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CHARACTERISTICS OF TIDE LEVEL AFFECTED BY KUROSHIO

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Abstract: With the aim of better understandings on the tide level, which repeats a cyclic motion under the influence of a strong current "Kuroshio", we observed it over a few years. We then analyzed its time series data on a time-frequency basis by wavelet and short time Fourier transform techniques using a Gabor function. The time-frequency representation revealed a remarkable effect of the winding of the current. With the beginning of the winding, a phase gap between 12 hrs and 24 hrs periodic modes resulted in markedly, and the reappearance period of these modes decreased from about 400 hrs to 300 hrs.
Keywords: tide level observation, wavelet transform, short time Fourier transform

1 INTRODUCTION

In Japan, tide levels have been measured and recorded at many tide observation stations located around the Islands over a long period of time because it is closely connected with fishery industries and security of ship navigation [1]. Its variations in time and space are very complicated especially in the east side of the main islands facing the Pacific Ocean. In addition to astronomical and geographical influences, meteorological influences such as atmospheric pressure and ocean currents affects the tide level.

There is an strong ocean current called Kuroshio which flows along the east coast of the main islands with 4 to 7 [km/hr] of velocity and 70 to 100 km wide. It is known that the Kuroshio can take three types of path, which are indicated by a solid, chain and dotted lines in Figure 1, respectively [2]. When the path winds eastward as shown with the solid line, a big, cold eddy generates near shore to off shore of the Kii peninsula in Figure 2 and it causes serious damages on near shore fishery industries. On the other hand, its closer approach to the coast results in a flood because the tide level can rise over half a meter. It is therefore very important to predict when and which path the Kuroshio begins to take.

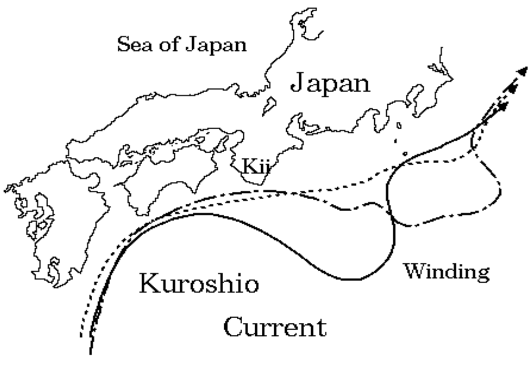


Figure 1: Three typical paths of Kuroshio

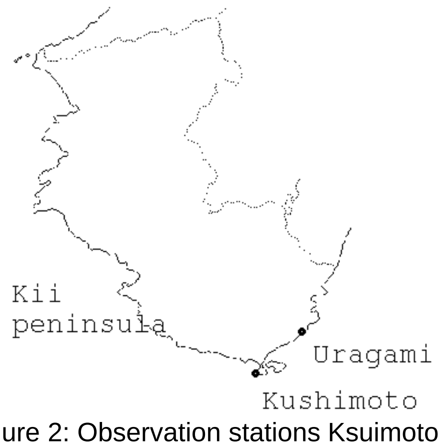


Figure 2: Observation stations Ksuimoto and Uragami

It is well known that difference of an averaged sea level on daily basis between Kushimoto (tip of the peninsula) and Uragami (behind Kushimoto and only 15 km apart from Kushimoto) becomes smaller during the winding period [3,4]. Consequently, observing tide level on daily or hourly basis is one of the most efficient approaches to find the beginning and ending of windings.

The hourly time series have long been used in the fields of the oceanography from practical demands. Though they look to be a simple, modulated cyclic pattern, its strange behavior on periodicity, amplitude and phase are worth to study from a view of chaotic signal processing.

In this study, we analyze the long-term observation data under an influence of the Kuroshio to demonstrate how the tide levels are affected by it. For this purpose, we use two analytical techniques, i.e., short time Fourier transform and wavelet transform with a Gabor function together with the conventional methods of the non-linear time series analysis.

2 ANALYTICAL METHOD

Two types of methods of the time-frequency analysis are used to investigate the time series of hourly-based tide level. The first approach is a short time Fourier transform (STFT) using a Gabor function *w(t)* as a window function for localizing time. It is given by

$$w(t) = \frac{1}{2\sqrt{p}\, s} e^{-\frac{t^2}{s^2}}, \tag{1}$$

where *ó* is a width of the time window which determines a time resolution. Then, STFT of a signal *f(t)* is described by

$$\hat{f}(w,b) = \int_{-\infty}^{\infty} \frac{1}{2\sqrt{p}\, s} e^{-\frac{(t-b)^2}{s^2}} e^{-iwt} f(t)dt. \tag{2}$$

Here *b* and *ù* show a shift parameter and a frequency at time *t*, respectively. In addition to the time-frequency analysis, we use STFT to detect an information associated with phase shifts in a localized time region of the data.

The second approach is a wavelet transform (WT) with the Gabor function as a basic wavelet. The wavelet of a signal *f(t)* is described as follows

$$\hat{f}(a,b) = \int_{-\infty}^{\infty} \frac{1}{2\sqrt{p}\, s} e^{-\frac{(t-b)^2}{s^2 a^2}} e^{-i\frac{t-b}{a}} f(t)dt, \tag{3}$$

where *a* and *b* are a scale and shift parameter, respectively. The technique using WT is prevailing because of its high time resolution, but STFT may however be comparable to WT if we choose an appropriate window function and its time width [5]. We therefore determined an optimal value of *ó* through an analysis.

3 TIME SERIES DATA

We analyze three types of hourly time series to clarify the strong influence of the Kuroshio. According to Kawabe [2], its winding lasted for 4 years and 7 months from August 8, 1975 to May 15, 1980. The differences in tide levels between Kushimoto and Uragami are shown in Figure 3 for 1 year including the ending period of the Kuroshio’s winding, where we can see a remarkable change in the amplitude.

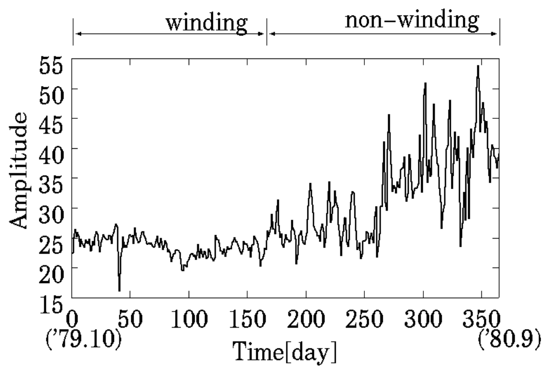


Figure 3: Difference of tide level between Kushimoto and Uragami

Figures 4(a)-(c) show the time series data analyzed in the present study. These data were measured at the Kushimoto observation station. They range from the beginning of winding (Figure 4(a), July, 1975 to August, 1975) to the steady state without winding (Figure 4(c), June, 1981 to July, 1981) through a steady winding state (Figure 4(b), May,1976 to June, 1976). Although they show a typical semi-diurnal variation of tide, we can see the Kuroshio's influence which makes them modulated complicatedly.

4 RESULTS

4.1 Non-linear analysis

To investigate the non-linear properties of the tide level variations, we use the conventional techniques in chaos analysis, i.e., drawing phase trajectory, Poincare's return map and correlation dimension.

4.1.1 Phase trajectory

Figures 5(a)-(c) show the phase trajectories on the *x(t)-x(t+ô)* plane (*x(t)*: data at time *t*) for the time series in Figures 4(a)-(c). The time lag *ô* was determined by the mutual information of the data. All the trajectories look smooth and elliptic at a first look, and its center positions stay around (175, 200). However, the trajectory (a) at the transient state differs a little from the others ((b) and (c)) which resemble each other irrespective of winding. It can be ascribed to the remarkable variation of tide level at the beginning of the winding in the transient state (a).

4.1.2 Poincrare's return map

Figures 6(a)-(c) show the Poincare's return maps corresponding to Figures 4(a)-(c), respectively.

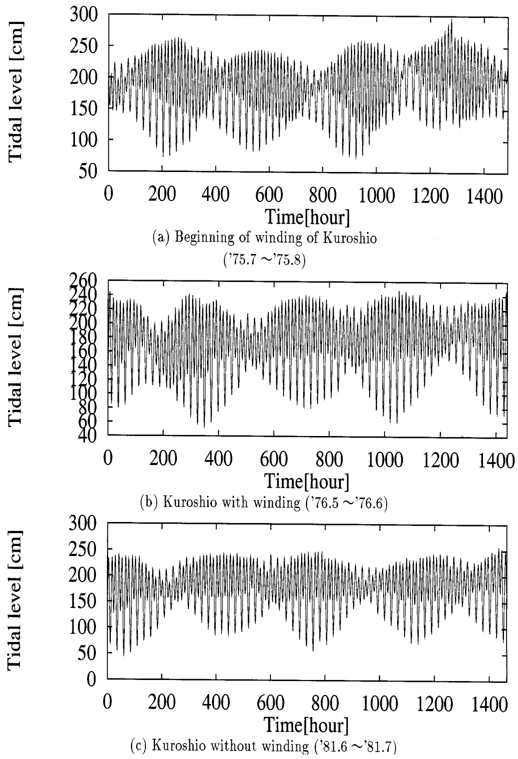
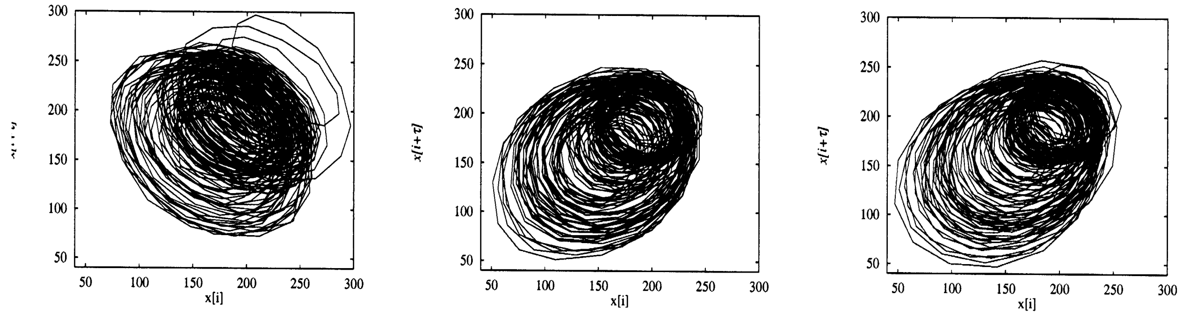
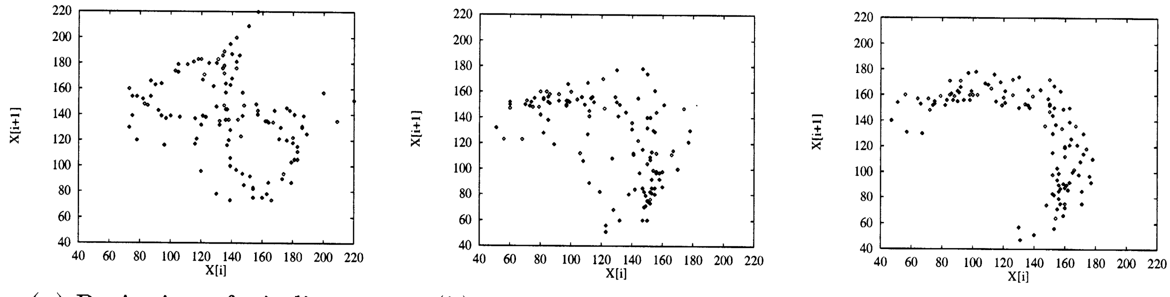


Figure 4: Time series data under the influence of three states of the Kuroshio



(a) Beginning of winding (b) Steady with winding (c) Steady without winding

Figure 5: Phase trajectories of tide level under three states of the Kuroshio



(a) Beginning of winding (b) Steady with winding (c) Steady without winding

Figure 6: Poincare's return maps of tide level under three states of the Kuroshio

In this study, the maps were constructed by plotting the two successive minima of the tide level called low water. The Poincare's return map is much instructive in comparison with the phase trajectory as seen in its geometry. The return map at the beginning of the winding (a) looks a pattern synthesized by two different process, while that of (c) looks very simple, and probably one of them in the map (a).

4.1.3 Correlation dimension

Figure 7 shows the correlation dimension against embedding dimension for the three states of the Kuroshio. The dimension without winding (square symbol) takes the lowest value at a saturation, while other two scatter between 3 to 4 even in a large degrees of embedding dimension. In spite of this, the correlation dimension hardly exceeds 4 even when the Kuroshio is winding and stays between 3 to 4. This indicates that the correlation dimension can change by 1 at most depending on the intensity of the Kuroshio's influence.

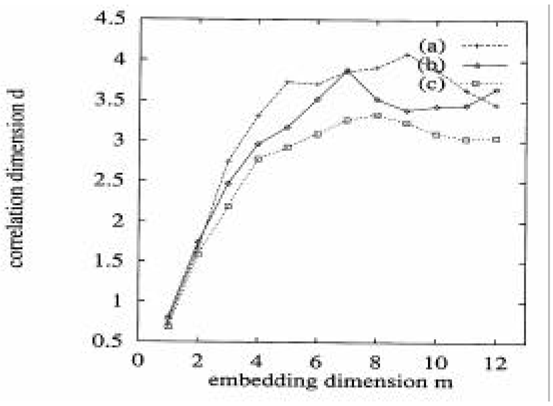


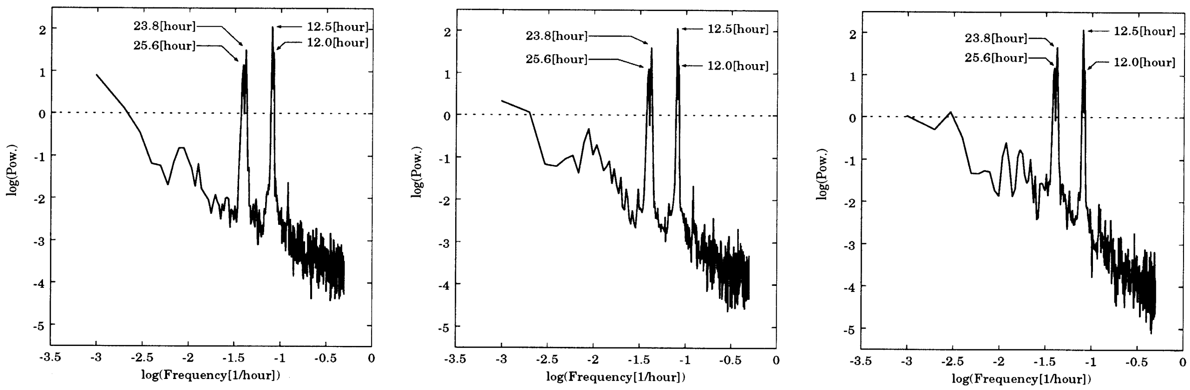
Figure 7: Correlation dimension of tide level

4.2 Time-frequency analysis

A cyclic change between high and low water of tide level is caused by the influences of lunar and solar forces. An averaged half lunar day is 12 hours and 25 minutes (semidiurnal tide) at the Kushimoto observation station. In this section, we describe the results of time-frequency analysis.

4.2.1 Spectral analysis by FFT

Prior to time-frequency analysis, we applied a FFT technique to the semidiurnal tide data. Figures 8(a)-(c) show the power spectral densities (PSDs) corresponding to Figures 4(a)-(c) in double logarithmic scale. The four dominant periods of 12.0, 12.5, 23.8 and 25.6 were estimated for all cases irrespective of winding. The periods of 12.0 and 12.5hrs correspond to the two dominant component of the semidiurnal tide, respectively, and the periods of 23.8 and 25.6[hrs] correspond to those of the diurnal tide, as well [6]. This small difference in each periodic mode is caused by the influences of lunar and solar forces at Kushimoto. However, this approach didn't disclose the difference in periodicity for the three states of the Kuroshio.



(a) Beginning of winding (b) Steady with winding (c) Steady without winding

Figure 8: PSDs for each state of the Kuroshio by FFT

4.2.2 Time-frequency analysis by WT and STFT

The time-frequency pattern maps obtained by WT are shown in Figure 9. We set ó in Eq.(3) at 8 in this analysis considering the width of the time window. In the figures, we applied an image processing technique to visualize the intensity of periodicity. Here, the strength of frequency components is inversely proportional to the gray level. As seen from Figure 9, an appearance of 12 hrs periodic mode as well as 24 hrs repeats regularly an increase and a decrease in a cycle of about 400 hrs for the steady state of the Kuroshio with or without winding. The period of 400 hrs is considered to correspond to that of spring or neap tide. On the contrary, the reappearance period of these modes decreased from about 400 hrs to 300 hrs during the period of transient state shown in Figure 9(a). In addition to this, the 24 hrs periodic mode went ahead of 12 hrs one and a phase gap between them resulted in markedly during this episode only.

The time-frequency pattern maps by STFT are shown in Figure 10 as well. In this study, we set *ó* in Eq. (1) such that the frequency resolution becomes 0.02 [1/hr], and then the temporal resolution is 25 hrs. From the figures, we can see the same features with respect to the two periodic modes of 12 hrs and 24 hrs as mentioned above. Though both figures show the same periodic structure composed of two dominant periods of 12 hrs and 24 hrs, we can see the temporal variation of the intensity of these periodic components more clearly in Figure 9 than Figure 10. On the other hand, from Figure 10 we can see the existence of four periods during the period corresponding to the neap tide, which are considered to correspond to those in Figure 8. As a result, STFT is superior to WT in frequency resolution, while WT superior to STFT in time resolution as known.

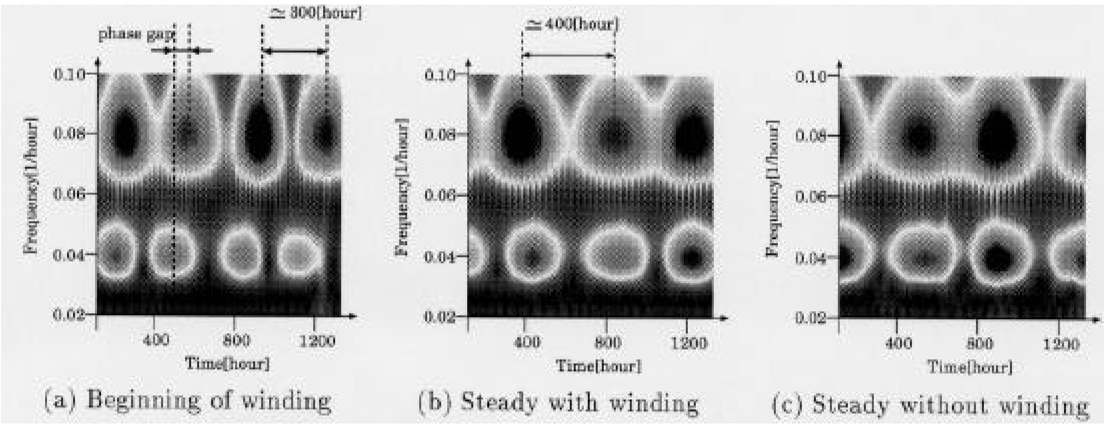


Figure 9: Time-frequency pattern map for each state of the Kuroshio by WT

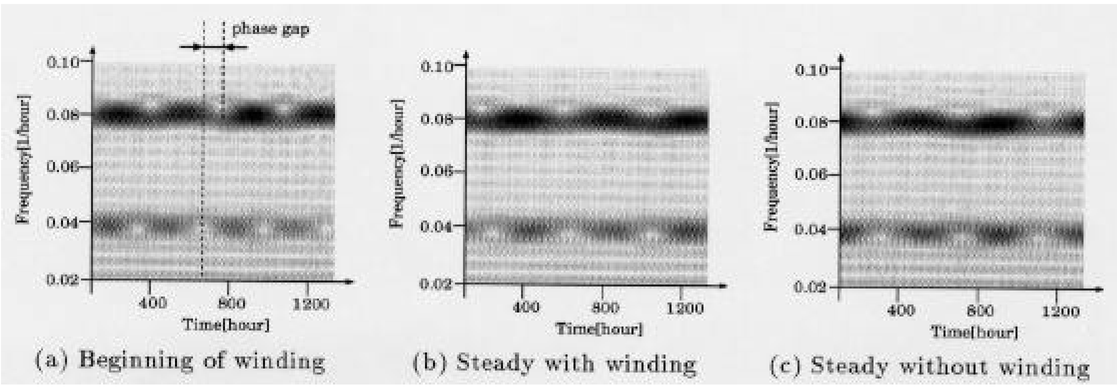


Figure 10: Time-frequency pattern map for each state of the Kuroshio by STFT

4.2.3 Phase analysis by STFT

From our numerical experiment using an artificial time series data, it was confirmed that discontinuities in a signal within some localized time region could be detected by phase analysis in the present study using STFT. The results obtained for the present data are shown in Figure 11 where white and black lines correspond to *0* and *ð* [rad] in phase, respectively. In the figures, the arrows on the right side of the figure indicate frequency regions where the existence of periodic mode was detected. The white circles in the pattern maps are the time regions where discontinuities in the frequency were detected.

Figure 11 indicates that these discontinuities can take place at the time when an intensity of the periodic modes of 12 and 24 hrs becomes weak due to neap tide, while the corresponding figures in Figure 9 by WT didn’t disclose them. It can be conjectured that the phase shifts or discontinuities in dominant periodic mode occur in the neap tide. With respect to the phase discontinuities in 24 hrs periodic mode, it also goes ahead of those in 12 hrs periodic mode only in the transient state of winding.

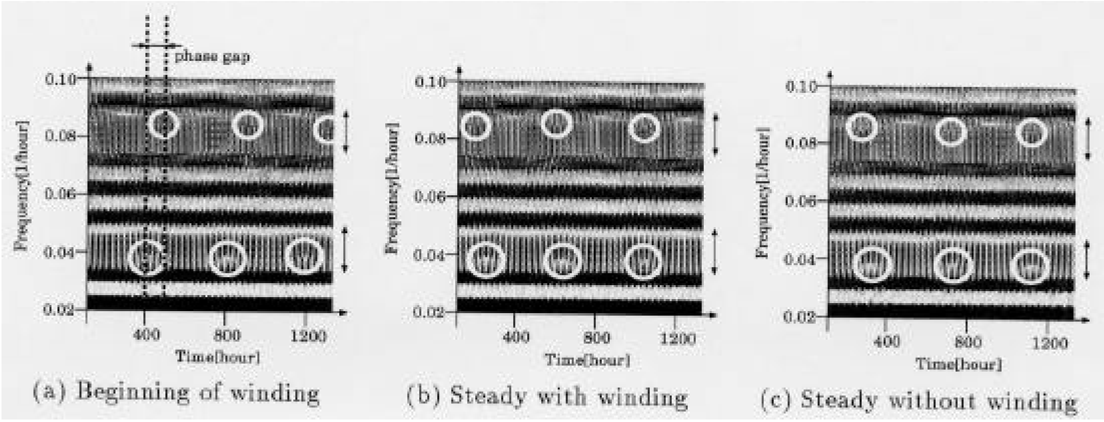


Figure 11: Time-frequency pattern map by phase analysis with STFT

5 CONCLUSIONS

The present study is summarized as follows:

1. The influences of the Kuroshio’s winding on tide level at Kushimoto are larger in the transient state at the beginning of winding than the steady state of with or without winding.
2. The beginning of the Kuroshio’s winding, therefore, is predictable from the time series of the tide level at Kushimoto by WT or STFT analysis.
3. The Kuroshio does not affect the periodic structures of the hourly tide level at the steady state irrespective of winding.

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