Ph.D. Program in Civil, Chemical and Environmental Engineering
Curriculum in Engineering for Marine and Coastal Environments

Department of Civil, Chemical and Environmental Engineering
Polytechnic School, University of Genoa, Italy.

Wave hindcast development and applications: from wave energy assessment to wave systems detection in the Pacific Coasts of Central America and Mediterranean Sea

Manuel Alejandro Corrales Gonzalez

WAVE HINDCAST DEVELOPMENT AND APPLICATIONS: FROM WAVE ENERGY ASSESSMENT TO WAVE SYSTEMS DETECTION IN THE PACIFIC COASTS OF CENTRAL AMERICA AND MEDITERRANEAN SEA

BY

MANUEL ALEJANDRO CORRALES GONZALEZ

Dissertation discussed in partial fulfillment of

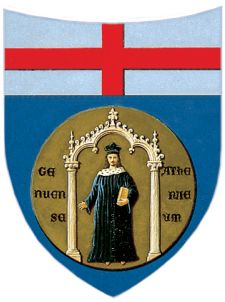
the requirements for the Degree of

DOCTOR OF PHILOSOPHY

Civil, Chemical and Environmental Engineering

curriculum in Engineering for Marine and Coastal Environments,

Department of Civil, Chemical and Environmental Engineering, University of Genoa, Italy



December, 2023

Adviser:
Prof. Giovanni Besio - Department of Civil, Chemical and Environmental Engineering, University of Genoa, Italy

External Reviewers:
Prof. Giuseppe Giorgi - Marine Offshore Renewable Energy Lab, Politecnico di Torino, Italy

Prof. Jesús Portilla-Yandún - Departamento de Ingeniería Mecánica, Escuela Politécnica Nacional, Ecuador

Ph.D. program in Marine Science and Technologies
Curriculum in Engineering for Marine and Coastal Environments
Cycle XXXVI

To my parents, Matilde and Victor

ACKNOWLEDGEMENTS

I would like to thank God and my family in first instance, especially my mother and my father. They have always given me their love and full support in the pursuit of my dreams. I thank the support and kindness of my siblings Daniela, Tavo and Jenny throughout my studies period.

I am very grateful for the tireless company of Inés, who has always supported me unconditionally, for her lovely care she gives me, and for her presence in very important moments of my life.

I am grateful for the integral and exemplary formation I have received from Professor Giovanni Besio, he is a person I admire; I am grateful for his professional guidance during my doctorate. Thank you Giovanni for giving me the opportunity to work in the field of marine and coastal engineering in a high-level international environment.

To Francesco De Leo, I thank him for his collaboration, companionship, honesty, guidance and for being a friend I have come to hold in high esteem. To Andrea Lira-Loarca, I thank her for sharing much of her knowledge with me, for accompanying me from the beginning of my PhD in this process, for her wise advices and her nice friendship; she together with Francesco represent a pair of mentors to me. All the best for you guys.

I also would like to thank Professor George Lavidas for opening my mind to the questioning of many academic challenges and also for integrating me in my research internship into his working group at TU Delft in an immediate and very kind way.

I would like to thank all my PhD colleagues and administrative personnel at the University of Genoa for having shared good times with me. I will keep the nice memories and an extraordinary intercultural learning that I got from them. At the end of the day, the important thing is that all of them have understood that *la pura vida* is not about being idle but about carrying on with the daily life and transmitting a positive vibe to everyone.

DECLARATION

I hereby declare that the work presented here has been developed by me, or in collaboration with other colleagues, in an authentic manner and has not been submitted to any other institution for the purpose of obtaining a degree or academic qualification.

Chapter 2 of this dissertation has been published in the journal Sustainability, titled as: *Feasibility of Wave Energy Harvesting in the Ligurian Sea, Italy*, under the authorship of Manuel Corrales-Gonzalez, George Lavidas, Andrea Lira-Loarca and Giovanni Besio.

The work presented in Chapter 3 is under review by the journal Frontiers on Marine Science, a paper entitled *Wave energy assessment and wave converters applicability at the Pacific coast of Central America*; co-authored by Manuel Corrales-Gonzalez, George Lavidas and Giovanni Besio.

Chapter 4 was published in the journal Applied Ocean Research, under the title *Climate analysis of wave systems for multimodal sea states in the Mediterranean Sea*; co-authored by Francesco De Leo, Guilia Cremonini, Manuel Corrales-Gonzalez and Giovanni Besio.

Manuel Corrales-Gonzalez
December 2023

SUMMARY

Ocean waves carry various implications for socio-economic activities in the marine environment. The study of ocean waves at a given site is crucial e.g., to ensure safety to infrastructures placed both off-shore and in coastal areas, to characterize littoral transport and coastal morpho-dynamics, to infer useful information for marine eco-systems management, among others. Therefore, the proper characterization of the wave climate is of paramount importance.

In this framework, wave main characteristics such as significant wave height, mean and peak periods and directions, can be forecasted and/or reconstructed over past time slices (i.e., the so called hindcast or reanalysis) through proper numerical models capable to describe the main physical processes involved in the growth and development of random sea states. Several wave hindcast databases have been developed worldwide; however, to date, high-resolution databases are still not available in the Central American Pacific region. Nonetheless, in-situ wave records have been logged at several coastal locations in the area, allowing a proper calibration and validation of wave modelling, opening the door activities of the present PhD research.

The Central American Pacific region analized in this study includes the national sea waters belonging to the following countries: Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Colombia and Ecuador. This study yields a reliable benchmark for the regional wave climate that will serve as a reference for activities such as coastal protection, navigation, fishing, offshore operations and tourism, which are relevant to this region. In particular, maritime trade by vessels is of pivotal importance along the studied region owing to the presence of the Interoceanic Panama Canal.

Waves represent an energetic resource that can be adopted as a new sustainable source of energy to supply into the renewable electricity mix. The net wave energy production is directly related to the wave characteristics and the employed extraction devices. There exist wave energy harvesting devices that work on different principles of mechanical energy transformation and their adaptation to the regional wave conditions is crucial for an efficient exploitation of the resource. Whilst wave energy is currently in the early development stages, the evaluation of the efficiency of converters and their adoption in specific regions represents an important milestone for the implementation of wave energy exploitation projects.

The main scope of the present PhD thesis is to develop and analyze a sound and rich wave hindcast in order to provide useful indicators for marine energy exploitation projects and for the characterization of the wave climate. First, an optimized wave hindcast is implemented, spanning the 1980-2021 period, by the use of the WavewatchIII numerical model. Wave characteristics are estimated over an unstructured computational grid with a resolution of 1 km between nodes along the Pacific coastline of Central America. The zeroth-order wave height (H_{m0}) produced by the wave model is calibrated on the basis of satellite data. Calibrated wave data is then validated with wave records measured at different locations distributed in the coastal

zone.

Next, a wave energy assessment and the analysis of the wave power potential is developed considering nine energy converters through the Central American Pacific region; after validating the workflow for wave energy assessment, the analysis is replicated in the Ligurian Sea by accounting for eight different devices. Both marine environments present wave characteristics that differ from each other, however, the wave energy potential in the Ligurian Sea and in the Pacific coast of Central America are quantitatively similar, both are classified as low energy seas. The best wave energy converters were found for both regions going through an analysis of the best performing scale in order to improve the called "Capacity Factor" of the different devices.

Finally, as complementary research, a methodology for the detection of directional wave systems is presented: the method relies on image segmentation algorithms and is applied to several hindcast nodes in the Mediterranean Sea. As a result, a new methodology for the automated detection of wave systems was developed, which also allows to estimate the occurrence and simultaneously of the existing wave systems in the Mediterranean Sea, with a specific attention related to those ones crossing seas, important mainly for safe navigation, coastal and offshore engineering projects, and marine energy exploitation.

INDEX

List of Figures

List of Tables