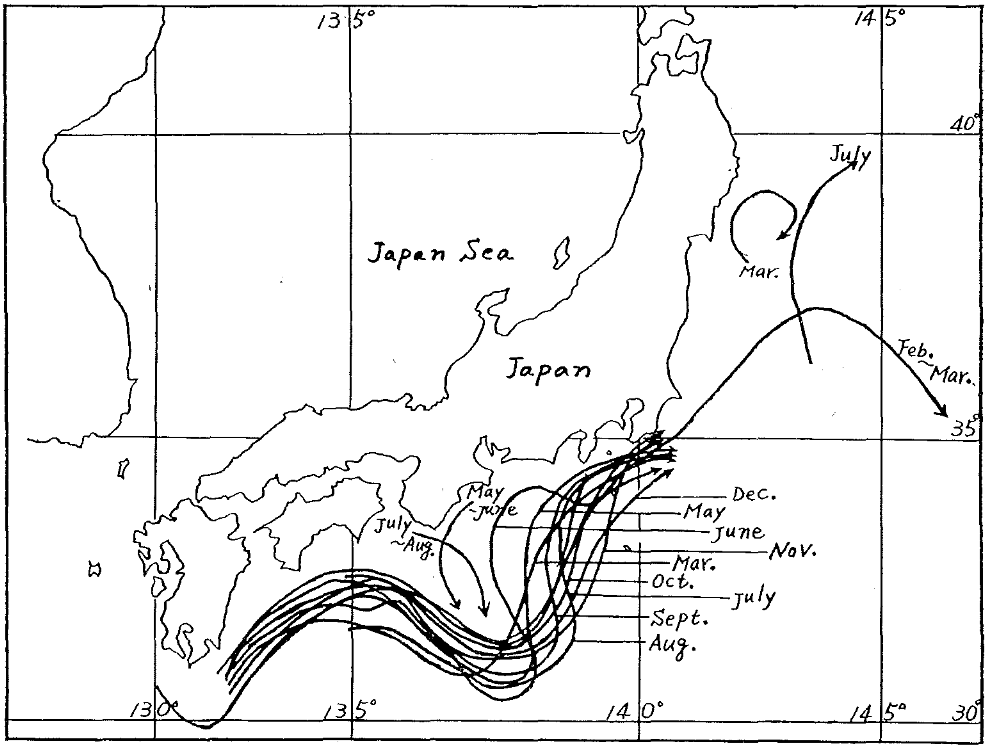

Fig. 3. The change of main stream of the Kurosio on the south Coast of Japan in 1960.

The feature of power spectrum of Tyosi is different to other spectra, that is, the spectrum has two significant peaks at frequency of 0.1333, 0.0583 cpd. This difference may be caused by the discharge of Tone River and complicated oceanographic conditions in this area where the Kurosio and the Oyasio are intricate each other.

As next consideration, it is necessary that the effect of wind on the mean sea level is investigated, but it is very difficult to evaluate it, because the wind direction and velocity are scarcely invariable all through the day. Therefore, in order to study the wind effect, graphical method is applied. The graphs of the mean sea level, wind direction, and wind velocity are compared by the visual inspection. As result, when the wind velocity is under about 10 m/sec the wind effect is scarcely found, and when the velocity is over about 10 m/sec in favorable direction, the effect is found, forced fluctuations are about 12 mm at

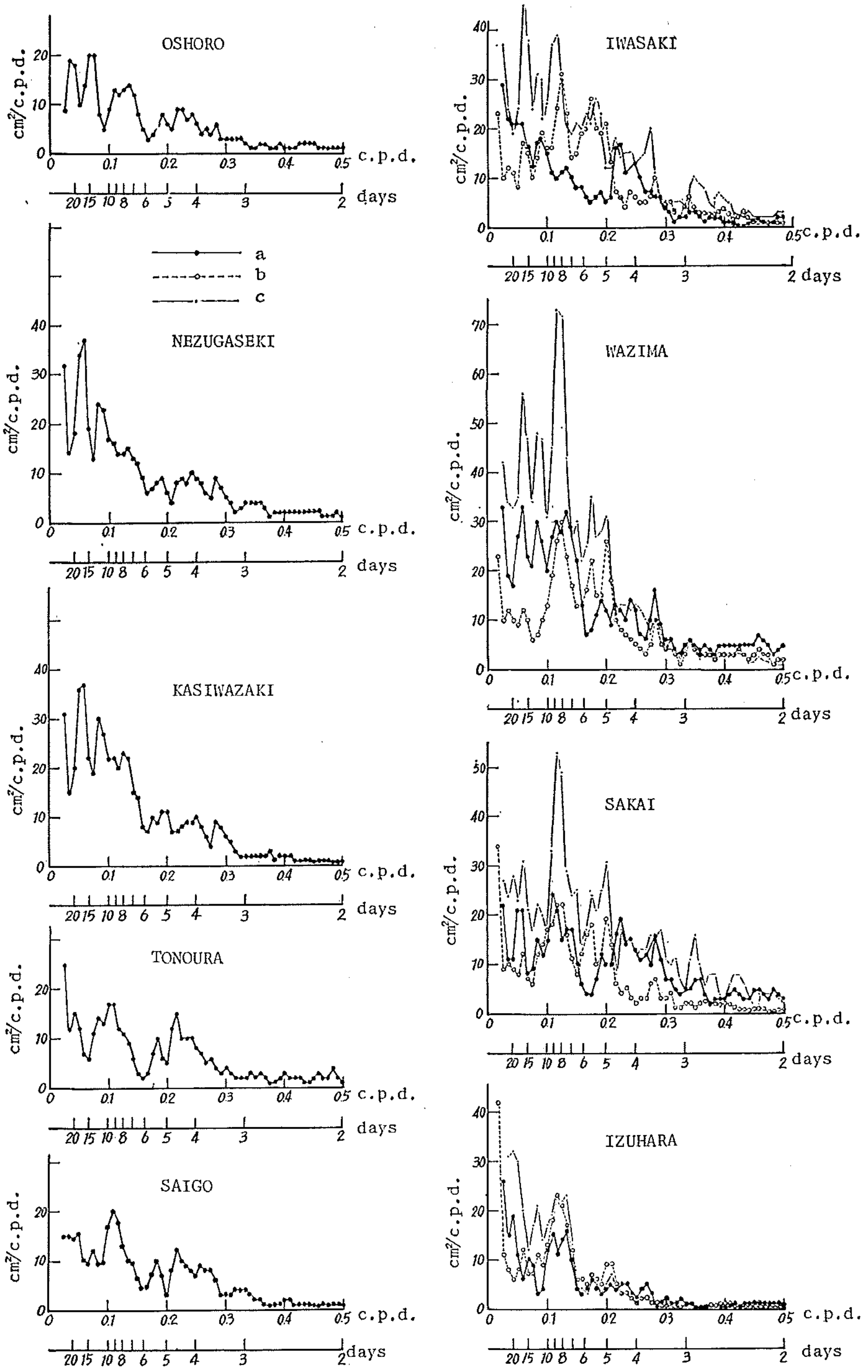

Fig.2c. Power spectra of daily mean sea level, adjusted daily mean sea level and daily mean atomospheric pressure; a) adjusted daily mean sea level; b) daily mean atomospheric pressure; c) daily mean sea level, along the Japan Sea coast in 1960.

Mera and Okada.

Hamon (1966) discussed the effect of wind stress on the daily mean sea level, and suggested the effect is not so large on Australia coast.

Groves and Grivel (1962) reported the a subsequent cross spectrum analysis of two years simultaneous series of the sea level and surface wind components indicated a significant coherence, but there is no evidence of a corresponding spectral peak in the wind. It is necessary to study in detail the wind effect on the mean sea level.

## 6. The power spectra of the Japan Sea coast

The power spectra are shown in Figs. 2c and 2b. The main feature of power spectra show complicated construction as compared with the pacific Ocean coast, that is, the power spectra consist of one prominent peak and 3 or 4 subpeaks, the power is distributed in the frequency of broader range.

The significant peaks are found at the various frequencies of 0.0583, 0.1333, 0.1083 cpd. The amplitude of significant peak is similar in magnitude compared with the Pacific coast. These magnitude is between 46 mm at Iwasaki and 63 mm at Nezugaseki.

Maximum total power is 117 $cm^2$ at Tonoura, minimum power in 72 $cm^2$ at Iwasaki. The peak of frequency of 0.0666 cpd which correspond to the frequency of tide components is found as subpeak. Therefore, the effect of tide components is small compared with other effects such as seasonal or local wind actions.

Robinson (1964) discussed theoretically that the low frequency traveling wave

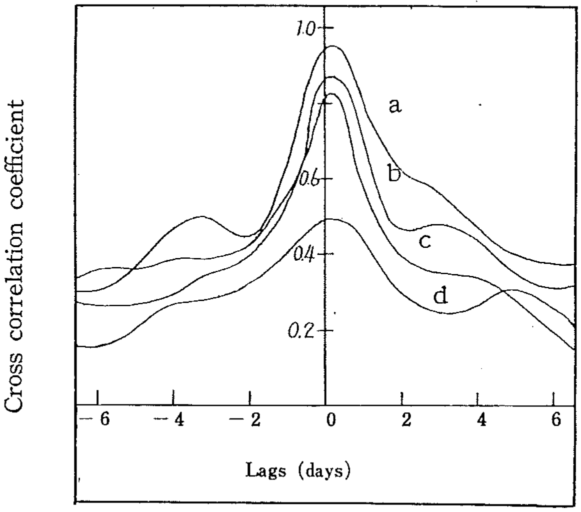

Fig. 5. Cross correlation of adjusted daily mean sea level, alog the Japan Sea coast in 1960.

a) Wazima - Nezugaseki, b) Sakai - Wazima,
c) Nezugaseki - Iwasaki, d) Simonoseki - Sakai.

which is forced by atmospheric pressure variation.

Hamon (1966) reported the presence of the traveling wave (continental shelf wave) with velocity about 400 cm/sec, which is forced by atmospheric pressure variation on the Australia coast.

Recently, Mysak (1967) developed detailed discussion of the continental shelf wave, and Mooers and Smith (1968) reported the presence of the continental shelf wave with periods 2～10 days off Oregon coast.

The simultaneous mean sea level records and the results of the cross correlation analysis are examined. It is found that conspicuous crest and trough progress from south to north as Fig. 4 shows.

Maximum cross correlation coefficients indicate some lagged time between five tidal stations on the mean sea levels. The results are given in Fig. 5. These facts suggest that the traveling wave progresses from south to north. Fig. 6 shows accumulated lag of crest and trough in reference to Simonoseki. Observed wave velocities are estimated about 320～450 cm/sec from the fitted straight line in Fig. 6. Observed wave frequency is estimated about 0.1333 cpd from the power spectra.

This frequency is in good agreement with the frequency of the atmospheric pressure variations as shown in Fig. 2c. This phenomenon indicates that a resonant response to the atmospheric pressure variation may occur on shelf.

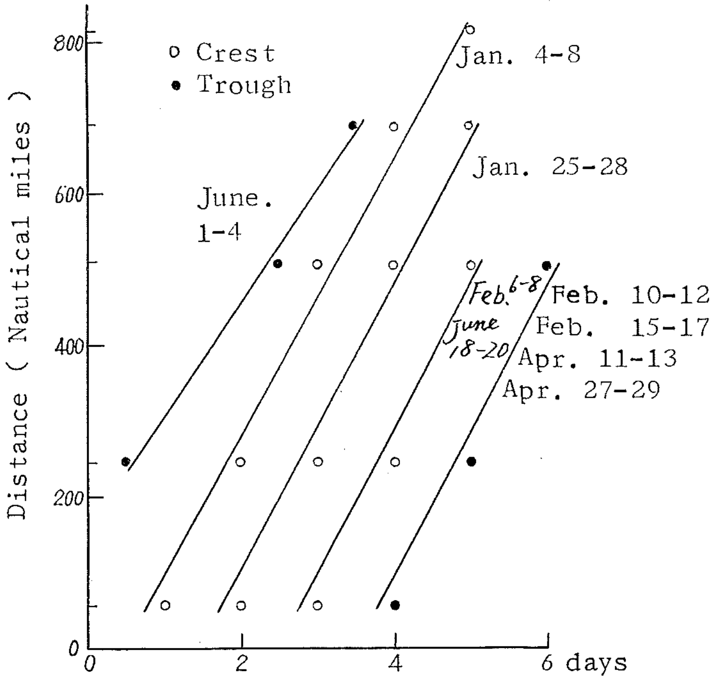

Fig. 6. Accumulated lag of crest and trough on adjusted daily mean sea level, along the Japan Sea coast in 1960.

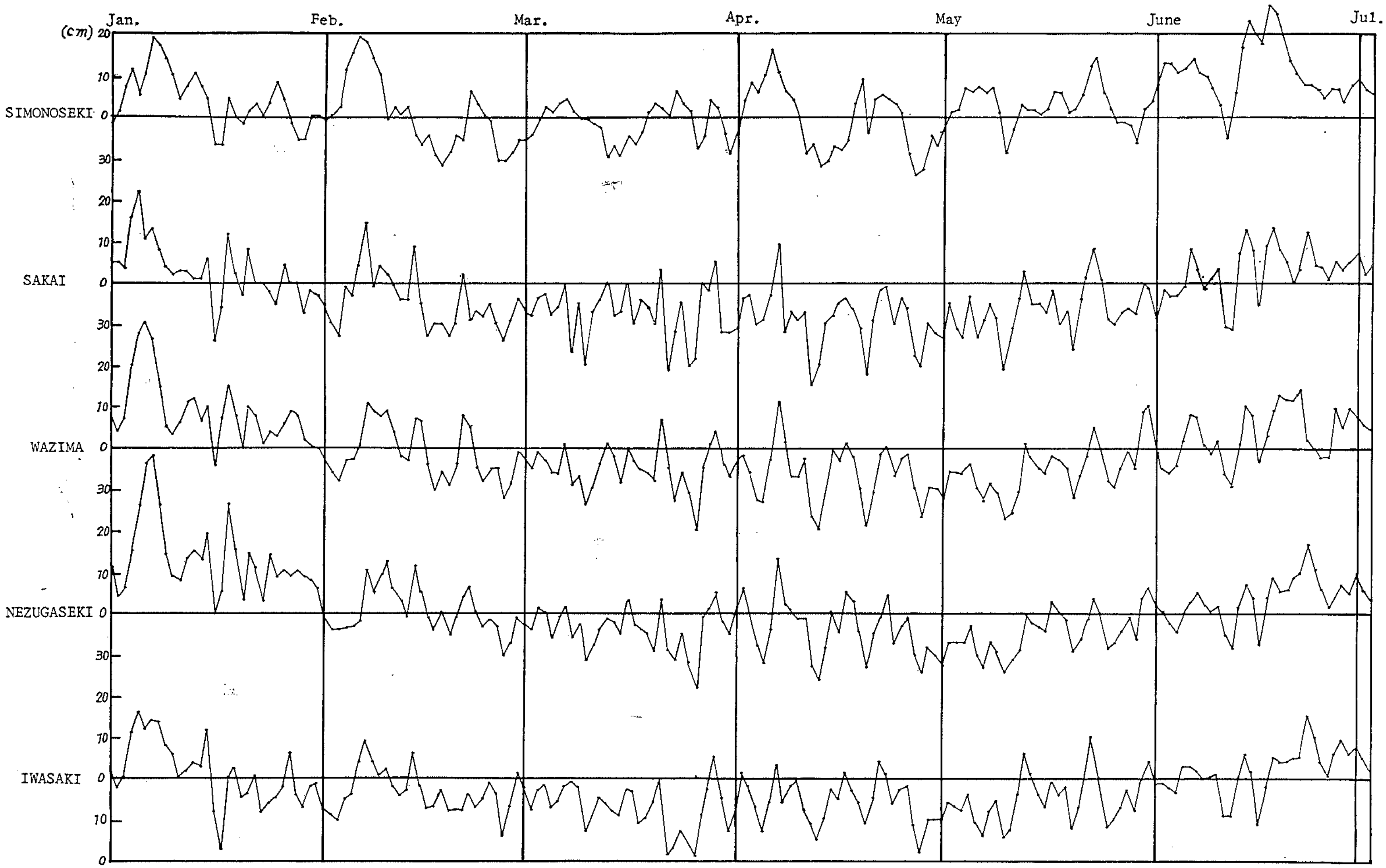

Fig. 4. Adjusted daily mean sea level variation of the Japan Sea coast in 1960.

According to Mysak's paper (1967), the continental shelf wave velocity of the lowest mode is expressed theoretically by $C=fL/1.44$, where $f$ is Coriolis parameter, and $L$ is continental width.

Taking realistic values for $L=6\times10^6$ cm, $f=0.87\times10^{-4}$ sec $^{-1}$, on the Japan Sea coast, $C=360$ cm/sec is estimated. The wave velocity derived by the theory is in good agreement with the observed velocity, hence the presence of continental shelf wave may be expected. The continental shelf wave is forced probably by the variation of atmospheric pressure and strong south or south-east wind.

Besides these considerations, if we assume that the Japan Sea is a bay, the existence of internal standing wave is anticipated. Its velocity and period in the presence of two layers are expressed by

$$C=\sqrt{g\frac{\rho-\rho'}{\rho}\frac{hh'}{h+h'}} \quad (9) \qquad T=\frac{2l}{nc} \quad (10)$$

where $l$ is length of oscillation, $\rho'$ and $h'$ are density and thickness of the upper layer, $\rho$ and $h$ are those of lower layer and $n=1, 2, , , ,$.

Take actual values for $\rho=1.027$ *c.g.s.* $h=1.5\times10^5$ cm, $h'=2\times10^4$ cm, $\rho-\rho'=3\times10^{-3}$ *c.g.s.* $l=1.75\times10^8$ cm, $n=1$, $C=224$ cm/sec and $T=8.8$ days are roughly estimated.

The values are also the same order as observed values, but we have not sufficient observed data to distinguish whether the continental shelf wave or the internal standing wave. It will be necessary to have detailed examinations for these waves of low frequency mode.

## 7. Conclusions

In this paper, we study for the mean sean level by spectral analysis and other methods. From the above investigations, we can conclude as follows; on the Pacific coast, the prominent spectral peak is found at the frequency of 0.0666 cpd, the peak indicates that there is notable fluctuation which may be forced by the components of tide and the variation of the Kurosio.

On the Japan Sea coast, the power spectra are very complicated and several peaks are found, the peaks may be due to seasonal or local wind actions, and the continental shelf wave which is induced by the atmospheric pressure variation, and strong wind actions.

## Acknowledgements

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(Oceanographic Section)

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