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Space-time extreme wind waves: Analysis and prediction of shape and height

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ABSTRACT

In this study, we present the analysis of the temporal profile and height of space-time (ST) extreme wind waves. Wave data were gathered from an observational ST sample of sea surface elevations collected during an active sea state, and they were examined to detect the highest waves (exceeding the rogue wave threshold) of specific 3D wave groups close to the apex of their development. Two different investigations are conducted. Firstly, local maximum elevations of the groups are examined within the framework of statistical models for ST extreme waves, and compared with observations and predictions of maxima derived by one-point time series of sea surface elevations. Secondly, the temporal profile near the maximum wave crests is analyzed and compared with the expectations of the linear and second-order nonlinear extension of the Quasi-Determinism (QD) theory. Our goal is to verify, with real sea data, to what extent, one can estimate the shape and the crest-to-trough height of near-focusing large 3D wave groups using the QD and ST extreme model results. From this study, it emerges that the elevations close to the crest apex are narrowly distributed around a mean profile, whilst a larger dispersion is observed away from the maximum elevation. Yet the QD model furnishes, on average, a fair prediction of the maximum wave heights, especially when nonlinearities are taken into account. Moreover, we discuss how the combination of ST extreme and QD model predictions allows establishing, for a given sea condition, the portrait of waves with very large crest height. Our results show that these theories have the potential to be implemented in a numerical spectral model for wave extreme prediction.

1. Introduction

Extreme oceanic surface waves are topical for scientist, mariners and engineers (Muller et al., 2005). Indeed, their relevance and apparently elusive nature make extreme waves a well-studied topic by pure and applied researchers. In the oceanographic community, extreme waves are often referred to as “rogue” or “freak” (a notion which was first introduced by Draper, 1965) when the crest-to-trough height H is at least about twice the significant wave height H_s, or the crest height exceeds $1.25H_s$ (Dysthe et al., 2008; Kharif et al., 2009). For the simplest case of linear waves with infinitively narrow spectrum, the occurrence probability of rogue waves is rather small (a rogue wave with $H > 2H_s$ should appear on average once among about 3000 individual waves), and for a given sea state the theory fails to predict the probability of waves much larger than those in the surrounding field. Generally, rogue waves appear in a wave record apparently out of nowhere in small groups either singly (Gemmrich and Garrett, 2008; Kharif et al., 2009). The use of theoretical models that deviate from linearity increases the understanding of the occurrence and magnitude of extreme events for two principal mechanisms. First, waves with finite amplitude generate second- and higher-order nonlinearities that make wave crests sharper and higher (Forristall, 2000; Sharma and Dean, 1979; Tayfun, 1980). Second, considerable deviations from linearity are also given by nonlinear four-wave interaction that produces, under certain circumstances, very large waves in such a way that extreme events become more likely (Janssen, 2003; Onorato et al., 2013, 2001). By analyzing a large dataset of field measurements, Christou and Ewans (2014) provided evidence that rogue waves are not directly governed by sea state parameters, and at the time of the rogue wave event almost all frequency components with nonzero spectral values are approximately in phase with each other. Nonlinearities are also responsible of changes in the dynamics of large wave groups (Adcock et al., 2015).

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In addition to non-Gaussian sea conditions, large probabilities of occurrence of very high waves are attained when the statistics applied to one-point observations is extended to incorporate the probability that maxima occur over a specific sea surface region. The statistical distribution of maximum sea surface elevations over a spatial or spatio-temporal (ST) domain is thereby derived (Fedele, 2012; Krogstad et al., 2004). This approach considers the sea surface elevation as a multi-dimensional (2D space + time) Gaussian field, whose probability of maxima is linked to the geometrical and statistical properties of the ST field, according to the Piterbarg's theorem (Piterbarg, 1996) or the Euler Characteristic approach (Adler and Taylor, 2007; Adler, 2000). ST extreme stochastic model results have been assessed and discussed using numerical (Barbariol et al., 2015; Krogstad et al., 2004; Socquet-Juglard et al., 2005) and observational data (Benetazzo et al., 2015; Fedele et al., 2013), and extended to incorporate weakly nonlinear waves by Socquet-Juglard et al., (2005), Fedele et al., (2013), and Benetazzo et al., (2015). More recently, Fedele (2015) confirmed that in the ST models the second-order nonlinearities cannot be neglected, while it is expected a modest contribution due to third-order nonlinearities. The ST extreme model based on the Euler Characteristic technique will be used in this study to characterize the maximum elevations of specific 3D wave groups close to the apex of their development.

Indeed, there is a close connection between ST maxima and spatio-temporal modulation of unsteady and dispersive wave groups (Boccotti, 2000; Fedele et al., 2013). In particular surface elevations around the maximum wave crests can be derived by the shape of specific 3D wave groups whose apex occurs at time and position of the crest itself. In this study we use the principal results of the Quasi-Determinism (QD) theory (Boccotti, 2000, 1983) that predicts the ST Gaussian free surface displacement and the velocity potential around a large wave occurring at a fixed time and location. There are two versions of the QD theory: the first version (used in this study) analyzes the ST shape of wave groups reaching a maximum crest elevation, while the second version emphasizes on the shape when the groups experience the maximum wave height. The two forms of the QD are consistent with each other as they reveal that the two extreme states are specific conditions of well-defined ST wave groups. As important corollaries of the QD theory, Boccotti (2000) derived the asymptotic form of the probability distribution of wave heights (generalized for nonlinear waves by Alkhalidi and Tayfun, 2013), and characteristic periods of the highest waves in a sea state with a given energy spectrum. Both formulations of the QD theory were extended to second-order in the Stokes expansion by Arena (2005) and Fedele and Arena (2005). The QD theory was verified in different small-scale field experiments with undisturbed waves (Boccotti et al., 1993b) and waves interacting with structures (Boccotti et al., 1993a), but a thorough assessment using open sea data is still missing. However, scholars have already used the QD model results to characterize the shape of rogue waves. For example, this model has been corrected up to fifth-order by Walker et al., (2004) to clarify the magnitude and character of the nonlinear contributions in describing the shape of the Draupner "New Year" rogue wave (Haver, 2004). Walker et al., (2004) found that nonlinear contributions decrease rapidly as the order increases, and that effects of nonlinearity are more pronounced close to the apex of a crest.

In this study, the QD theory, at first- and second-order of approximation, has been used to investigate the shape of observed extreme waves, and obtain, as corollary, a predictive framework for their wave height H. Predictions of the ST and QD models are evaluated using real wave data recorded by means of a stereo wave imaging system (namely Wave Acquisition Stereo System, WASS; Benetazzo, 2006; Benetazzo et al., 2012) installed on an offshore oceanographic research platform in the northern Adriatic Sea (Italy). Space-time sea surface elevation fields were collected during an active sea state, and analyzed to extract time records at the spatial positions where the ST wave groups were close to the apex of their development stage (Benetazzo et al., 2015). We selected only groups whose maximum crest height exceeded the threshold $1.25H_s$, thus obtaining a sample of 23 rogue waves. These represent the sample used for our analysis. We review main results of QD and ST extreme theories aimed at improving (supported by field measurements) the link between them, attempting to define a predictive framework for the shape and height of large waves in a sea state with given directional energy spectrum.

The paper is organized as follows. In Section 2.1 we summarize and discuss main characteristics of the QD model for linear and second-order nonlinear wave fields. Moreover, results of the theory are used to derive an expectation of the crest-to-trough height of maximum waves. Section 2.2 describes the statistical model of ST extreme waves resulting in nonlinear sea surface elevation fields, which were measured in open sea using a stereo wave imaging system (Section 3). The latter are used to assess ST extreme wave predictions, which are also compared with outcomes of time-based statistical theories for wave extremes. In Section 4, results from QD and ST models are used to analyze the height and the temporal profile of extreme waves detected by the stereo system; results of both models are then combined in a framework to predict the profile and height of very high waves. Last section summarizes main findings of the study.

2. Theoretical framework

2.1. Expected shape and height of large waves

2.1.1. Gaussian wave fields

In this section we analyze and discuss basic elements of the QD theory for the general case of a Gaussian 3D random wave field with a given directional energy distribution. Let the sea surface elevation field, with zero-mean and standard deviation σ, be $\eta_1(x, y, t) = \eta_1(\boldsymbol{x}, t)$, where η_1 is the Gaussian component of the field $\eta(x, y, t)$, $\boldsymbol{x} = (x, y)$ denotes the horizontal coordinate vector, and t the time. Next, let $\eta_{1\mathrm{cm}} = \max\{\eta_1(\boldsymbol{x}_0, t_0)\}$ represent the elevation of a local wave maximum (crest) occurring at the horizontal position $\boldsymbol{x}_0 = (x_0, y_0)$ and instant $t = t_0$, such that the sea surface gradient $\nabla\eta_1(x_0, y_0, t_0) = 0$. Now we denote by $\boldsymbol{X} = (X, Y)$ the 2D horizontal vector measured from $\boldsymbol{x}_0$, and τ the time lag from t_0. In the finite coordinates $\boldsymbol{X}$ and τ the ST autocovariance function of $\eta_1(\boldsymbol{x},t)$ is given by

$$\psi_1(\boldsymbol{X}, \tau) = \mathrm{E}\{\eta_1(\boldsymbol{x}_0, t_0)\eta_1(\boldsymbol{x}_0 + \boldsymbol{X}, t_0 + \tau)\} \tag{1}$$

where E{} denotes expectation.

The QD model predicts that the sea surface elevation field surrounding the maximum wave crest is that of a stochastic ST wave group whose conditional mean surface profile $\overline{\eta}_1(\boldsymbol{X}, \tau)$ is given by (Boccotti, 2000, 1983, Lindgren, 1972, 1970; Slepian, 1962)

$$\begin{aligned}\overline{\eta}_1(\boldsymbol{X}, \tau) &= \mathrm{E}\{\eta_1(\boldsymbol{x}_0 + \boldsymbol{X}, t_0 + \tau)|\eta_1(\boldsymbol{x}_0, t_0) = \eta_{1\mathrm{cm}}\} \\ &= \overline{\eta}_{1,\mathrm{det}} + R_1(\boldsymbol{X}, \tau)\end{aligned} \tag{2}$$

where

$$\overline{\eta}_{1,\mathrm{det}} = \eta_{1\mathrm{cm}}\frac{\psi_1(\boldsymbol{X}, \tau)}{\sigma^2} \tag{3}$$

is of $O(\eta_{1\mathrm{cm}})$ and denotes the deterministic part of the process. The other way around, a large wave crest, with height $\eta_{1\mathrm{cm}}$, occurs where and when the wave is at its maximum elevation within a linear 3D group (with mean ST shape $\overline{\eta}_{1,\mathrm{det}}$, shown, for instance, in Fig. 1) that evolves over background random waves represented by $R_1(\boldsymbol{X}, \tau)$. The residual $R_1(\boldsymbol{X}, \tau)$ is Gaussian, with $\mathrm{E}\{R_1(\boldsymbol{X}, \tau)\} = 0$, and it is of $O(\eta_{1\mathrm{cm}}^0)$, and it will be neglected in the following analysis. The variance of the profile is a function of $(\boldsymbol{X}, \tau)$, it attains