Re-analysis of extreme sea state events modelling using a data-driven technique

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ABSTRACT

With the objective of answering marine and coastal engineering needs, sea state databases are created by hindcast simulations over long periods. The wave hindcast ANEMOC-3 database, built using the spectral model TOMAWAC for wave generation and propagation and the hydrodynamic circulation model TELEMAC-2D for tidal water levels and currents calculation, covers a period of 45 years from 1979 to 2023. During the calibration of the database, the numerical results must be consistent with past observational data (in situ or satellite measurements). Among other things, this process relies on calibration to determine "empirical adequacy". In particular, the calibration aims at simulating a series of reference events by adjusting some uncertain physically-based parameters until the agreement with available data reaches a satisfactory level. The objective of this work is to implement an efficient calibration algorithm, capable of processing measurements optimally, and to estimate the partially known parameters in the numerical model.

1. Introduction

Many problems in science and engineering require the estimation of unknown or uncertain parameters that will produce a solution that best fits a finite set of measurements. Modelling of marine flows and waves is no exception. Hindcast wave databases are sophisticated computer-based simulations providing complete time series of wave parameters and/or full wave spectra with a fine spatial resolution. They are powerful tools for a range of applications, including marine engineering, coastal infrastructure design, offshore operations, wave power assessment and environmental studies. By providing a detailed understanding of past sea states over several decades, they help researchers and professionals make informed decisions and predictions related to ocean environments and their impact on various activities. In this framework, EDF R&D LNHE together with the Cerema developed the hindcast wave database ANEMOC about 16 years ago with the main interest devoted to the French coastal areas of the Atlantic Ocean, English Channel and North Sea (Benoit *et al.*, 2008). With the significant advances in the means of observing continental waters, the ability to exchange data as computational results has become a growing need. Data assimilation algorithms for integrating observation data into real cases are now increasingly applied to hydraulic problems with two main objectives: optimizing model parameters and improving hydraulic and wave simulation and forecasting. The objective of this work is to implement an efficient calibration algorithm, based on data assimilation, to best estimate partially known parameters of the source and sink terms in the wave model (namely wind generation and white capping dissipation coefficients).

2. Optimal Calibration using variational data assimilation 3D-VAR

A variational data assimilation algorithm is here used for inverse parameter estimation from observations (here wave buoy data) and numerical results. On the one hand, observations are not perfect. On the other hand, one may have a first guess for the parameters (physical knowledge, previous simulations, etc.), but the latter is uncertain. To find the best compromise between measurements errors and parameters first guess errors, the optimization takes the form of a minimization problem, for the function defined as follows:

$$\boldsymbol{J}(\mathbf{X}) = \frac{1}{2}(\mathbf{X}-\mathbf{X_b})^{\mathbf{T}}\mathbf{B}^{-1}(\mathbf{X}-\mathbf{X_b}) + \frac{1}{2}\big(\mathbf{Y}-\boldsymbol{\mathcal{H}}(\boldsymbol{\mathcal{M}}(\mathbf{X}))\big)^{\mathbf{T}}\mathbf{R}^{-1}\big(\mathbf{Y}-\boldsymbol{\mathcal{H}}(\boldsymbol{\mathcal{M}}(\mathbf{X}))\big)$$

where $\mathbf{Y}$ is the observation vector, $\mathcal{M}$ the numerical model, $\mathcal{H}$ an operator from the simulation to the observation space, $\mathbf{X}$ the set of unknown parameters and $\mathbf{X}_\mathrm{b}$ a background knowledge (or first guess) of the parameters. The background and observation errors are represented by error covariance matrices, respectively denoted B and R. This formulation of the optimal search of control vector $\mathbf{X}$ is known as the traditional variational data assimilation cost function, called 3D-VAR.

3. ANEMOC hindcast wave numerical database application

The hindcast database ANEMOC is built from simulations with the TOMAWAC model (Benoit et al., 1996) and provides sea-state conditions over the Atlantic Ocean. It has been updated several times and now covers the period from 1979 to 2023. It is composed of computations over two nested meshes. The first mesh, called "oceanic", covers the most of the Atlantic Ocean. It has a relatively coarse spatial resolution with a minimum element size of approximately 20 km along the European coastline. Its main purpose is to make computations for providing boundary conditions to the other (finer) mesh, the "coastal" mesh. This latter one has an element size of under 1 km along the French coastline. The results presented hereafter concern the oceanic domain only. TOMAWAC solves the wave action balance equation with energy source/dissipation processes modelled with semi-empirical parameterizations. The physical processes considered in the numerical model are described in Teles *et al*. (2022). In this work, the focus is done on wind generation (wind coefficient $\boldsymbol{\beta_m}$ and $\boldsymbol{\alpha}$ of the Janssen's model (Janssen, 1991)) and white-capping dissipation parametrization (white-capping coefficients $\boldsymbol{C_{mout3}}$ to $\boldsymbol{C_{mout6}}$ from the Komen *et al.* (1984) model). The numerical model gives hourly output of wave parameters such as spectral significant wave height H_{m0}. The capability of ANEMOC to model regular and extreme sea states is here evaluated based on buoy measurements during the one-month period of February 2014, as several very intense storms occurred over the northern part of the Atlantic Ocean over this time frame.

This study has been carried out following the Application Programming Interface (API) framework described by Goeury *et al.* (2022). First of all, the identification of the most influential input parameters by sensitivity analysis has been led to target the calibration parameters. In this work, a polynomial chaos expansion has been carried out to estimate Sobol's sensitivity indices. Among all model parameters, the wind coefficient $\boldsymbol{\beta_m}$ of the Janssen's model is one of the most influencing variables. Consequently, as a first application, the calibration of the model is focused on this parameter. Fig. 1 displays the results of calibration over the one-month period. The result emphasises the efficiency of the inverse parameter estimation with simulated wave height much closer to the buoy measurements after calibration.

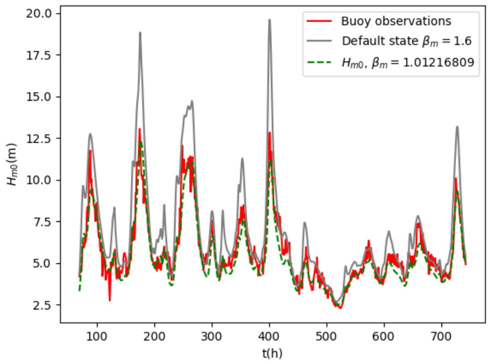

Fig. 1. Calibration results at Ouessant buoy (offshore French Britany coastline)

4. Outlooks

The data-driven algorithm deployed here could be extended to (i) different numerical models (larger and/or more refined area covering for instance the European coastline), (ii) test alternative parameterizations of the physical sink and source processes in the wave model to better reproduce extreme events, (iii) integrate more observation data (remote sensing altimeter data, for instance), or (iv) correct the simulated wave spectra using observations.

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