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Calibrating wave resource assessments through application of the triple collocation technique

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A R T I C L E I N F O

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A B S T R A C T

Numerical wave models are often used to hindcast wave conditions and predict the theoretical energy production from wave energy conversion (WEC) devices. It is widely acknowledged that numerical model suffer from bias's and uncertainties which ultimately affect the final predictions of WEC power. In this case study, a Simulating WAves Nearshore (SWAN) hindcast, based on the ECMWF wave and FNMOC wind boundary conditions, is used to predict sea states off the Canadian west coast and the triple collocation technique is applied to quantify the model result bias's, and systematic and random errors. To analyze the error and calibrate the results from the hindcast, two in-situ collocated wave measurement devices are deployed; A TriAxys wave measurement buoy and a Nortek AWAC. The triple collocation technique is used to compare the significant wave height and energy period parameters over a three-month period, from October to December 2014. The triple collocation technique assumes linear relationship between the measured value and true value, and outputs the bias, calibration slope and the measurement random error. This study implements two previously utilized calibration regimes, a single value and monthly calibration regime, as well as presenting two novel methods to improve the impact of the calibration; a bivariate calibration and a spectral calibration. The two standard calibration techniques resulted in negligible improvements in data correlation. The spectral method suffered from high computational cost and only 3.4% improvement in significant wave height correlation. The bivariate calibration regime, following the International Electrotechnical Commission (IEC) wave resource histogram parameters, resulted in 5% and 26% improvements in the significant wave height and energy period correlations respectively. Calibration of the SWAN hindcast reduced the gross wave energy transport values by 900 MWh, yet the final WEC production estimates only varied by 1.5 MWh but greatly improved their time-series correlation. It is shown that the triple collocation technique, under the bivariate distribution regime, provides a more realistic presentation of future WEC power production and eliminates known short-comings of numerical model outputs.

1. Introduction

Wave energy and the associated potential power production from wave energy converters holds great promise as an abundant, carbon neutral source of electricity generation for generations to come. The International Energy Agencies (IEA) Ocean Energy Systems (OES) [1] estimates that the global wave resource could provide up to 29,500 TWh of carbon-neutral electrical energy annually through the use of wave energy conversion (WEC) technologies.

Numerical wave models are often used to hindcast wave conditions over decade-long time frames and large spatial areas. In some cases, these models assimilate altimeter and in-situ measurement device data [2]; such as remote measurements from satellite observations and radars, or in-situ wave measurement buoys or acoustic wave and current profilers (AWAC). However, it is widely acknowledged that both numerical wave models and wave measurement systems suffer from systematic biases and random uncertainties [3]. A wave measurement is only one realization of the underlying spectrum; slight variations in measurement device, sensors, measurement timing, frequency bands and record length will all result in variations in the final spectrum. In contrast, a wave model provides an estimate of the underlying spectrum. The numerical model biases and uncertainties result from a number of factors including, but not exclusive to, input boundary conditions

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and their resolution, numerical model physics and associated assumptions, numerical errors, and inaccurate and insufficient bathymetric resolution.

It is important to be able to quantify the errors and uncertainties associated with both the numerical hindcast and the measurement data source, before utilizing the wave data to predict the power or annual energy productions from WEC's.

The triple collocation technique has been widely used to estimate measurement errors and the systematic biases between three different data sources [4–9]. Stoffelen [10] first used the triple collocation technique to estimate the wind speed error characteristics from wind buoys, an environmental forecast model, and a European Remote-Sensing Satellite (ERS) scatterometer. Caires and Sterl [7] built on this work and applied the triple collocation technique to validate both significant wave height and wind speed fields from European Centre for Medium Range Weather Forecasts (ECMWF) re-analysis ERA-40 against wave measurement buoys, ERS-1 scatterometer, and Topex altimeter. Uncertainties and calibration constants were determined on both an annual and latitude based matrix. More recently, Janssen [8] compares wave heights from an ECMWF wave forecasting model for both buoy data and altimeter wave data from ERS-2. Janssen et al. suggests that monthly calibration parameters were necessary to capture the variation in the calibration coefficients. Abdalla et al. [11] used Jason-2 radar altimeter, in-situ measurements and a non data assimilating version of the ECMWF model. They presented relative measurement errors for both significant wave height and wind speed, based on discretizing measurement value magnitudes, monthly time spans and collocation distances.

In order to assess the impact of numerical hindcast (inherently dependent on the input boundary conditions) and wave measurement device uncertainties on annual WEC energy production, this study investigates the impact of model hindcast and device uncertainty under four differing calibration regimes; firstly, the impacts of model calibration under the regimes suggested by Caries and Sterl [7], and Janssen et al. [8] are quantified. Subsequently, two novel model calibration regimes are introduced and their performance quantified; one based on a bivariate distribution of significant wave heights and energy periods, while the other utilizes the entire frequency domain variance density spectrum.

The paper is structured as follows: Section 2 details the database of SWAN, buoy and AWAC measurements used as inputs to the triple collocation technique. In Section 3, a brief overview of methodology applied as part of the triple collocation technique is presented and discussed. Section 4 presents the calibration regimes investigated and the differences in the resulting bias, calibration parameter beta and uncertainty are discussed. The correlation impact of the differing calibration regimes and a discussion of regime limitations, is presented in Section 5. Section 6 explores the impact of the triple collocation method on wave energy period and presents results on the variation in energy production from WECs. Section 7 and Section 8 discuss the inconsistencies in the study results and presents conclusion's respectively.

2. Wave measurements and models

The West Coast Wave Initiative at the University of Victoria runs an unstructured Simulating WAves Nearshore (SWAN) V40.91A model for the west coast of Vancouver Island in order to provide a 10 year hindcast of wave conditions [12]. SWAN is a third generation phase-averaged Eulerian numerical wave model designed to simulate the propagation of waves in shallow near-shore areas [13]. The model utilizes offshore wave conditions from the ERA-interim 6-hourly reanalysis [14], provided by the European Centre for Medium Range Weather Forecasts (ECMWF), and 3-hourly wind forcing inputs from the Fleet Numerical Meteorology and Oceanographic Centre (FNMOC) COAMPS model [15]. The errors of the SWAN-based hindcast system are directly linked to the errors in both boundary condition datasets, but a discrete analysis of boundary condition errors is beyond the scope of this study. For simplicity, the SWAN-based hindcast system will be referred to as the SWAN model.

Within the region of interest, the model spatial resolution is ~100 m/node, outputs data at hourly temporal resolution, the variance density spectrum features 36 frequency bins, between 0.035 Hz and 1.00 Hz, and 3° directional resolution [3].

In order to apply the triple collocation technique, two wave measurement devices were deployed; a moored AXYS Technologies TRIAXYS wave measurement buoy and a seafloor mounted Nortek Acoustic Wave And Current (AWAC) profiler. These devices were collocated at Port Renfrew, Canada during September–December 2014 in ~30 m of water. As the buoy hull and incoming wave interact, the TRIAXYS buoy utilizes rate gyros and accelerometers to record the buoy motions and calculate the directional wave spectrum. Conversely, the AWAC utilizes acoustic measurements of the water surface and orbital velocities of particles near the surface to recreate the directional wave spectrum. For this study, the buoy data has a 20-min temporal resolution with a 0.005 Hz spectral and 3° directional resolution, while the AWAC data is at a 1 h temporal resolution and a 0.01 Hz spectral and 2° directional resolution.

Fig. 1 presents the significant wave height from the buoy, AWAC, and SWAN between October 1st and December 31st, 2014.

Fig. 2 illustrates the high degree of correlation between the two measurement devices (buoy and AWAC), while Fig. 3 indicates the significant scatter when comparing the SWAN model against the AWAC data. The AWAC and buoy data feature a correlation of 0.97, a root mean square error (RMSE) of just 0.12 m and a scatter index (SI) of 0.10. As shown in Fig. 2, the linear best-fit follows the perfect

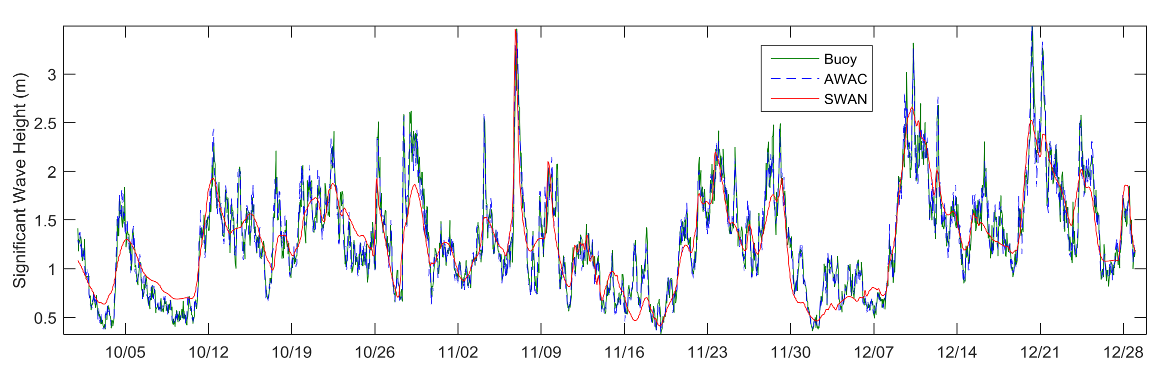

Fig. 1. Raw significant wave heights from SWAN model, AWAC and TriAxys buoy.