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Wave spectral response to sudden changes in wind direction in finite-depth waters

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ABSTRACT

The response of a wind-sea spectrum to sudden changes in wind directions of 180° and 90° is investigated. Numerical simulations using the third-generation wave spectral model SWAN have been undertaken at micro timescales of 30 s and fine spatial resolution of less than 10 m. The results have been validated against the wave data collected during the field campaign at Lake George, Australia. The newly implemented 'ST6' physics in the SWAN model has been evaluated using a selection of bottom-friction terms and the two available functions for the nonlinear energy transfer: (1) exact solution of the nonlinear term (XNL), and (2) discrete interactions approximation (DIA) that parameterizes the nonlinear term. Good agreement of the modelled data is demonstrated directly with the field data and through the known experimental growth curves obtained from the extensive Lake George data set.

The modelling results show that of the various combinations of models tested, the ST6/XNL model provides the most reliable computations of integral and spectral wave parameters. When the winds and waves are opposing (180° wind turn), the XNL is nearly twice as fast in the aligning the young wind-sea with the new wind direction than the DIA. In this case, the young wind-sea gradually decouples from the old waves and forms a new secondary peak. Unlike the 180° wind turn, there is no decoupling in the 90° wind turn and the entire spectrum rotates smoothly in the new direction. In both cases, the young wind-sea starts developing in the new wind direction within 10 min of the wind turn for the ST6 while the directional response of the default physics lags behind with a response time that is nearly double of ST6.

The modelling results highlight the differences in source term balance among the different models in SWAN. During high wind speeds, the default settings provide a larger contribution from the bottom-friction dissipation than the whitecapping. In contrast, the whitecapping dissipation is dominant in ST6 while the bottom-friction generated by the new model with ripple formation provides a significant contribution during strong winds only. During low wind speeds and non-breaking wave conditions, a separate swell or non-breaking dissipation source term continues the decay of waves that cannot be dissipated by the whitecapping dissipation function.

1. Introduction

Wave growth in response to varying wind fields was studied during the JONSWAP field experiment (Hasselmann et al., 1973) in the North Sea, and the more recent field experiments, conducted at Lake George, Australia (Young and Verhagen, 1996; Young, 1999). For the first time under field conditions, the Lake George project obtained estimates of the spectral distribution of the wave breaking dissipation (Babanin and Young, 2005; Manasseh et al., 2006; Young and Babanin, 2006a). Measurements of the wind-input spectral function were conducted at moderate-to-strong wind forcing (Young et al., 2005), and the outcomes were parameterized as source functions suitable for spectral wave models (Donelan et al., 2005, 2006; Babanin et al., 2007). The input and dissipation source functions exhibited a number of physical features that were not previously accounted for. These have been implemented in the third-generation models (Babanin et al., 2010; Tsagareli et al., 2010; Rogers et al., 2012; Zieger et al., 2015) and have resulted in considerable improvement

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in the prediction of the wave energy and spectral downshifting of energy in the wave models (Zieger et al., 2015).

However, modelling of the directional response of waves due to sudden changes in wind direction, particularly in shallow coastal waters still remains a challenge. This is mainly because of the complex physics of the shallow water environment and the paucity of wind and wave measurements at finer time scales of few minutes within which the sudden wind changes occur. Such measurements are essential for the testing, calibration, and validation of wave models. In particular, when existing parameterizations are generally based on data where sudden wind shifts may not have been accounted for. Further, the dynamics of shallow water are more complicated than deep water considering the interactions with the coast and the sea-bed, the influence of local wind, and the enhancement of whitecapping and nonlinear interactions (Young, 1988).

In spectral wave models, the growth in wave energy is governed by the energy transfer equation where physical processes are described by individual source terms. The sum of all source terms determines the spectral evolution. Although all source terms contribute to the balance of the source terms, Young and van Vledder (1993) have demonstrated that the nonlinear term plays a central role in development of the spectrum and acts to balance the other source terms. The influence of the nonlinear term is especially dominant for sudden and large wind shifts (Young et al., 1987; van Vledder and Holthuijsen, 1993) where the nonlinear interactions enable the transfer of energy from the old wave system into the new developing young wind-sea.

The response of the wave spectrum for a sequence of wind-direction changes ranging from 30° to 180° has been investigated by Young et al. (1987) using numerical simulations. The simulations consisted of academic exercises with a third-generation model, 3G-WAM using discrete interaction parameterization and the Exact-NL (Hasselmann and Hasselmann, 1982) model with exact solutions for the nonlinear term. Their experiments were simplified by using a constant wind speed as the driving wind field in one-dimensional mode. In the absence of relevant field data, only a qualitative agreement was shown with the analyses of JONSWAP field measurements. The results indicated that for wind shifts of less than 90°, the high frequency components rapidly rotate to align with the new wind direction. For wind shifts of greater than 90°, there is no tendency for the spectrum to rotate in the new direction. Instead, a new secondary peak develops in the young wind-sea resulting in a bimodal spectrum. However, analysis of measured directional spectra during hurricanes from buoys in Western Australia did not indicate any bimodal peaks in either frequency or direction (Young, 2006).

While most of the earlier studies recognize the importance of the nonlinear interactions during wind shifts, there have been limited numerical studies using exact solutions of the nonlinear term in two-dimensional models, in particular for finite-depth waters. In addition to the complexities of shallow water dynamics, the intensive computational effort required for exact computations has been a major issue. With the recent technological advances in the development of parallel processing protocols and high performance computing that enable computations to be distributed among multiple cores and multiple processors of a computer, the application of two-dimensional models with exact solutions has now become more practical, albeit with limited domains or limited resolutions.

Previous studies (Hasselmann et al., 1980; van Vledder and Holthuijsen, 1993; Quanduo and Komen, 1993) of wave response to turning winds have generally been conducted in deep waters. A correction method was developed by van Vledder and Holthuijsen (1993) to handle inhomogeneities in the wave field, which have multiple causes, e.g. swells, radiative effects, wind inhomogeneities. Other constraints applied to the above models included the omission of events where the differences in mean wave direction and the local wind were more than 90°. This was done to reduce noise in the modelled waves resulting from slanting fetch conditions.

Most of the earlier studies mentioned above have been validated against observations of buoy data or remote sensing data, which are usually averaged at intervals of 20 min to few hours. Such observations are unable to account for the wind turns that may occur within a span of few minutes or seconds.

The present study differs fundamentally from the approach of previous studies (e.g. van Vledder and Holthuijsen, 1993) in that the modelling generates a two-dimensional non-homogeneous wave field albeit with spatially uniform wind conditions that vary in time.

This study seeks to investigate the wave response in finite-depth waters due to sudden changes in wind by conducting numerical simulations at high temporal and spatial resolutions using a third-generation spectral model. The nonlinear interactions are studied by the application of both the exact solution (XNL) and the discrete approximate interactions (DIA) methods using high performance parallel computing. The use of the wind and wave data for this study from the Lake George experimental site overcomes many of the issues associated with swell, slanting fetch, and wind variability over fetch encountered in open ocean and coastal areas. Lake George is an endorheic lake or a closed basin where there is no outflow (or inflow) to the rivers or the ocean. The study site at Lake George is thus free from swell contamination. An almost flat bathymetry and a fairly uniform wind across the large fetches of 10–20 km provide nearly ideal conditions for fetch-limited and depth-limited wind-generated wave measurements at Lake George. Nevertheless interactions with the bottom are an issue and have been examined in this study by including a new bottom-friction model (Smith et al., 2011) that explicitly accounts for site-specific physical parameters including grain size, specific gravity of the bed material, ripple formation, and sheet flow.

The purpose of the study is to employ modelling techniques that will lead to improvements in the predictive modelling of rapid wind shifts when the angles between the wind and the waves are large in finite-depth waters. This has strong implications for tropical cyclones where sudden wind shifts are ubiquitous. Rapid changes in wind direction occur frequently in milder conditions also, as will be described in this study.

This study analyses the wave response to sudden wind turning when the difference between the new wind direction and the existing wave direction is 90° and greater. Numerical experiments using the third-generation model, Simulating WAves Nearshore (SWAN) (Booij et al., 1999; SWAN Team, 2014), have been undertaken for two specific wind-shift events: (1) wind turning by 180°; and (2) wind turning by 90°. The objectives of the study are to evaluate the effectiveness of the new physics implemented in the third-generation models for the purpose of predicting the spectral response of the waves to turning winds at microscales of time and space; and to validate the model results with direct field observations at Lake George, Australia. Whilst the new physics (referred to as 'ST6') has been implemented both in SWAN (Rogers et al., 2012) and WAVEWATCH III® (Tolman, 2014; Zieger et al., 2015), SWAN has been selected for this study because the implicit numerical schemes employed in SWAN have been considered to be more efficient in undertaking simulations at high resolutions as required for this study than the explicit schemes of WAVEWATCH III®.

The following section provides a description of the SWAN model and the source functions. A brief description of the Lake George experiment and the field data used in this study is presented in Section 3. The numerical simulations using the SWAN model and the modelling results are discussed in Section 4 and the conclusions are summarized in Section 5.

2. SWAN model

SWAN is a third-generation phase-averaged model. The evolution of the wave spectrum is described by means of the radiative transfer