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Generation and validation of the Chilean Wave Atlas database

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A B S T R A C T

This paper summarizes the calibration and validation of a 35-year wave hindcast database used to create the Chilean Wave Atlas. The hindcast was generated with the Wavewatch III wave model and consists of: i) time series of wave statistical parameters in a $1^\circ \times 1^\circ$ grid throughout the Pacific Ocean; ii) spectral data at points latitudinally spaced every 2° off the Chilean coast. A comprehensive calibration process was undertaken in order to assess the performance of statistical parameters at different locations under normal and extreme conditions. A multi-criteria performance score was defined to select the optimal Wavewatch III model configuration. Few buoy records available and a broad set of satellite data were used in this process. A correction method was then applied to the statistical parameters in order to reduce systematic errors of the model. The Atlas showed better performance when compared to existing databases under normal wave conditions. However, the accuracy was shown to be lesser for the highest wave heights, consistently following the behaviour of other databases. This deficiency in the estimate of extreme values has important consequences in the design of coastal structures, and its improvement remains to be solved.

1. Introduction

Paradoxically, ocean waves have been poorly investigated in Chile, a country with near 4.000 km of continental coasts and a maritime territory larger than its land surface. Extreme waves have shown significant variability between existing hindcasts compared at the same locations along Chile (Gallardo et al., press; Winckler et al., press). This local variability confirms the findings of Ardhuin et al. (2011), who found that the possible cause of differences in global wave hindcasts is the accuracy of wind reanalysis, especially during the strong winds responsible of the most energetic sea states.

The project entitled "Chilean Wave Atlas" (referred as Atlas hereafter) was conceived in order to make the information of the wave climate freely-accessible to the public. The main purpose of the project is to create a wave hindcast database with a locally calibrated model and an accompanying document that comprehensively describes the wave climate in Chilean coasts, including a thorough characterization of uncertainty and errors. The Atlas, documentation and database are accessible in www.oleaje.uv.cl (Beyá et al., 2016).

Wave climate statistics based on NOAA/NCEP and ECMWF wave reanalysis are available in coarse regional maps off the Chilean coasts (e.g., Cornett, 2008; Cruz, 2008). Wave climate studies in the region stem from the recent interest in understanding the global impacts of climate change (e.g., CEPAL, 2011; Hemer et al., 2013a,b, 2015; Wang et al., 2014, 2015), while others de-

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Acronym list

AOC1	Main wave hindcast generated for the Atlas
AOC2	Alternative wave hindcast used to show variability of extreme waves in the Atlas
BIAS	Bias, the average of the error
CNES	Centre National d'Études Spatiales
CFSR	Climate Forecast System Reanalysis
CFSv2	Climate Forecast System version 2
CIMFAV	Centro de Investigación y Modelación de Fenómenos Aleatorios, Valparaíso
CS05	Caires and Sterl (2005)
DIA	Discrete Interaction Approximation (Hasselmann et al., 1985)
DOP-MOP	Dirección de Obras Portuarias, Ministerio de Obras Públicas
ECMWF	European Centre for Medium-Range Weather Forecasts
EEM	Explorador de Energía Marinas
ENVISAT	Environmental Satellite
ERA-Interim	Global atmospheric reanalysis from 1979, continuously updated in real time
ERS-1	European Remote Sensing Satellite 1
ERS-2	European Remote Sensing Satellite 2
ESA	European Space Agency
ETOPO1	1 arc-minute Gridded Global Relief Data
ETOPO2v2	2 arc-minute Gridded Global Relief Data
GEBCO	General Bathymetric Chart of the Oceans
GFO	GEOSAT (Geodetic Satellite) Follow-On
GMD	Generalized Multiple DIA (Tolman and Grumbine, 2013)
GSE	Garden Sprinkler Effect (Booij and Holthuijsen, 1987)
GSHHS	Global Self-consistent, Hierarchical, High-resolution Geography
IFREMER	Institut français de recherche pour l'exploitation de la mer
IOWAGA	Interdisciplinary Ocean wave for geophysical and other applications
LN1	WWIII-Switch, Linear energy growth, Cavaleri and Malonotte-Rizzoli parametrization (1981)
MAE	Mean absolute error
MPI	Message Passing Interface
MPS	Model performance score
NASA/CNES	National Aeronautics and Space Administration/Centre National d'Études Spatiales
NCEP	National Centers for Environmental Prediction
NL2	WWIII-Switch, nonlinear wave interactions resolved by DIA method
NL3	WWIII-Switch, nonlinear wave interactions resolved by GMD method
NOAA	National Oceanic and Atmospheric Administration
NOAA WWIII	Archived wave modelled data from NOAA WWIII operational model
NOAA CFSR	Wave reanalysis based on CFSR winds
PR2/UQ	WWIII-Switch, Ultimate Quickest scheme and diffusive correction method for GSE alleviation
PR3/UQ	WWIII-Switch, Ultimate Quickest scheme and spatial averaging method for GSE alleviation (Tolman, 2002)
RMSE	Root mean square error
R^2	Coefficient of determination
SEED	WWIII-Switch, linear energy growth by seeding algorithm (Tolman, 2014)
SI	Scatter index
SHOA	Servicio Hidrográfico y Oceanográfico de la Armada
SS	Skill score
ST1	WAM3 source term package
ST2/STAB2	WWIII-Switch, Growth and Wind Dissipation Package by Tolman and Chalikov (1996)
ST3/STAB3	WWIII-Switch, Growth and Wind Dissipation Package by WAM cycle 4 (Bidlot et al., 2005)
ST4	WWIII-Switch, Growth and Wind Dissipation Package by Ardhuin et al. (2010)
ST6	WWIII-Switch, Growth and Wind Dissipation Package by BYDRZ
WAM	3rd generation wave model (WAMDI, 1988)
WWIII	Wavewatch III v.4.18 (Tolman, 2014)

rive from wave energy assessments (e.g. Arinaga and Cheung, 2012; Barstow et al., 1998; Cornett, 2008, 2009; Cruz, 2008; Gunn and Stock-Williams, 2012; Krogstad and Barstow, 1999; Pontes, 1998; Santo et al., 2016). On a local level, wave energy assessments with higher spatial resolution at selected nearshore locations along the Chilean coasts have been carried out by Barstow et al. (2009), Contreras and Winckler (2008), Cruz et al. (2009), DGF (2013), Guzmán (2012), Mediavilla and Sepúlveda (2016) and Monárdez et al. (2008). These studies, based on both proprietary and freely available wave databases obtained using Wavewatch III (Tolman, 2014) and WAM (WAMDI, 1988), do not provide detailed information of the offshore wave climate.

Unfortunately, the quality of data sets off the Chilean coasts is poor due to the lack of a permanent offshore data buoy network, as those existing in United States (e.g., Hamilton, 1980), Spain (Clemente, 2001) and Italy (Arena et al., 2001). Indeed, the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) intermittently operates a single Watchkeeper directional buoy located offshore Valparaíso and occasionally deploys short term nearshore buoys or ADCP's for specific purposes. A wave assessment study (CORFO-INNOVA 09CN14-5718) produced buoy records in central and south Chile during 2011 and 2013, which comprise the longest records available for the calibration and validation of the Atlas.

The present study explains the methodology for the calibration and validation of the database of the Atlas. Section 2 describes the data sources used for wave modelling and explains the methodology for model calibration and error correction. Section 3 presents the results of the model calibration, correction of systematic errors, validation of the database and comparison with existing wave hindcasts. Section 4, presents the discussion of the results and Section 5 the conclusions of the study.

2. Methodology

Data sources, modelling and systematic error correction methodologies used for the generation of the Atlas database are described below.

2.1. Satellite and buoy data

The following satellite altimeter data, available at different time and space resolutions since 1991, were collected from the following databases: ERS-1 (Attema and Francis, 1991), ERS-2 (Francis et al., 1995), ENVISAT (Louet, 2001), Jason-1 (Ménard et al., 2003), Jason-2 (Lambin et al., 2010), GFO (SPAWAR, 2010) and