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Technical note: Common characteristics of directional spreading-steepness joint distribution in freak wave events

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Abstract

Seven freak wave incidents previously documented in the real ocean in combination with model hindcast simulations are used to study the variations associated with freak wave-related parameters, such as wave steepness, directional spreading, and frequency bandwidth. Unlike the strong correlations between the freak wave parameters and freak waves' occurrence which were obtained in experimental and physical research, the correlations are not clear in the freak waves occurred in the real ocean. Wave directional spreading-steepness joint distribution is introduced and common visual features were found in the joint distribution when freak waves occur among seven "freakish" sea states. The visual features show that freak wave incidents occur when the steepness is large and directional spreading is small. Besides the steepness is large and directional spreading is small, a long-duration relatively rough sea state is also necessary for the freak wave generation. The joint distribution is more informative than the sequential variation of any single statistical wave parameter. The continuous sea states of local large steepness and small directional spreading are supposed to be "freakish" sea states, and two-dimensional distribution visualization is found to be a useful tool for freak waves forecast. The common visual features of joint distributions supply an important cue for the theoretical and experimental research.

1 Introduction

Freak wave (also known as rogue wave, extreme wave, and unexpected wave) has been a hot topic during the last decades in engineering and science research. Recently, two candidate mechanisms that lead to freak waves are debated. One is linear and the other is nonlinear. The linear mechanism is considered as a result of linear focusing in fixed time and position due to water wave's dispersion, geometrical, current and wind force (Kharif and Pelinovsky, 2003). Nevertheless, freak wave is essentially a nonlinear phenomenon because of the large wave steepness of freak waves. Freak waves could also be produced as a result of the instability of water waves. Because of the abrupt and huge energy focusing characteristics of freak waves, the instability is more considered to be self-instability rather than externally forced. Benjamin and Feir (1967) found the instability of uniformly traveling trains of Stokes waves, the Benjamin–Feir instability (B–F instability). B–F instability is considered as the most probable candidate for the freak wave occurrence, which has been validated by lots of experimental and physical results. The studies on freak waves' dynamics are mostly focused on the B–F instability and the extreme wave events can be caused by B–F instability in different circumstances.

From the engineering point of view, the experimental and theoretical achievements should be validated in the ocean and be applied in practice. Its validation is difficult due to the rareness of freak waves and insufficient large-scale measurements. Most of the in-situ observations of freak waves are time-series surface elevation measurements, which can not provide spatial and directional spectrum information. There are some efforts that aim to set up a freak wave early-warning system in the ocean by experimental and theoretical research (Janssen, 2003; Mori and Janssen, 2006; Mori et al., 2011; Akhmediev et al., 2011a, b). Recent research found that some wave parameters have high correlation with freak waves' occurrence. Under unidirectional or small directional spreading (long-crested) conditions, the probability of freak waves is considered to increase when wave steepness increase and spectrum narrows (Gramstad and Trulsen, 2007; Waseda et al., 2009; Onorato et al., 2010). According to the results of hindcast simulated "freakish" sea states, it is expected to find the conditions that trigger freak waves in the ocean and check if the theoretical and experimental achievements are also applicable to oceanic freak waves. It will give useful information of certain circumstances which trigger freak waves and complement existing theoretical framework of freak waves.

2 Model configurations

As a state-of-the-art third generation spectral model, WAVEWATCH III (WW3) (Tolman, 2002, 2009) offers good descriptions of statistical sea states from a kinetic approach that well mimics directional spectrum. Short-lived freak waves can last only for 1 to 10 wave periods (Janssen, 2003) and hardly influence relatively long-time wave statistical characteristics (Toffoli and Bitner-Gregersen, 2011). Nevertheless, even in complex conditions, the evolution of spectrum with the spectral kinetic description appears to be consistent both qualitatively and quantitatively with solutions for the weakly nonlinear dynamical equations for water waves (Zakharov et al., 2007; Badulin et al., 2008).

Seven freak wave incidents in the ocean used in this study are shown in Table 1. Hindcast simulations are conducted by WW3 multi-grid technique. The coarse resolution for outer grid is $0.25^{\circ} \times 0.25^{\circ}$ and the fine resolution for the inner is $0.1^{\circ} \times 0.1^{\circ}$. We use the Cross-Calibrated, Multi-Platform Ocean Surface Wind Velocity (Atlas et al., 2011) to force the wave model. A reanalysis ocean current from National Marine Data & Information Service (China) is also taken into account in the model. The nonlinear wave-wave interaction term is calculated by high resolution WRT method (Tolman, 2002).

3 Results and discussion

Seven hindcast simulations are aimed to obtain the directional spectrum that covers time span for the freak waves. Statistical wave parameters, including significant wave height (Hs), wave steepness (δ), directional spreading (σ_θ), frequency peakedness (Q_p) and BFI (the ratio between steepness and spectra bandwidth) are derived from directional spectrum. The Hs, δ, σ_θ are defined following Tolman (2002). Q_p, BFI (Eqs. 1 and 2) are defined as Janssen and Bidlot (2003). We seek to check the parameters that set close relationship with freak wave occurrence and find physically-meaningful

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factors common to “freakish” sea states.

$$Q_\mathrm{p} = 2m_0^{-2} \int_0^\infty \sigma \left[\int_0^{2\pi} F(\sigma,\theta)\mathrm{d}\theta \right]^2 \mathrm{d}\sigma \tag{1}$$

$$\mathrm{BFI} = k_o m_o^{1/2} Q_\mathrm{p} \sqrt{2\pi} \tag{2}$$

Where k_o is the wave number, F is the frequency spectrum, m_o is the zero order moment of F.

Hs is an important parameter that characterizes the mean sea states. It always takes local extreme value (case1, case3, and case6) or near the extreme value when freak waves occur (Fig. 1). Many in-situ observations have demonstrated that the freak wave occurrence will increase significantly in quite rough seas (Guedes et al., 2003; Liu et al., 2009), so the quasi local extreme value feature is self-consistent to some extent. Case 5 indicates the freak wave events occur when the Hs are not the highest locally in continuous time series unlike others’ quasi local extreme value feature (Fig. 1, case5). This means freak waves can also take place relatively far away from local extreme sea states.

Steepness, spectra bandwidth and directional spreading are fundamental wave indices for freak wave occurrence. BFI has been considered as a good freak wave occurrence indicator (Janssen, 2003), yet it does not work very well for directional ocean waves (Gramstad and Trulsen, 2007; Onorato et al., 2010). Steepness in cases 1 to 6 is always above 0.08 when freak waves happen, which is a relatively large value for ocean waves’ statistical characteristics (Fig. 2). Spectra bandwidth is parameterized by frequency peakedness. The temporal change of frequency peakedness (Fig. 3) is often time similar with that of BFI (Fig. 4) for the direct proportion relation between them according to Eq. (2), such as cases 1, 4, 5, and 6. BFI at freak wave occurrence time are too small to be consistent with experimental and physical conclusions; BFI is supposed to be larger than 1 when freak waves occurs (Janssen, 2003). Similar results are also found by Bertotti and Cavaleri (2008), Burgers et al., (2008). Freak waves are

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influenced significantly by the directionality of water waves and it is almost impossible to generate freak waves in large directional spreading. As such, the directionality of ocean waves is thought to be responsible for the inconsistency. The directional spreading values among cases 1 to 6 are relatively small and are less than 25° except case2 (37.3°) (Fig. 5). It also demonstrates that the freak waves are not clearly related to any wave parameter's absolute value. In contrast, the freak waves should be more associated with the wave parameter's value relative to before and after during a period of time.

In summary, there are no obvious relationships between single wave parameters and freak wave incidents. Freak wave is more considered as a result of B–F instability, so it should be triggered under multi-conditions rather than one and it is not easy to find any clues from single wave parameters.

Joint distributions of multi-wave parameters that are in close relation with freak wave occurrence are more reasonable representation. Tamura et al., (2009), In et al., (2009) have introduced frequency peakedness-directional spreading joint distribution to explore the freak wave occurrence circumstance. The joint distributions of two freak wave samples that they used in their research show similar visual feature. Freak waves are strong nonlinear phenomena, whose occurrences are closely related to ocean waves' directionality. With a consideration of nonlinearity and directionality of ocean waves, wave directional spreading-steepness joint distribution is used to analyze the freak wave incidents in this research.

An obvious visual common feature is shown in six wave directional spreading-steepness joint distributions (Fig. 6). Although it is not obvious in any single parameter, the joint distributions show large steepness and small directional spreading characteristics at freak waves' time. This is quantitatively consistent with experimental and theoretical research conclusions (Gramstad and Trulsen, 2007; Waseda et al., 2009; Onorato et al., 2010). Second, the points are intensive around freak waves' time. It means that large steepness and small directional spreading are continuous over a long period of time. New information given in two characteristics implies certain circumstance

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that is suitable for triggering freak waves. A continuous sea state with large steepness (> 0.08) and small directional spreading (< 27°) lasting a long time means a "freak-ish" sea state. Third, the freak wave occurrence time is always near or in the extreme point of joint distribution. It demonstrates the freak wave sea states are near or at the maximum of wave steepness or minimum of directional spreading.

The case 2 was moderate sea state; the steepness was 0.082 and the directional spreading was 37.3° when the suspected freak wave occurred. The directional spreading in case 2 is too broad to trigger freak waves according to experimental and numerical research results. But for local characteristic, it is relatively small during seven days period (Fig. 6, case2). The freak wave occurrence point is also on the upper left corner of Fig. 6, which is similar with distribution in other cases. For this, it is thought that freak waves are dependent more on relative sea states rather than absolute sea states. Some freak wave incidents also occurred in rather low sea states with the scenario of rapidly changing conditions or crossing seas (Toffoli et al., 2004). Joint distribution in case2 (Fig. 6) shows a rapid change condition in direction spreading, and therefore it may be responsible for the suspected freak waves. The obvious visual commonness of the joint distribution shows local extreme conditions and rapid changes of sea state parameters. It always signifies a considerable increase of freak wave occurrence as wave steepness increases and directional spreading narrows. What's more, the long duration of this combination may be necessary for "freakish" sea states.

4 Conclusions

Both experimental and theoretical approaches suggest that the freak waves are triggered under small directional spreading, large steepness and narrow spectrum bandwidth conditions. The attempt to characterize freak wave sea states from single wave parameters is likely impossible. The characteristics with regard to variability of steepness and directional spreading are shown by joint distributions. There are regions that always mean "freakish" seas, which are situated on the upper left corner of the joint

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distribution figure. In long duration joint distribution of directional spreading-steepness, “freakish” sea states have a visual common feature that steepness is large and directional spreading is narrow relatively and the state last a long time.

Multi-dimensional evolution of wave parameters contains more information, so it is better suited for more variables analysis. The visual commonness feature would be supposed to be used as a tool to characterize freak wave sea states and can be validated by long time-series observation in the future.

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Table 1. Time and position information of freak wave incidents.

Case	Time(UTC)	Position	Note
case1	30 Dec 1980 05:30	$156^\circ 11' $ E, 31° N	Northwest Pacific
case2	23 Jun 2008 04:00	144–145° E, 35–36° N	Northwest Pacific
case3	13 Dec 1978 00:00	44° N, 24° E	Atlantic
case4	1 Jan 1995 15:20	$2^\circ 28'$ E, $58^\circ 11'$ N	New Year Wave
case5.1	18 Nov 1997 01:10	$1^\circ 44'$ E, $60^\circ 45'$ N	Alwyn oil platform
case5.2	20 Nov 1997 01:51		
case6	27 Jul 2002 12:00	22.17° E, 37.97° S	FA platform

case1, case2 and case3 are for ship sinkings which are thought to be caused by freak waves. case4, case5 and case6 are freak waves that are recorded by in-situ measurements.

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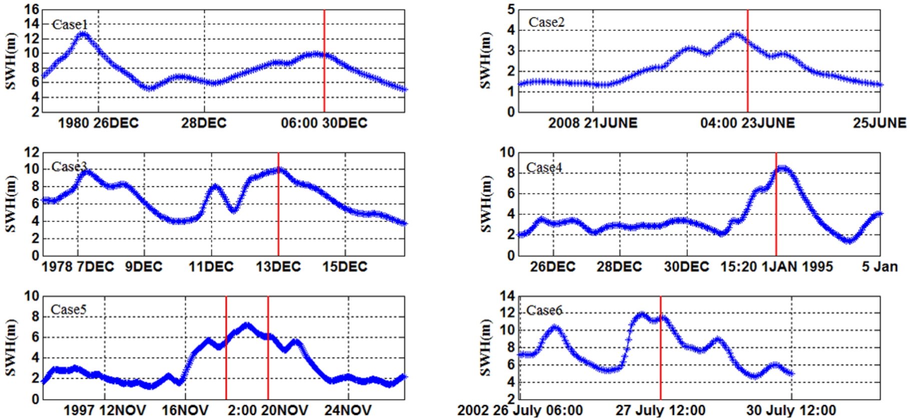

Figure 1. Time series of simulated significant wave height (case1–case6), redlines refer to the freak waves occurrence time.

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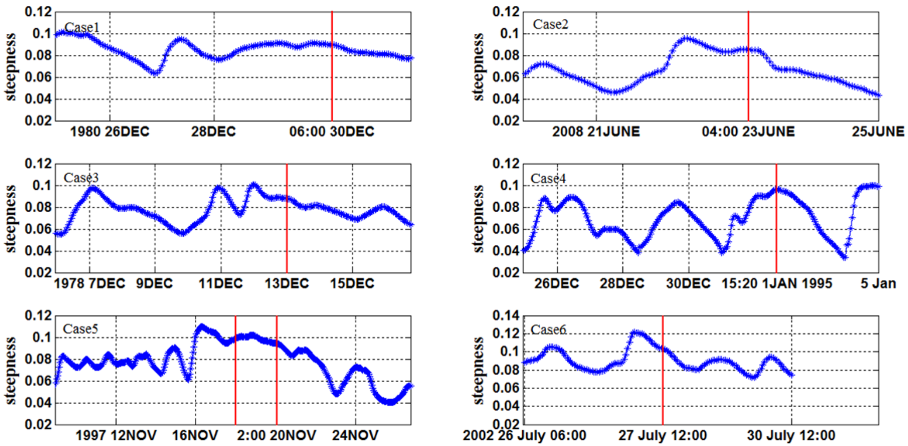

Figure 2. Time series of simulated wave steepness (case1–case6), redlines refer to the freak waves occurrence time.

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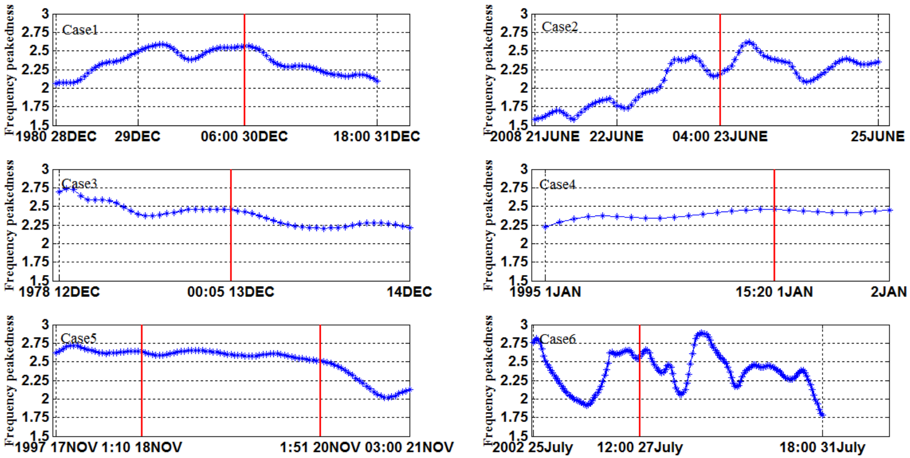

Figure 3. Time series of simulated frequency peakedness (case1–case6), redlines refer to the freak waves occurrence time.

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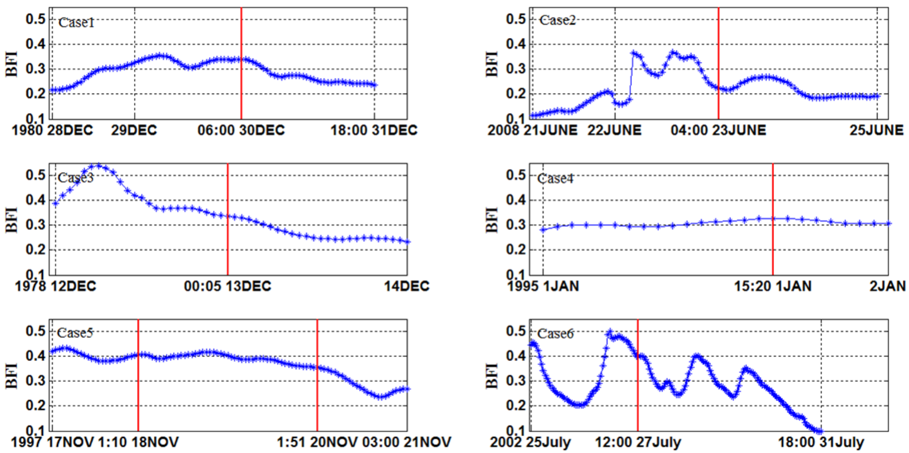

Figure 4. Time series of simulated BFI (case1–case6), redlines refer to the freak waves occurrence time.

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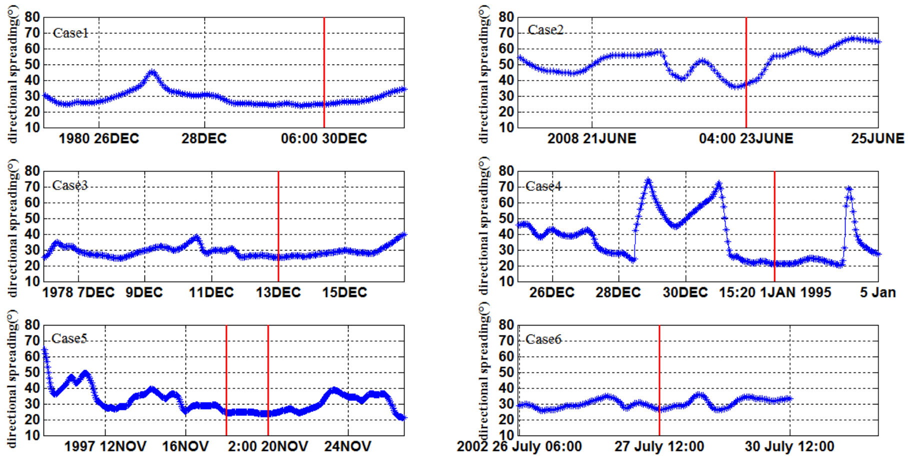

Figure 5. Time series of simulated directional spreading (case1–case6), redlines refer to the freak waves occurrence time.

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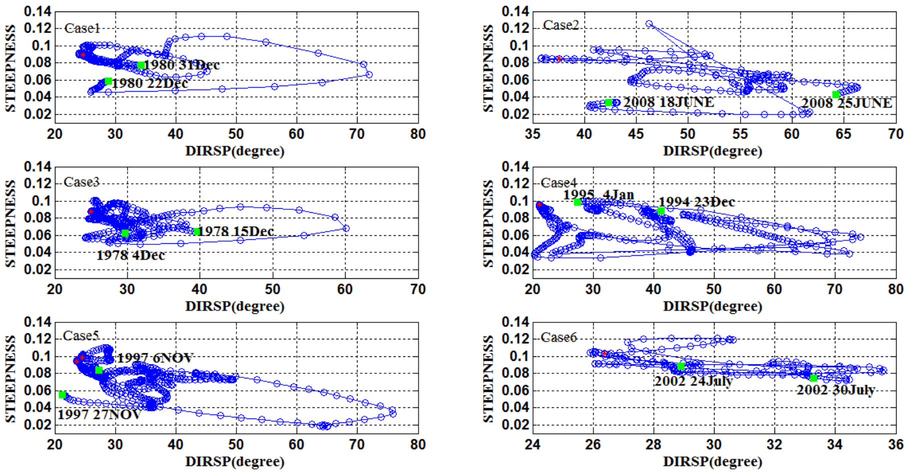

Figure 6. Joint scatter plot of directional spreading and steepness by 1 h during 7–20 days around the freak waves occurrence time (case1–case6), red star refer to the freak wave occurrence time, green rectangles refer to the start and end time.

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