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Extreme wave analysis in the space-time domain: from observations to applications

Francesco Barbariol (1), Jose-Henrique Alves (2,3), Alvise Benetazzo (1), Filippo Bergamasco (1,4), Sandro Carniel (1), Yung Y. Chao (2), Arun Chawla (2), Antonio Ricchi (5), and Mauro Sclavo (1)

(1) Institute of Marine Sciences - Italian National Research Council (ISMAR-CNR), Venice, Italy (francesco.barbariol@ve.ismar.cnr.it), (2) Marine Modeling and Analysis Branch, Environmental Modeling Center, NCEP/NOAA, College Park, MD, USA, (3) Systems Research Group Inc., CO, USA, (4) DAIS, Universita Ca'Foscari, Venice, Italy, (5) DISVA, Università Politecnica delle Marche, Ancona, Italy

The occurrence of extreme waves is one of the most dangerous marine hazards and one of the most challenging sea surface phenomena to be understood. Many severe accidents and casualties at sea are ascribed to the occurrence of abnormally high waves. Despite significant efforts to investigate their occurrence, up to now research has not yet provided exhaustive experimental and theoretical frameworks able to fully explain the development of extremely large waves (i.e. waves that are outlier from standard wave statistics).
Recently, relying on the stereo-photogrammetric instrumentation known as "Wave Acquisition Stereo System", it was observed that the number of waves that can be labeled as "freak" increases significantly if the domain of observation is extended from the time (i.e. the classical point time series), to the space-time (i.e. a time sequence of sea surface snapshots covering an area). The empirical statistics of such extremely high waves gathered during a sea state over an area, outlying standard linear and nonlinear extreme value models, have been found in fair agreement with a statistical model accounting for the probability of a maximum crest height occurring in a space-time domain of given size. This model, developed by Fedele (2012) and extended to second order nonlinear waves by Benetazzo et al (2015), relies upon the Euler Characteristics approach of Adler and Taylor (2007), and upon the knowledge of kinematic and geometric properties of the sea state that can be obtained from the directional spectrum of the sea surface.
Therefore, new efforts have been put on applying this approach to provide an interpretation of the occurrence of extreme crest heights in sea states, observed via stereo photography. Results have allowed the development of applications in ocean engineering and weather forecasting. In the former, the statistical model of Fedele has been used to investigate the role of metocean forcings on the space-time extremes of sea states. To this end, analytical directional spectra that explicitly depend upon the wind forcing (e.g. Pierson-Moskowitz or JONSWAP frequency spectra, combined with a cos2 directional distribution) have been integrated to provide kinematic and geometric parameters of the sea state as a function of the wind speed and fetch length. Then, the SWAN numerical wave model has been modified in order to compute kinematic and geometric properties of the sea state, and run under different wave-current conditions and bathymetric gradients. In doing so, it has been possible to estimate the contribution to the space-time extremes variation due to the wind inputs, to current speed and to depth gradients.
Weather forecasting applications consist of using spectra simulated by wave forecasting models to compute space-time extremes. In this context, we have recently implemented the space-time extremes computation (according to the second order Fedele model) within the WAVEWATCH III numerical wave model. New output products (i.e. the maximum expected crest and wave heights) have been validated using space-time stereo-photogrammetric measurements, proving the concept that powerful tools that provide space-time extremes forecasts over extended domains may be developed for applications beneficial to the marine community.