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Study on the Characteristics of Storm Surge over Taiwan Eastern Waters by Wavelet Transform

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ABSTRACT

This paper adopts wavelet transform to study the phenomena of storm surge based on the observed tidal data. The characteristics of space and frequency distributions of this feature can be revealed by wavelet energy. This analysis demonstrates when weather conditions are stable, the changes of the wavelet energy deviation closes to zero. However, the wavelet energy of storm surge increases along with the typhoon approaching. If the wavelet energy frequency is less than 1 day^{-1}, the distributions of storm surge graph are similar to that of energy curve. Wavelet energy distribution of surge can therefore acquire accurately the time of the occurrence of max surge. Meanwhile, it can reckon the influential time of storm surge on shore from the variety of the wavelet energy.

KEY WORDS: wavelet transform, storm surge

INTRODUCTION

Taiwan is located between the tropical and subtropical regions of the northwest Pacific Ocean. It is the path of the typhoon during summer. Generally speaking, there are 3 to 4 typhoons invade and attack Taiwan Waters in averaged through the years. However, the trend has increased in recent years.

The eastern water of Taiwan faces the Pacific Ocean directly, where the typhoon is activity over there. When the typhoon hit eastern Taiwan, it is able to generate storm surge due to the water level rising within the typhoon scope. And storm surge makes big damage over the coast area. Therefore, storm surge phenomenon over Taiwan waters is a major product of typhoon. The processes of change of this kind of storm surge wave motion have three steps which are forerunner surging, storm surge, and resurgence.

The forerunner surging is made by the typhoon swell approaching coast region in advance to make the increment of the slowness of water level. The storm surge along the coast water level is rapidly increasing due to the air pressure descend gradually due to the typhoon effect. The resurgence is a wave motion that typhoon storm surge remains later on. These phenomena can maintain a longer time, and the amplitude of oscillation becomes smaller and is near go back to astronomy tide level.

Hsu (1998) studied the sea water level ringing caused by various typhoon routes based on the born location and path sorts of the typhoon from 1994 to 1997. The result displays the water level of storm surge is influenced by the following factors which are typhoon dimension, intensity, route, movement speed, and locally topography, water depth and astronomy tide level.

Cheng (2003) seek the relation between storm surge and typhoon characteristic and find out that the storm surge at coast is under the influence of typhoon parameters such as center pressure, movement speed, typhoon radius, and the distance to the station. The order of the storm surge over the eastern water is highly directed and closed to the distance between station and typhoon center. The result of Wu (2005) points out, the storm surge will reach the maximum under the condition that the typhoon hit land. The amplitude of storm surge is higher than that of adjoin area. The results from the model simulation also showed the storm surge over eastern water is dominated by the typhoon center pressure which called reverse pressure effect. The order of the storm surge induced by the wind stress factor is not important.

Tou et al. (1986) adopted the linear model to analyze the spectral of the storm surge over Victoria Harbor and found out that the spectrum revealed a narrow band during the tidal energy frequency range. For the energy spectral of 2.3×10^{-5} Hz, it is accordance with the semi-diurnal tide. By making use of the analysis of frequency chart for the tide level from the historical data, it is able to understand the variation of low frequency tide and then to predict the starting time of the variation of the water level and the time of the ends.

The Fourier transform is generally used to study the tide data. Its result emphasizes the relation between the frequency and energy. This method can not obtain the energy distribution on the time domain. However, it is able to understand the distribution of spectral density and frequency energy in the time domain. The application of the wavelet theory is gradually widely used in recent years, for example: Jay and Flinchem (1999), Luettich Jr. et al. (2002), Pancheva and Mukhtarov (2000), Flinchem and Jay (2000), Chambers et al. (2002), Lims and Lye (2004), Huang (2005). Those researchers apply wavelet theory to analyze tide data which makes the judgment of the information easier.

This paper uses wavelet theory to analyze tide data during the typhoon period. The result is for the discussion of the energy variation generated following the storm surge in the time and frequency domain.

OVERVIEW OF WAVELET TRANSFORMS

For time series of signal $\eta(t)$, it carries on the Fourier transform and converts it to the spectral function defined as follow:

$$\eta(f) = \int_{-\infty}^{\infty} \eta(t) e^{-i2\pi ft} dt \tag{1}$$

Where t and f are the time and frequency respectively.

The energy spectral of signal is obtained by the square value of the coefficient for the real and imaginary parts of the spectral function. This spectral is denoted by the averaged spectral density for each frequency band. It is not able to show the response form message of local time domain. If the row data contains the noise, the spectral will be affected by the signal. Therefore, this method is meaningful for the stationary time series analysis. Gabor (1946) proposed short time Fourier transform to solve the non-stationary signal problem. But it can not retrieval the local information for the abruptly sensitive reaction semaphore (Chui, 1992).

The wavelet analysis is the method to use the window dimension fixedly, but its time and frequency windows all convertible times and frequencies locally. The meaning of the wavelet transform is an inner product between the data series $x(t)$ and mother wavelet function $\psi(t)$ which needs displacement shift τ and under different scaled a.

$$WT_x(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\, \psi^*\left(\frac{t-\tau}{a}\right) dt \tag{2}$$

The equivalent expression of frequency domain:

$$WT_x(a,\tau) = \frac{\sqrt{a}}{2\pi} \int_{-\infty}^{\infty} X(\omega)\, \psi^*(a\omega) e^{i\omega\tau} d\omega \tag{3}$$

where $X(\omega)$, $\psi(\omega)$ is the Fourier transform of $x(t)$, $\psi(t)$ respectively.

The characteristic of window for time and frequency domain has quite different between the wavelet transform and Fourier transform. The index τ is only affect the window location in time axis. However, the index of a is not only influent window position in the frequency axis but also affect the window shape. Therefore, the time step of data sample is adjustable for the different frequency. That is to say, the window width used in wavelet transform is adjustable for the time and frequency domain in accordance with the location of frequency domain.

The aim of this paper is to obtain the information of tidal energy distribution for the time and frequency domain. Therefore, mother wavelet function of complex type is adopted for the application basis. In this condition, Morlet function is chosen to be the mother wavelet for the analysis of the tidal data, the function is:

$$\psi_k(t) = e^{ikt} \cdot e^{-t^2/2} \tag{4}$$

Its frequency domain function is Fourier transform of $\psi_k(t)$ as:

$$\hat{\psi}_k(\omega) = (2\pi)^{-1/2} \cdot e^{-(\omega-k)^2/2} \qquad \omega > 0 \tag{5}$$

$$\hat{\psi}_k(\omega) = 0 \qquad \omega \le 0 \tag{6}$$

The frequency window structure of the Morlet function is shown in figure 1. Its frequency window is a symmetry Gaussian distribution curve, and energy is concentrated in centre, and there is good localization on the area of frequency domain.

THE ANALYSIS OF STORM SURGE BY WAVELET TRANSFORMS

ChengKung tidal station is located along the Eastern Taiwan coast, which is facing the spacious ocean with bottom of sea configuration steep to fall. Due to this feature, the tide phenomena of this station is not affecting by the sea bottom topography. This is the reason for this paper to choose this station to study the storm surge by the wavelet transform to discuss the characteristics of four tidal components, which are M_2, S_2, K_1 and O_1. The amplitude of these four tidal components is much more significant than other components in 1994 from the figure 2 by the harmonic method.

Typhoon Tim (No. 9405) took place from July 9th to July 11th of 1994 which passing by the ChengKung tidal station as shown in figure 3. The time series of observed tidal level and astronomy tide level and storm surge are shown in figure 4. Figure 4 revealed the maximum surge appeared at 20 pm of July 10. Figure 5 is the wavelet energy distribution of wavelet transform of the observed tidal data and astronomy tide data at ChengKung station. It is shown that the energy is very small for the frequency bellow 0.6 day^{-1} for the astronomy tide. However the observed tide has part energy existed below the frequency of 0.6 day^{-1} which is induced by the meteorology tide. Hence the wavelet energy distribution in the time and frequency domain can be obtained from the energy difference between the observed tide and astronomy tide as shown in figure 6.

The averaged wavelet energy in Figure 6 is obtained by the integration from the frequencies of 0.1 day^{-1} to 1 day^{-1}. This energy comparing to total frequency will to be used as the basis of the follow-up analysis. Figure 7 shows the distance between typhoon center, tide station, an azimuth (upper part), the time series of pressure, storm surge (middle part), the deviation of the storm surge and averaged wavelet energy (lower part)

The lower part of figure 7 shows that the variation of amplitude is small due to the energy of wavelet energy is closed to zero under the stable weather condition. However, when the typhoon center is approaching the tidal station, the typhoon make the barometric pressure of tidal station descend, the storm surge anomaly and average wavelet energies are gradually increased at this time. The air pressure of station decline to the lowest level under the typhoon center nears to the tidal station, the air pressure of station decline to the lowest level. At the same time the storm surge anomaly and averaged wavelet energies increase to maximum. When typhoon centre keeps off the tidal station gradually, the barometric pressure of tidal station runs high and the storm surge anomaly and average wavelet energies reduces gradually.

CONCLUSION

This paper adopts wavelet transform approach to study the phenomena of storm surge based on the observed tidal data. The characteristics of space and frequency distributions of this feature can be revealed by the wavelet energy. This demonstrates when the weather conditions are stable, the changes of the wavelet energy deviation closes to zero. However, the wavelet energy of storm surge increases along with the typhoon approaching. If the wavelet energy frequency is less than 1 day^{-1}, the distributions of storm surge graph are similar to that of energy curve. Therefore, according to the wavelet energy distribution of surge, it can acquire the time of the occurrence of max surge accurately. Meanwhile, it can confirm the influence time of storm surge on shore from the variety of the wavelet energy

The storm surge attains maximum under the condition of typhoon center is near the tidal station landing in this case from the Taiwan eastern water. However the time of maximum averaged wavelet energy is lag couple hours after typhoon center pass.

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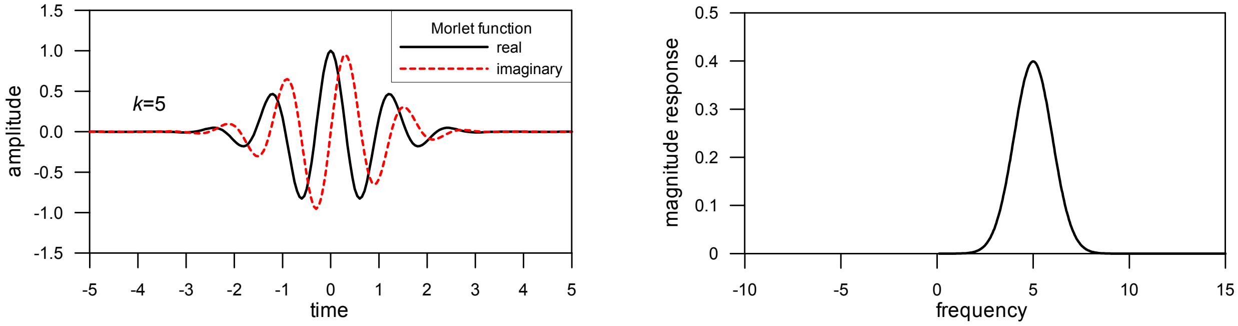


Figure 1 The shape of Morlet wavelet function in the time and frequency domain

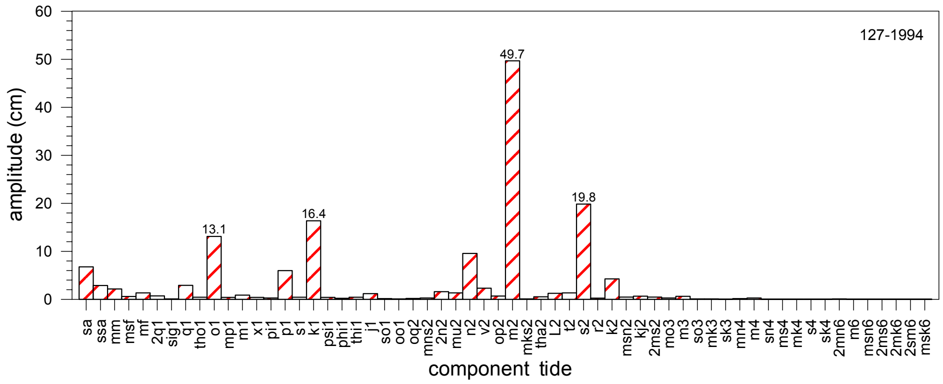


Figure 2 Sixty tidal components in 1994 for ChengKung tidal station.

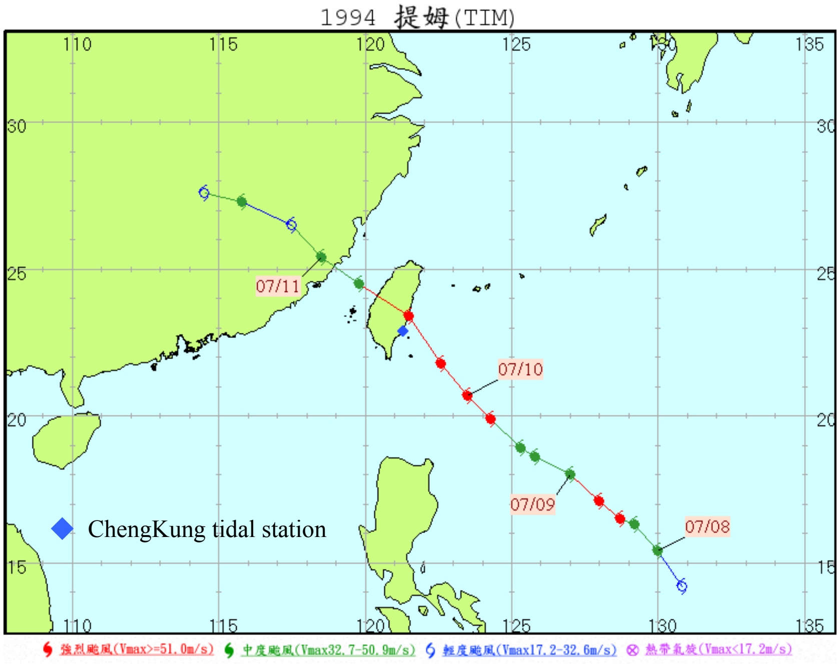


Figure 3 Tim typhoon route in 1994 (http://www.cwb.gov.tw/)

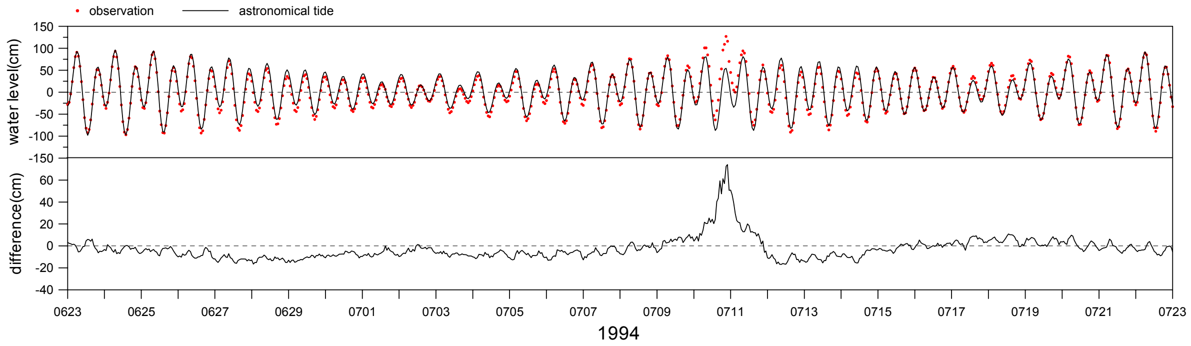
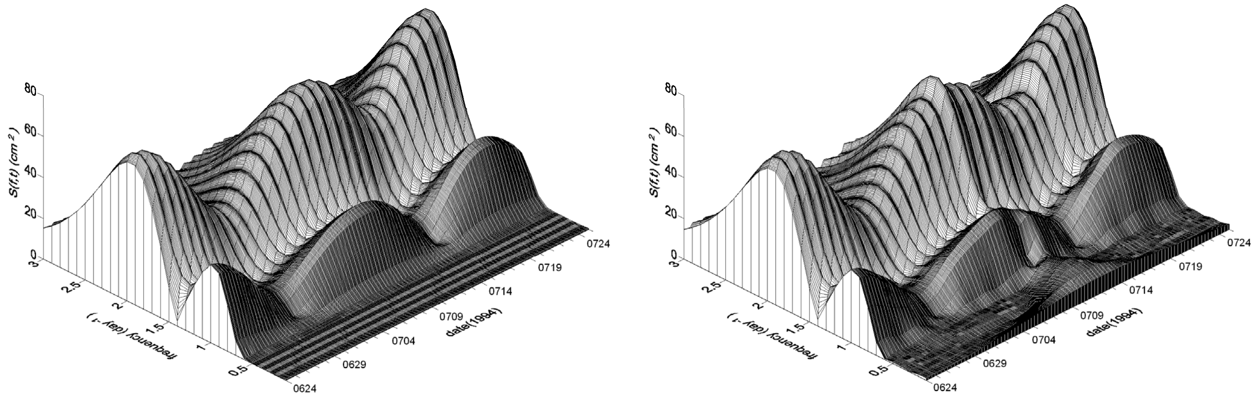


Figure 4 Tidal data series diagram at ChengKung tide station in Typhoon Tim.



The wavelet energy of the astronomy tide

The wavelet energy of the observation tide

Figure 5 The wavelet energy of observed tidal data (right) and astronomy tide data (left) during the Tim typhoon.

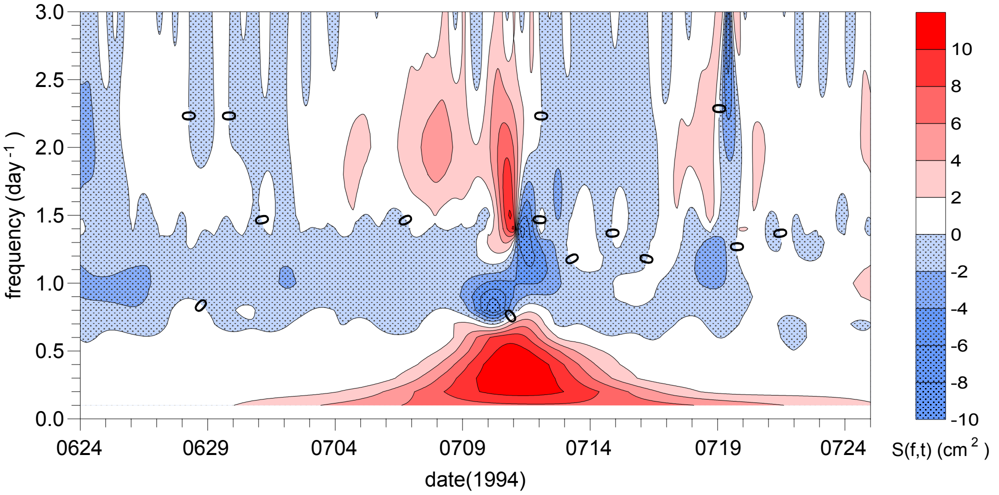


Figure 6 The wavelet energy distribution of storm surge during typhoon Tim.

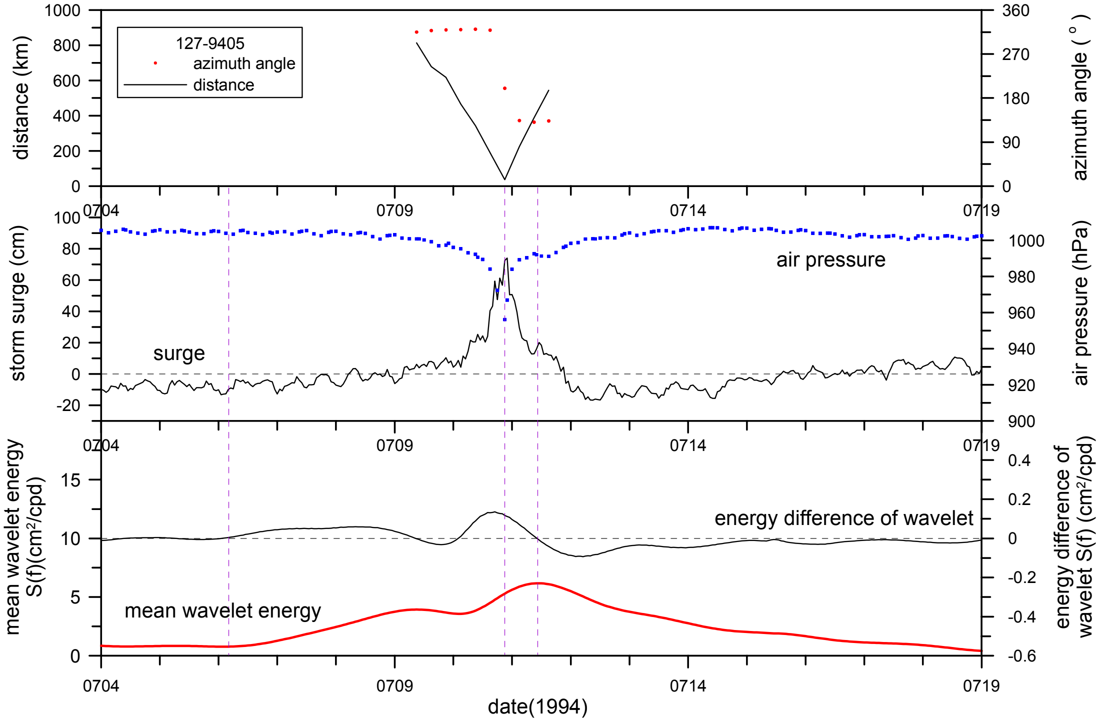


Figure 7 Diagram of time series of the distance between the typhoon center and tide station and an azimuth (upper part), the time series of pressure and storm surge (middle part), and deviation of the storm surge and averaged wavelet energy (lower part) during typhoon Tim in 1994.