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ORIGINAL RESEARCH PAPER

Seasonal variations of wind and waves over Taiwan waters

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Abstract We here investigate the frequency and intensity of oscillations in oceanographic data within intraseasonal time scales using spectral analysis of surface wind and wave time-series data collected at off-island weather stations or moored buoys around Taiwan. Data from marine weather stations were used to trace atmospheric conditions, while we used buoy data to examine sea states. The spectra and wavelet scalogram of the wind fields revealed oscillations with a period of around 20–33 days, and the energy density of the wind field at the off-island stations was stronger than that at the data buoy stations. However, the wavelet scalogram of the wave height measured at the buoy stations was stronger than its associated wind field. This long-period oscillation is consistent with the wavelet scalogram of the wind field calculated from the off-island weather stations. About 20–33 day oscillations exist within intraseasonal variations, which are closely linked to the atmospheric environment and to wind and ocean wave fields. Oscillations with a period of 5–10 days are a pronounced feature over northeastern Taiwan waters during the winter season and can be interpreted as the wave pattern following synoptic weather systems.

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Introduction

The heat storage capacity of the oceans, which cover about 70% of the Earth's surface, is four times greater than that of the land. This is one of the reasons that the world ocean plays a critical role in adjusting regional climate and in global climate variation. Thus, a great deal of research focus has been placed on air–sea interactions and their relationship with climate.

The Pacific Ocean is the largest body of water on Earth, and is therefore a good example to study air–sea interactions in relation to marine meteorology, including heat and moment transfer in different oscillations in different periods.

Many studies have revealed that some physical parameters in the Pacific follow long-period oscillations of 20–50 days. For example, Chen and Murakami (1988) reported the existence of 30–50 days of convective activities in the western Pacific, while Lau et al. (1988) reported 20–40 day oscillations in rainfall records over the ocean around East Asia. Every year, the oscillatory period of surface wind velocity from September to December is 20–25 days over the western Pacific (Hartmann et al. 1991).

Different kinds of time and spatial scale interactions between the atmosphere and the ocean exist, and momentum and heat transfer via these interactions. Krishnamurti and Mehta (1988) analyzed global sea surface temperature (SST) and discovered a 30–50 day oscillation period. They proposed that fluctuations in wind speed and SST control the heat and moisture fluxes on time scales of 30–50 days. Furthermore, Madden and Julian (1994) argued that oscillations on the scale of tens of days are important in affecting the characteristics of ocean waves, currents, and air–sea interactions. However, most studies to date have focused on the characteristics of oscillations that occur in the Equatorial Ocean or in the tropical Pacific. Similar studies of the oscillations present in subtropical areas are needed.

Taiwan, located between the tropics and the subtropics, lies on the border between the largest land mass and the largest ocean in the world, so that the marine and atmospheric environments here are complex and sensitive. Lau et al. (1988) reported the existence of low frequency oscillations in the atmospheric environment here, and Lee et al. (2000) indicated that ocean waves in Taiwan waters are mainly influenced by seasonal variations in the local wind field.

According to wind wave theory wind and ocean surface waves are linked to the momentum transfer between the air and the sea. As a result, many marine researchers study the relationships between wind and waves. In this study, we analyzed wind speed records from data buoys and off-island weather stations and detected oscillations on the scale of tens of days. Our results verify the conclusions of Lau et al. (1988) and Hartmann et al. (1991). As the relationships between wind and ocean waves are closely correlated, oscillations from the wave field also should be detectable, but previously this issue has received little attention. Thus, we examined atmosphere and ocean oscillations to verify the argument posed by Madden and Julian (1994), which attempted to reveal the existence of wind and waves in seasonal variations over Taiwan waters.

Description of stations and data collection

In this paper, we studied the seasonal variation of atmospheric–ocean phenomena by analyzing field data collected from six in situ stations around Taiwan, all of which are located in the open sea. Three of these are data buoys and three are weather stations (Fig. 1; Table 1). The buoys are located about 2.0 km offshore of Taiwan, where water depths are 20–30 m. In contrast, the weather stations are located on small islands located 45–70 km from Taiwan. Figure 1 illustrates that stations Hsinchu and Dongji Island are located in the fetch-limited straits, whereas the other four stations are located in the open sea, which can receive unlimited wind energy. We discuss the influences of the wind data from different locations in a later section. Wind data from both buoy and weather stations were processed in the same way. We calculated geometric mean wind speeds over 10 min measurement intervals. Data were recorded from January 1999 to November 2002.

Wavelet transform and its scalogram

Fourier transform is a useful tool in spectral analysis. Wavelet transform is similar to Fourier transform in that it breaks signals into their constituents. However, wavelet transform breaks the signal into different kinds of wavelets, which then can be scaled and shifted relative to the so-called mother wavelet. Wavelet transform allows exceptional localization both in the time domain, via translations of the wavelet, and in the frequency domain, via dilations. Wavelet transform of the time series, $f(t)$, is defined as the following inner product:

$$WT(a,b) = \int_{-\infty}^{\infty} f(t) \cdot \psi_{ab}^{*}(t)dt \tag{1}$$

where $\psi_{ab}^{*}(t)$ is the complex conjugate of $\psi_{ab}(t)$. $\psi_{ab}(t)$ is the wavelet function, which is generated from the mother wavelet function, $\psi(t)$, by translation and dilation:

$$\psi_{ab}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

where b is the translation parameter of the wavelet transform, which corresponds to the position of the wavelet as it is shifted through the time series, and a is the scaling parameter, which is related to the frequency of the time series.

The Morlet wavelet is one of the most commonly used mother wavelet functions, and it is used in this study. The Morlet wavelet is just a modulated Gaussian function, given by the equations:

$$\psi(t) = \exp(i\omega_0 t) \cdot \exp(-t^2/2) \tag{3}$$

$$\hat{\psi}(\omega) = \sqrt{2\pi} \cdot \exp\left[-2 \cdot \pi^2 \cdot (\omega - \omega_0)^2\right] \tag{4}$$

where ω_0 is the wave number of Morlet wavelet functions, and $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$.

Following Kareem and Kijewski (2002), the relationship between the scaling parameter, a, and the frequency of the time series, ω, in the wavelet is shown as:

$$\omega = \frac{\omega^*}{a} \tag{5}$$

where the parameter ω^* is the interval center of $\hat{\psi}$. The translation parameter, b, represents the location of the data in the time domain and is directly linked to the parameter t. Using the relationship between the scaling parameter and the frequency of the time series, the result of the wavelet transform, $WT(a,b)$, can be transformed again, and can be changed as a time–frequency signal representation, $WT(\omega,t)$, which is called the wavelet scalogram.

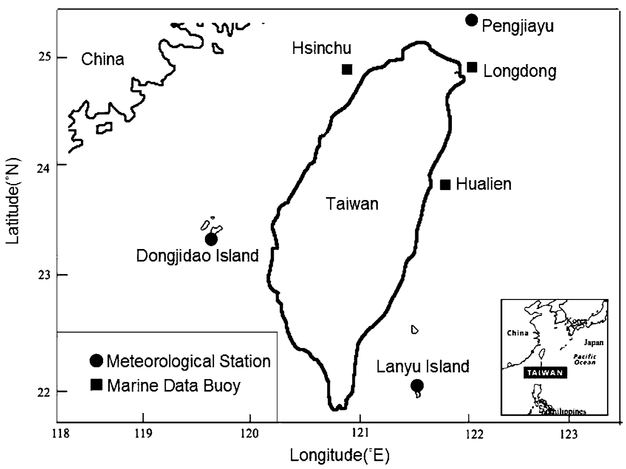

Fig. 1 Location of stations analyzed in this study. The buoys, installed in the sea, are located about 2.0 km offshore of Taiwan. The weather stations are located over 40 km away from Taiwan; the elevations of all weather stations are over 50 m on the offshore islands

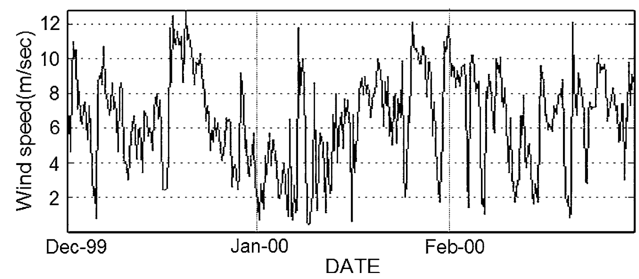

Fig. 2 Wind speed time series at Longdong buoy station. The long period oscillations were more obvious before the middle of January than after

Several researchers have used wavelet transform to analyze wind and waves (e.g., Liu 2000; Massell 2001; Afanasiev and Banakh 2006). We used this method to study the long-period oscillations of wind and wave time-series field data. Figures 2–4 show data from the Longdong buoy station. Figure 2 presents the wind time-series data, and Fig. 3 shows the spectrum derived from it by Fourier transform. The latter exhibits very fine resolution in the frequency domain of the energy density of the analyzed signal. Figure 4 shows the scalogram of energy density of the data revealed by wavelet transform analysis. The wavelet scalogram is contoured to show signal energy. Wavelet transform provides extra resolution to the signal energy density in the time domain, in addition to the frequency domain. Thus, this example illustrates the performance of the wavelet transform. It is a useful tool for determining the oscillation of atmospheric or oceanic data in time and in frequency domains simultaneously.

Figure 4 reveals that the long-period oscillations of wind speed occurred over periods of 25 days. Another clear long-period oscillation with a frequency of 0.14 (1/day) occurred in mid-January 2000, which represents the influence of the cold front system present during the winter season. However, the period of this oscillation varied in the wind time series. For example, the frequency of oscillations changed from 0.14 (1/day) to 0.33 (1/day) in February 2000. The long-period oscillations decreased gradually during February, as a result of the declining influence of the front system at the end of winter. The long-period oscillations were no longer apparent at the end of February.

Seasonal variations in the long-period oscillation

In this section we present our analysis of the wind speed and wave height time-series data recorded at the off-island weather and data buoy stations from 1999 to 2002. We analyzed the spectra and wavelet scalograms in order to understand the features of long-period oscillations and their relationship with seasonal variations in wind and waves over Taiwan waters.

Interpretation of wind spectra and wavelet scalogram

We first used the Fourier transform to detect wind variations at the three off-island weather stations and the three data buoy stations from 1999 to 2002. The wind spectrum

Table 1 Description of stations and data types used in this study

Station name	Station type	Data used	Station location	Altitude of the anemometer
Pengjiayu Island	Weather Station	Wind	On an Island. Distance to Taiwan 60 km	108 m
Hsinchu	Data Buoy	Wind, Wave	Offshore 1.5 km. Water depth 20 m	3 m
Dongjidao Island	Weather Station	Wind	On an Island. distance to Taiwan 45 km	53 m
Longdong	Data Buoy	Wind, Wave	Offshore 2.0 km. Water depth 30 m	3 m
Hualien	Data Buoy	Wind, Wave	Offshore 1.5 km. Water depth 23 m	3 m
Lanyu Island	Weather Station	Wind	On an Island. Distance to Taiwan 70 km	336 m

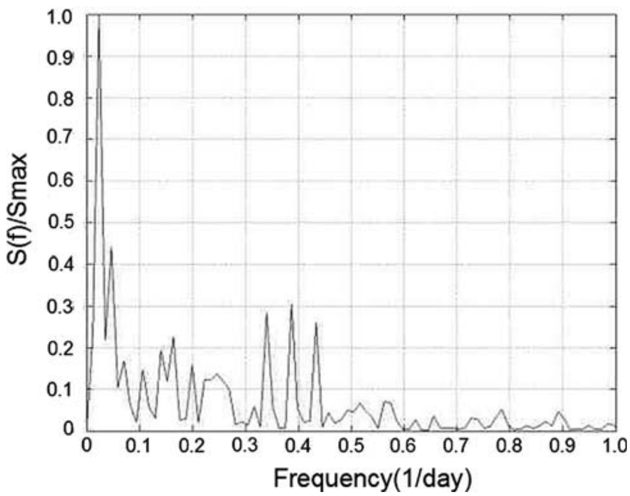

Fig. 3 Fourier spectrum from the time series shown in Fig. 2. The spectrum displays the averaging result of the whole time series, but information about partial energy from the whole time series could not be detected from the spectrum

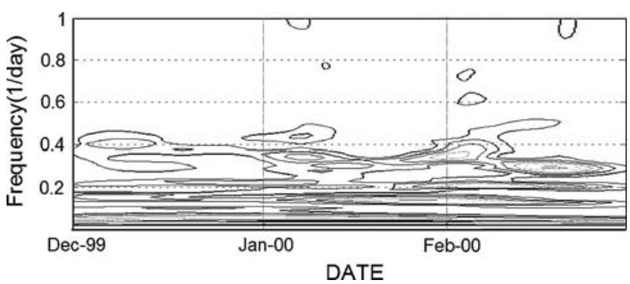

Fig. 4 Wavelet scalogram from the time series shown in Fig. 2. The contour in the scalogram is the strength of energy density. Information about time and the frequency domain can be obtained from the wavelet scalogram. The oscillations moved from 0.14 (1/day) to 0.33 (1/day) in February, 2000, which means that the low frequency oscillations decreased gradually

(Fig. 5) reveals the presence of dominant frequencies in the range of 0.03–0.05 (1/day), which correspond to periods of nearly 20–33 days observed for all stations. We verified the study of Lau et al. (1988) that reported the existence of low frequency oscillations in the atmospheric environment of East Asia. The spectra from the three off-island stations had more energy compared to the marine buoys. The peak frequency was concentrated within the range of 0.04–0.05 (1/day), which corresponds to the 20–25 day period seen in the off-island stations, as recognized by Hartmann et al. (1991). Thus, the analysis of field data supports the presence of seasonally variable wind data in the western Pacific Ocean.

A small quantity of energy density is apparent in all of the buoy station data around 0.55 (1/day); this phenomenon is not a long-period oscillation and is not considered further in this paper.

We here consider how the energy for the oscillations on the scale of tens of days is distributed between the different frequency–time domain. Wavelet transforms have the advantage of allowing investigation of the time variation of long-period oscillations. Figure 6, which shows the wavelet scalogram of the wind speed time-series data from the six stations, demonstrates two interesting features. First, the conspicuous energy associated with the dominant long-period oscillation (~25 days) occurred at the Pengjiayu, Dongjidao, and Lanyu Island stations. This strong signal phenomenon is particularly evident from summer to winter in 2000 and 2001. This pattern likely reflects the influence of the winter and summer monsoons. Second, oscillations with periods of 5–10 days occurred mostly from summer to winter, which can be interpreted as reflecting the variation of a synoptic-scale weather system during the summer monsoon, as well as the southward frontal passage that is accompanied by cold air masses from mainland China during the winter time.

Some features from the spectra and wavelet scalograms derived from the wind speed time series were more conspicuous in the off-island station data than in the buoy station data. The reason for the difference may be that the buoy stations are close to the coastal zone, and the observed wind speed is affected by the topography of Taiwan.

Interpretation of wave spectra and wavelet scalograms

Figure 7 shows the spectra of significant wave height at the Longdong, Hualien, and Hsinchu buoy stations from 1999 to 2002. The spectra pattern indicates that the energy density of the wave heights was mostly distributed in the frequency range of 0–0.3 (1/day). The peak frequency occurred in the range of 0.03–0.04 (1/day), which corresponds to a period of 25–33 days. The strongest spectra were observed at the Longdong buoy station, which means that the probability of high waves was greatest at this site.

The wavelet scalograms of wave height from the three buoy stations are shown in Fig. 8, the dominant long-period oscillation was 20–33 days. This oscillation showed two distinct spans at the Longdong buoy station: one from spring to fall of 1999 and the other from summer of 2000 to summer of 2002. This signal also was apparent in the record from summer of 2000 to summer of 2002 at the Hualien buoy station. After comparing the results of Figs. 6 and 8, we verified the spectra of wave height to be at a peak frequency period of 20–33 days at three buoy stations. This period oscillation was also observed from off-island wind speed scalograms. However, the wind signal of this period oscillation was not obvious at the buoy stations. This inconsistency is probably the result of the wind anemographs at the buoy stations being close to the coastal zone, while the wind signal from the wind anemographs at the

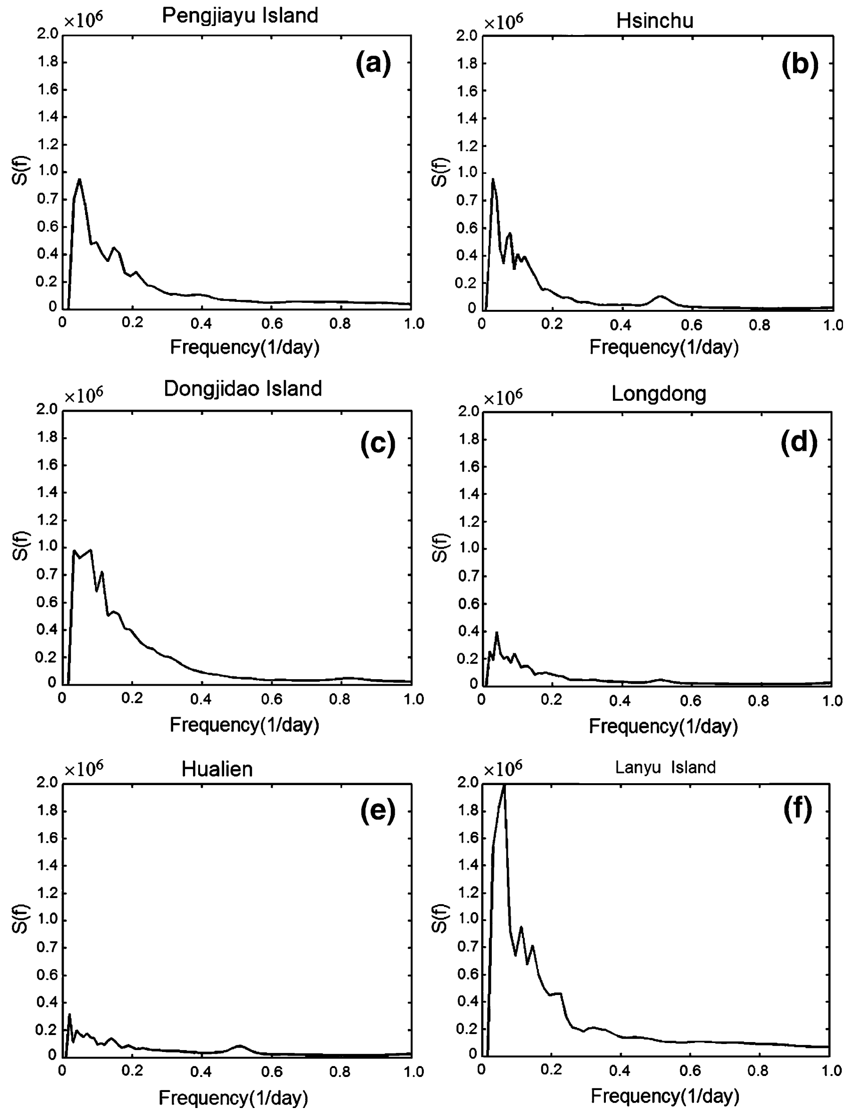

Fig. 5 Fourier spectra of wind speed from 1999 to 2002 for off-island and buoy stations: (**a**) Pengjiayu Island; (**b**) Hsinchu Buoy; (**c**) Dongjidao Island; (**d**) Longdong Buoy; (**e**) Hualien Buoy; and (**f**) Lanyu Island

buoy stations was affected by coastal topography. From the scalograms of wave height at buoy stations and wind signal at off-island stations, we revealed the existence of wind and waves in seasonal variations over Taiwan waters. 20–33 day oscillations existed within intraseasonal variations were closely correlated with wind and ocean wave fields. Our results are in accord with the work of Madden and Julian (1994) who argued that the oscillation on the scale of tens of days affects the characteristics of wind and ocean waves.

The intensity of wave height shown in the wavelet scalograms (Fig. 8) also indicates the presence of a 20–33 day oscillation at the Longdong buoy station; this site also exhibited stronger energies than did the Hualien station. This long-period oscillation of wave height was observed in northern and eastern Taiwan waters, while the intensity of the oscillation decreased from the northeast to the east of Taiwan. One possible explanation for this pattern is that the intensity of the wave pattern follows the synoptic-scale weather system, the intensity of which gradually decreases from north to south. This is also affected by the topography over the area offshore Hualien.

We also observed a 5–10 day oscillations from the wavelet scalograms for wave height. This oscillation was only observed during the winter season at the Longdong and Hualien buoy stations. We interpret this oscillation to be the result of the wind field within the seasonal weather system. The biweekly oscillation observed from summer to fall in 2000 is presently unexplained.

Conclusions

Taiwan is located in the subtropical zone of the western Pacific. Its weather system is influenced by both winter and

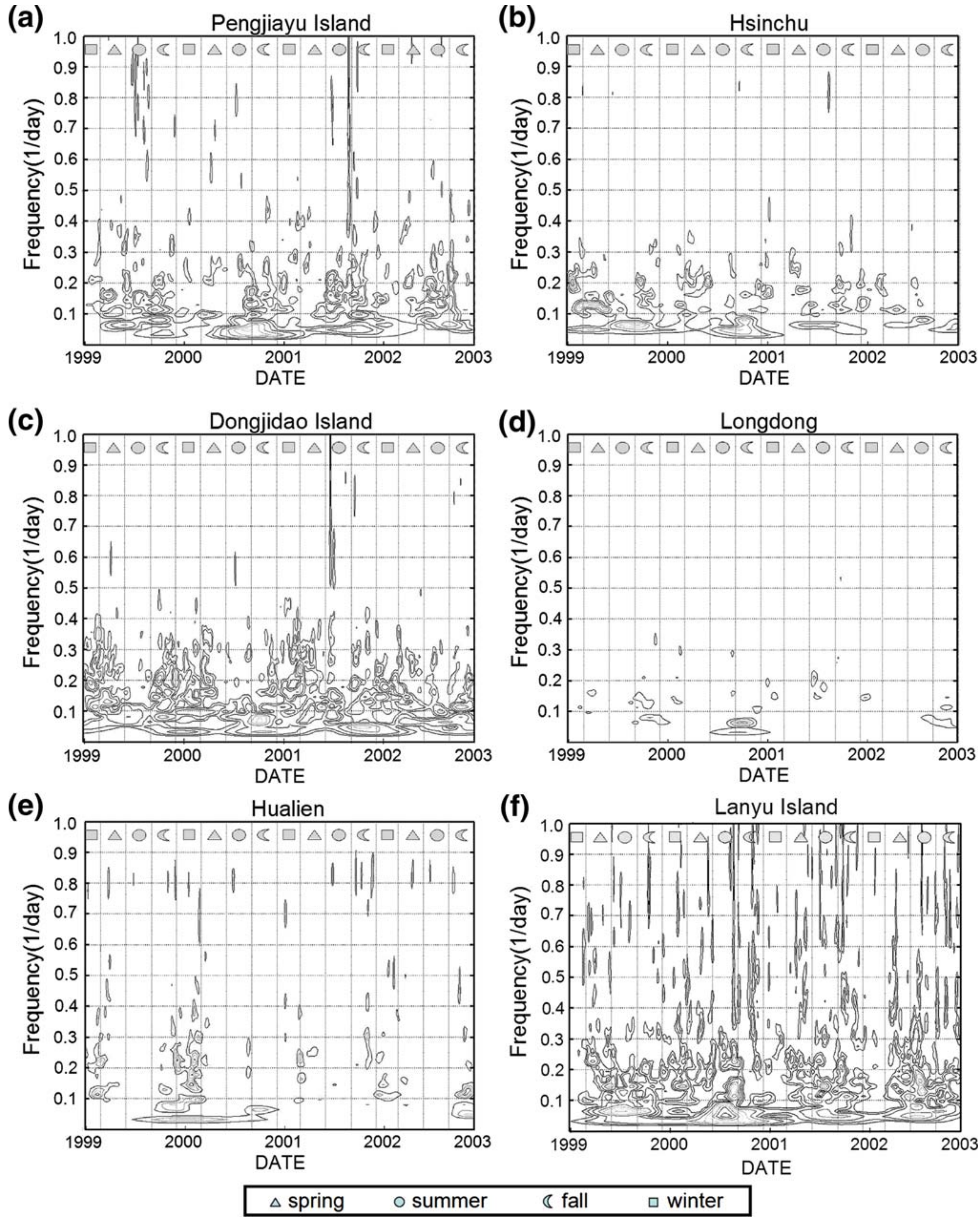

Fig. 6 Wavelet scalogram of wind speed from 1999 to 2002 for off-island and buoy stations: (**a**) Pengjiayu Island; (**b**) Hsinchu Buoy; (**c**) Dongjidao Island; (**d**) Longdong Buoy; (**e**) Hualien Buoy; and (**f**) Lanyu Island. The strong signal is particularly evident from summer to winter in 2000 and 2001

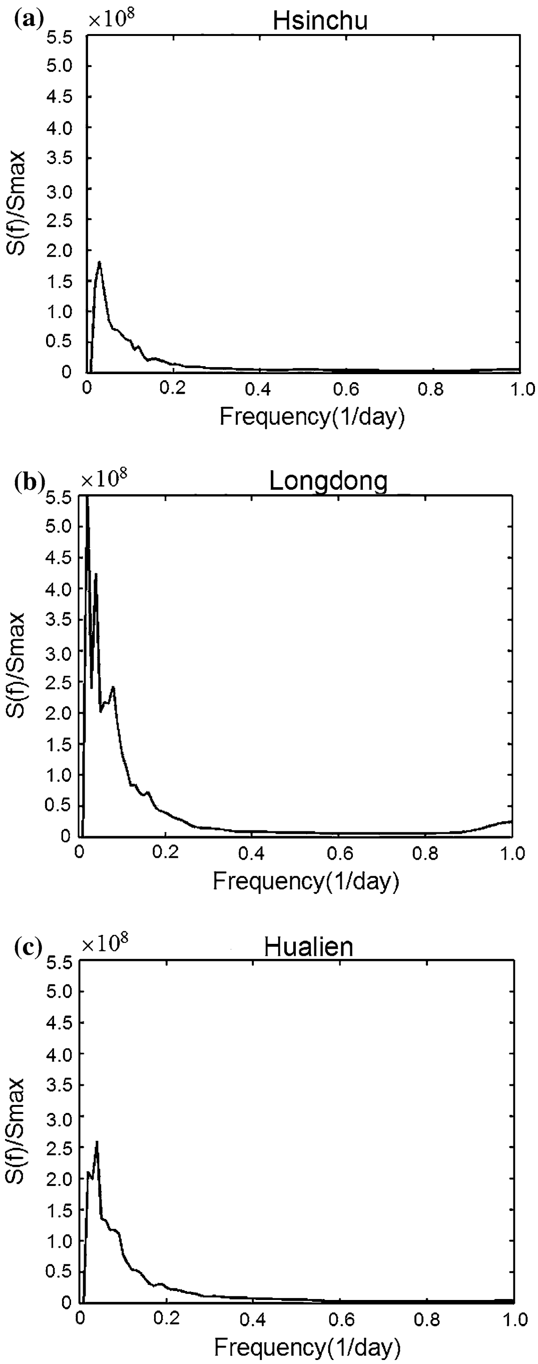

Fig. 7 Fourier spectra of wave data from 1999 to 2002 for buoy stations: (**a**) Hsinchu; (**b**) Longdong; and (**c**) Hualien. The spectral patterns indicate that the energy density of the wave height was mostly distributed in the frequency range 0–0.3 (1/day), and the peak frequency was located in the range 0.03–0.05 (1/day)

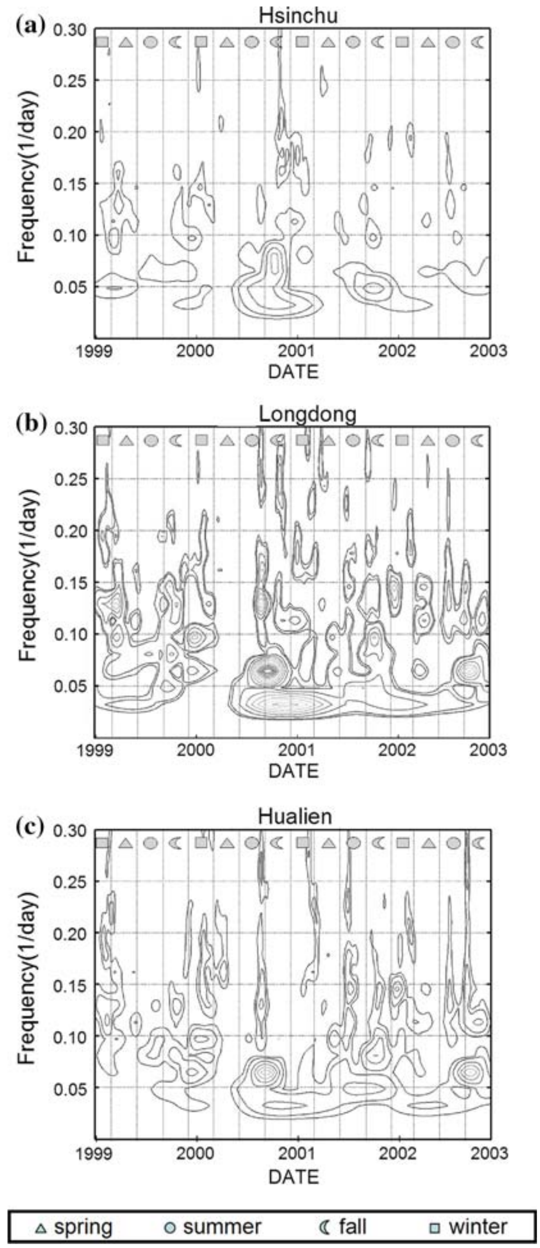

Fig. 8 Wavelet scalogram of wave data from 1999 to 2002 for buoy stations: (**a**) Hsinchu; (**b**) Longdong; and (**c**) Hualien. The Hsinchu buoy station, located in the Taiwan Strait, showed a dominant long-period oscillation of 20–33 days. This oscillation was apparently distinct in two spans for the Longdong buoy station: one from spring to fall in 1999 and the other from summer of 2000 to summer of 2002. This signal is also apparent in the record from summer of 2000 to summer of 2002 for the Hualien buoy station. The buoy station data from Longdong and Hualien were similar to the results of wind speed scalograms, as shown before for the off-island weather stations

summer monsoons, as well as by the typhoon season. Thus, the characteristics of wind and ocean waves are affected by seasonal changes in the weather pattern. In this study we used Fourier spectra and wavelet scalograms to analyze the long-period oscillation of wind and ocean waves within intraseasonal time scales for the seas around Taiwan. The wind spectra from three off-island weather stations showed a dominant frequency of long-period oscillation around 20–33 days. The peak frequency was concentrated within 0.04–0.05 (1/day), corresponding to a 20–25 day period.

This oscillation was also identified from the wavelet scalogram and was prominent in data observed from summer to winter in 2000 and 2001. This frequency may reflect the prevailing strong winds that are mostly influenced by winter and summer monsoons (c.f. Hartmann et al. 1991 in the western Pacific Ocean).

We also observed 5–10 day oscillations in the wind field at the off-island weather stations; we interpret this to be the result of the variation in a synoptic-scale weather system during the summer and the passage of weather fronts accompanied by cold air from mainland China to the south during the winter.

A spectrum of wave heights with a peak frequency periods of 20–33 days were observed at all three buoy stations. This observation verified the study of Lau et al. (1988) reporting the existence of low frequency oscillations in the atmospheric environment of East Asia. The long-period oscillation was also evident in the wavelet scalogram from 2000 to 2002 both northeast and east of Taiwan, corresponding to the Longdong and Hualien buoy sites. This is the only region where the winter 5–10 day oscillations occurred, a phenomenon that is due to the wave field of this area, and is accompanied by the wind field in the winter time.

Although spectra of wave height with a peak frequency periods of 20–33 days were observed at all three buoy stations, a wind signal of this period oscillation from the buoy stations was not evident. However, this period oscillation was consistent between off-island wind speed and the wave field recorded at the buoy stations, where it was strongly correlated during the summer and winter of 2000–2002 at the northeast and east of Taiwan and corresponds to the Longdong and Hualien buoy sites. Our work demonstrates the existence of wind and waves in seasonal variations northeast and east of Taiwan, and this result verifies the argument of Madden and Julian (1994) in relation to how oscillation on the scale of tens of days affects the characteristics of air–sea interactions. We also demonstrate that 20–33 day oscillations exist in the wave field due to the prevalence of high-energy waves in that region.

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