1. INTRODUCTION

1.1. Wave hindcast in the Pacific of Central America

Several socioeconomic activities are developed in coastal regions such as tourism, maritime commercial trade, fishing, and coastal management, which depend on the wave information for its safety and monitoring.

These activities interact daily with the hydrodynamic forces of the sea, among which waves are the most energetic component, and hence the need to study them. Therefore, monitoring the state of the sea is necessary to provide safety for coastal activities, however, the fact that wave measurements are available in certain locations leads to estimates this forcing along the oceans and their propagation into the coastal zone [Goda, 2010].

A wave hindcast consists of the reconstruction wave conditions of previous years based in several input data as bathymetry, wind drag forces, shorelines among others. The development of a wave hindcast requires numerical wave modelling, which simulates the state of the sea over space and time [Liu et al., 2021, Moeini and Etemad-Shahidi, 2007].

Existing numerical wave models estimate their results according to the physics solved by the model. Two prevalent types of sea wave models are employed to simulate the wave conditions, the spectral ones and wave-phase resolving ones, being the wave spectral models the commonly employed to determine the wave conditions over oceans and marine regions whose domains have a large surface area.

The spectral wave models are advanced numerical tools designed to simulate and analyze the behaviour of ocean surface waves in terms of the wave energy balance, either for wave hindcasting, nowcasting and for predicting wave conditions (wave forecasting) [Rogers and Wittmann, 2002]. These models are based on the concept of wave energy spectra, which characterizes the distribution of wave energy density across different frequencies and directions. The governing equations for spectral wave models corresponds to the wave action equation, which mainly describe the evolution of wave energy density spectra over time and space [Hasselmann et al., 1973]. The essential idea is to represent the complex sea state as a superposition of individual waves with varying frequencies and directions. [Soomere, 2023, Holthuijsen, 2007, 1983]. Wave modelling aids in understanding historical wave conditions, assessing the impact of extreme events, and designing structures that can withstand varying wave climates. The global development of wave hindcast models reflects ongoing efforts to improve the accuracy and reliability of predictions, ultimately contributing to more resilient and sustainable marine infrastructure and ecosystems.

Nowadays, there exist several wave hindcast worldwide at different spatial scales with different spatial and time resolution. To mention some examples there exist the wave hindcast performed over the Pacific Ocean such as EMC WIII global wave model Multi-1 [Chawla et al., 2009, Saha et al., 2014], which offers spectral 3-hourly parameters from 1979 onwards. The GOW2 model developed by Perez et al. [2017], offers hourly wave integral parameters globally. Moreover, the Chilean Wave Atlas database offers hourly spectral wave parameters. This database, developed by Beyá et al. [2017], comprises the period from 1979 to 2015.

The Multi-scale global hindcast, by Rascle and Ardhuin [2013] generated wave data from 1994 to 2012, obtaining 3-hourly integral parameters, under a structured grid of 0.5 ° of resolution. Besides, the WAVERYS model [Law-Chune et al., 2021] provides 3-hourly results along the structured grid of 0.2 ° of resolution. Spectral wave models are capable of estimating integral parameters of the energy spectra, which are representative of the sea state, and are specifically the parameters that are analysed for a variety of engineering, shipping and other applications.

On other the hand, a widely used is the ERA5 model, which corresponds to a global model and is the successor of the ERA-Interim model [Hersbach et al., 2018]. This model offers a large number of meteocean reanalysis quantities over a regular spatial grids of 0.25° x 0.25 ° (atmosphere), and 0.5 ° x 0.5 ° (ocean waves), with hourly outputs. ERA5, the fifth-generation reanalysis model of the European Centre for Medium-Range Weather Forecasts (ECMWF), was created to model global weather and climate over the past eight decades. This data are available from 1940 onwards.

In view of the computational characteristics of each type of numerical wave model and taking advantage of the open source wave spectral models and their already established parametrization packages, such as the renowned WAM [Group, 1988], SWAN model [Booij et al., 1996] and WavewatchIII [WAVEWATCH III Development Group, 2019, Tolman et al., 2009] (hereinafter WWIII), all of them solve the wave action equation. These models can be employed in large oceanic domains and regional and local regions given that they are primarily fed by wind and tidal inputs, and consider the main effects of wave generation, wave interaction, and dissipation of wave energy produced for example by wave white capping, wave shoaling and wave breaking, among others; however certain non-linear hydrodynamic processes in the coastal zone are not solved in this wave modelling approach.

Umesh and Swain [2018] indicate that models as WAM and WWIII present a more efficient performance in global scales owing their numerical schemes, whereas SWAN has the advantage at smaller scales. Besides, WAM, WWIII and SWAN models can be solved in either Cartesian or Spherical coordinates and all are finite difference models. Because of their similarities, all the three complement each other from various considerations. Another evaluations have shown that the variance density for the frequency is overestimated by SWAN model, while the lower frequency energies and the higher frequencies spectra are underestimated by WWIII model [Amarouche et al., 2023].

Each model is configured to parametrically solve the wave propagation using preprogrammed routines that vary between models, such as WWIII, which suits the wave hindcast requirements proposed through this work. Hence, nearshore evaluations such as coastal climate characterization, estimation of statistics based on integral wave parameters, and parameters derived from these, such as wave power, are part of the valid performances to be carried out with the model outputs.

Concerning the WWIII model, it is part of the third generation spectral wave models, which are based on its predecessors (e.g. WAM model), and integrates advanced numerical techniques and high-resolution spatial gratings. The inclusion of a diverse range of physical mechanisms in third-generation models enhances their capability to faithfully replicate real-world wave conditions [Booij et al., 1999]. The accuracy of the results provided by the numerical model depends on the quality of the input data, wind and bathymetry being the most relevant, the configuration of the set of equations that compute the geophysical phenomena, as well as the computational hydraulics involved [Cavaleri et al., 2007].

In particular, spectral models determine the shifting of wave energy flux over the wave frequencies and directions considering the source terms or forcing inputs, as explained in Chapter 2.

Hence, a complete wave information over the wave frequency bands and bins of wave directions is determined, which corresponds to the wave energy density spectrum of a sea state. Besides, various parameters used daily in marine engineering are calculated from such energy spectra. These parameters, or wave integral parameters, are the zeroth-order moment height (H_{m0}), defined the frequency domain in terms of the standard deviation of the wave spectral energy, i.e. $4\sqrt{H_{m_0}}$, being the m_0 the zero$\hat{th}$ order moment of a wave energy density spectrum. Likewise, the peak period (T_P) which indicates the wave period associated to the wave frequency of the maximum wave energy in the wave energy density spectrum; the wave direction linked to the peak frequency (D_P); and the wave spreading (σ_D) which indicates the mean angle of the dispersing waves [Kuik et al., 1988]. These parameters are required in several wave evaluations, for example to evaluate the probabilities of extreme events by means of statistics applied to the wave database, or find marked trends. Such evaluations provide valuable insights into wave climate, coastal erosion, and maritime safety.

A high percentage of commercial maritime transport takes place over the Pacific nearshore regions in Central America, the vessels traffic through the Panama Canal has a relevant impact on world maritime trade [COCATRAM, 2021, Authority, 2021]. Indeed, wave can affect negatively the transit of vessels, as well as the impact within a port, since this forcing can produce events of port agitation, unsafe boarding of cruiser and vessels, and even unbalance the loads of large vessels that carry out loading and unloading operations of goods [Díaz Hernández et al., 2017, Xu et al., 2020]. Therefore, proper wave monitoring is foreseen in order to reduce the potential negative socioeconomic impact.

Specifically, this region comprises the Exclusive Economic Zones (EEZ) of Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Colombia and Ecuador. Most of these countries have the advantage of having coastlines on both the Caribbean Sea and Pacific Ocean, which gives them access to the marine resource of two different oceans leading to ease of trade by maritime means. However, the hydrodynamics in both basins differ significantly from each other mainly due to the Pacific Ocean is one of the most energetic oceans given its atmospheric and wave-current interactions.

Moreover, the tourism is an one of the most relevant activity, particularly the so-called sun and beach tourism [SITCA, 2020] in the region, where more than the 50%, except in Nicaragua and Honduras with 39% y 42% respectively. Therefore, the safety of tourists at sea is directly dependent on the determination of wave conditions and their forecasting.

By developing a wave hindcast it is possible to determine the main wave integral parameters required in many applications; however, the evaluation of wave energy potential as well as the assessment of wave energy conversion devices are part of them and they have motivated the task outlined in the following Section.

1.2. Wave energy resource exploitation

Oceans present different kind of energetic sources depending on the water mass movements, the salinity content or temperature gradients along the water depth, as well as wind in offshore regions which is also considered as a marine renewable energy resource (see Figure 1.1). Among them, waves occurring in coastal areas present an attraction for feasible energy exploitation according to the behaviour of the maritime climate in a given locality [Vicinanza et al., 2013, Rusu and Onea, 2015, Martinelli and Zanuttigh, 2018, Mendoza et al., 2014].

Engineering and scientific knowledge have led to improved technologies for the conversion of wave energy into serviceable electricity. These mechanisms, called wave energy converters (WEC), interact with waves and convert their mechanical energy into exploitable energy by several mechanical systems plus minor losses that occur inherently in the process. The wave energy converters existing nowadays were categorised into different classifications; one of them based on the positioning of the converter with respect to the direction of the wave. A WEC which is positioned parallel to the direction of wave propagation is categorized as Attenuator. A Terminator converter has its longitudinal axis perpendicular to the direction of wave propagation; whereas a Point Absorber is independent of the wave direction, since its span is usually point-like and has a characteristic diameter.

Moreover, WECs have been classified according to the principle of operation of one or several devices that extract energy from the waves during their interaction:

- Overtopping principle: This type of devices have a reservoir which is filled with sea water from waves running up a slope located at a higher level than the mean sea level, then, a portion of the undertow back to the sea passed by a hydraulic turbine. Some examples of these devices are the Overtopping Breakwater for Cave Energy Conversion (OBREC) [Contestabile et al., 2020], or Sea-wave slone cone Generator (SSG), Wave Dragon [Cascajo et al., 2019].

- Oscillating bodies principle: a floating body is driven by the wave action. The motion produced over the device allows to extract the wave kinetic energy by means of hydraulic or mechanical transmission. Some examples are Pelamis [Bozzi et al., 2018], Floating 2-Body Heaving Converter (F-2HB), Floating 3-Body Oscillating Flap Device (Langlee) [Babarit et al., 2012].

- Oscillating water column systems: the also known OWCs have a system in which a oscillating water column movement pumps a portion of trapped air through a turbine. Examples of this devices are the Limpet, the OWC Mutriku [Torre-Enciso et al., 2009], and the Resonant Wave Energy Converter (REWEC3) [Arena et al., 2015].

The associated capacity of energy exploitation of each WEC can be represented by the so-called Power Matrix [Fairley et al., 2020, Bozzi et al., 2018, Zanuttigh et al., 2016, Bozzi et al., 2014, O'Connor et al., 2013], wherein the potential power of extraction is shown according the combination of the wave parameters H_{m0} and T_p.

Recently, technologies for exploiting wave energy are still at an early stage of experimentation [Faedo et al., 2023, Silva et al., 2023, Jin et al., 2022]. Over the last two decades, several

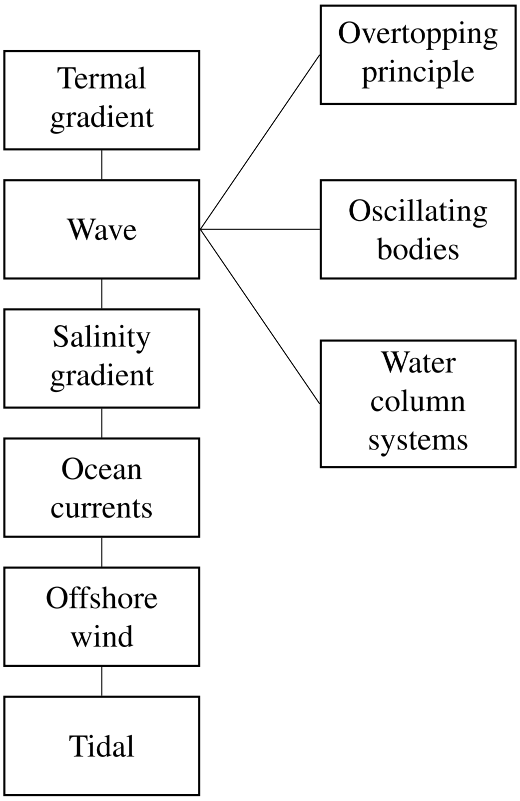

Figure 1.1: Schematic view of the renewable marine energy generation sources and mechanisms of wave energy conversion.

attempts were made to deploy WECs with no positive results and, on the contrary, previous efforts were doomed to abandonment of the deployment at the first stages of Technology Readiness Level (TRL) [Mayon et al., 2022].

To face this challenge, studies on wave energy harvesting worldwide provide detailed insights into the energy potential of ocean waves, revealing varying levels of wave power across different regions. For instance, the North Atlantic and North Pacific oceans are among the most energetic, with average wave power reaching up from 40 to 60 kW/m [Mackay et al., 2010].

The average of the annual wave power values over North Sea varies drastically depending the location; e.g. in coastal regions of Danish Continental Shelf 7 kW/m to 17 kW/m offshore, whereas in the Belgian Continental Shelf the annual average wave power varies from 1.5 kW/m near the coast to 4.6 kW/m offshore. On the other hand, according to measurements this at 21 km from the Norwegian coastline has shown an annual average wave power of 23.12 kW/m [Beels et al., 2007]. In the southern hemisphere, coastal areas of Australia and Chile boast significant wave energy potential, with averages ranging from 30 to 50 kW/m [Liu et al., 2023, Lucero et al., 2017].

Seasonality plays a key role in wave power distribution, with notable variations in different regions aroubd the world. Wave power tends to peak during the winter months, reaching its highest levels from October to March in the North Atlantic [Mackay et al., 2010]. Similarly, the North Pacific experiences an increased wave power during the winter, particularly from November to April [Jacobson et al., 2011]. In contrast, regions affected by monsoon patterns, such as parts of the Indian Ocean, see heightened wave activity during the summer months [Rizal and Ningsih, 2022]. Geographical factors also contribute to wave power variations, with areas exposed to prevailing winds, such as the West Coast of the United States and the West Coast of Europe, exhibiting higher average wave power [Martinez and Iglesias, 2020].

In particular, in the Mediterranean Sea several studies were carried out regarding renewable marine energies and wave energy. Estimations on wave energy potential have emerged in the last two decades owing the improvements in numerical wave modelling, examples of such studies are those carried out by Besio et al. [2016], Martinez and Iglesias [2020], and Lavidas et al. [2016]; Caloiero et al. [2022], the estimation of the wave energy along the Algerian coasts performed by Amarouche et al. [2020], or the wave energy estimations along the Italian nearshore held by Vicinanza et al. [2013] and Liberti et al. [2013], or Sierra et al. [2020] along the Moroccan coast. Even if the Mediterranean Sea is considered as a low energetic sea, wave energy exploitation may be feasible if WECs are adapted to the local wave conditions, as detailed in studies developed e.g. by Bozzi et al. [2014] and Bozzi et al. [2018] related to wave energy converters evaluation in the Mediterranean Sea.

Among the contributions on the wave energy converters feasibility some noteworthy studies corresponds to those developed by Archetti et al. [2011], De Andres et al. [2015], Rusu and Onea [2015], Lavidas et al. [2020], Simonetti and Cappietti [2023], Re et al. [2022], as well as the related ones to wave energy conversion systems along shorelines as Foteinis [2022], Cascajo et al. [2019] in the Spanish coasts, or those performed by Carapellese et al. [2022], Contestabile et al. [2022], Arena et al. [2018] along the Italian shorelines. The aforementioned studies agree that wave energy is an optimal renewable resource for clean energy supply, but wave energy technologies still need to be refined and studied in an integrated way to assess the environmental and economic impacts as well as their contrast with other renewable energy sources.

In contrast, the Pacific region of Central America presents less scientific exploration of wave energy than for the Mediterranean Sea. Studies produced by Castro [2016] and Hernandez-Madrigal et al. [2016] described particularly the wave power along the Costa Rican coast and its possible exploitability, whereas wave energy evaluations on energetic marine regions were carried out in recent years throughout the Pacific nearshore regions [Eelsalu et al., 2024, Ventura et al., 2022, Gorr-Pozzi et al., 2021, Mazzaretto et al., 2020, Lucero et al., 2017, Rusu and Onea, 2017, Mediavilla and Sepúlveda, 2016, Contestabile et al., 2015]. However, none of them were focused on the wave resource extraction by WECs in the Central American region of the Pacific nearshore.

These studies related to wave power carries significant importance for humanity's sustainable energy future. By harnessing the vast wave energy potential in these regions, it is possible to diversify the renewable energy sources and reduce reliance on fossil fuels. Remote coastal communities, islands, and developing nations stand to benefit greatly from wave energy technologies, providing them with a reliable and sustainable power source. Moreover, the predictability and reliability of waves make them an attractive option for continuous power generation. As the global demand for clean energy rises, understanding and tapping into the abundant wave power resources around the world can play a crucial role in combating climate change and achieving a more sustainable future for all.

Concerning the renewable energies, in general the selection of the energy source depends primarily on the availability of the resource, the amount of energy to be supplied, as well as a detailed study integrating technical, environmental and economic aspects [Hoogwijk, 2004]. Although renewable energy sources such as solar, geothermal, biomass and wind currently provide electricity, they can have high costs depending on the conditions of the site where they are implemented. Solar energy, for example, depends on environmental conditions such as cloud cover, temperature, as well as the time of day, which makes it difficult to produce at a constant rate of energy production [Sharadga et al., 2020].

On the other hand, wave power harnesses the energy from ocean waves and converts it into electricity that can be supplied to the coastal cities, where a majority of the world's population is settled [Ji and Wang, 2022, Zheng et al., 2020]. This form of renewable energy has several advantages, including its energy density, predictability, and low visual impact [Iglesias et al., 2009, Iuppa et al., 2015]. Indeed, several aspects might be considered to reach a optimal WEC or WEC array from different perspective, such as the amount of delivery energy, the balance between damping and energy absorption, costs, environmental and visual impact, proper connection to the electric grid, or even the subsequent coastal protection these devices can produce [Battisti et al., 2024].

Furthermore, wave power would play an important role in diversifying our electricity mix, reducing the carbon footprint and seeking a proper transition to the sustainability [Liberti et al., 2013, IPCC, 2017].

Figure 1.2 presents the mean global distribution of the annual wave power Mork et al. [2010]. High latitudes have higher wave energy potential, such as in the North Sea, North Atlantic Ocean, South Pacific Ocean and South Indian Sea, whereas seas in the inter-tropical regions present a medium wave power content compared to the high energy potentials in the upper regions of the tropics. Seas with enclosed basins have low wave energy potentials such as the Black Sea, the Caspian Sea or the Mediterranean Sea [Foteinis, 2022].

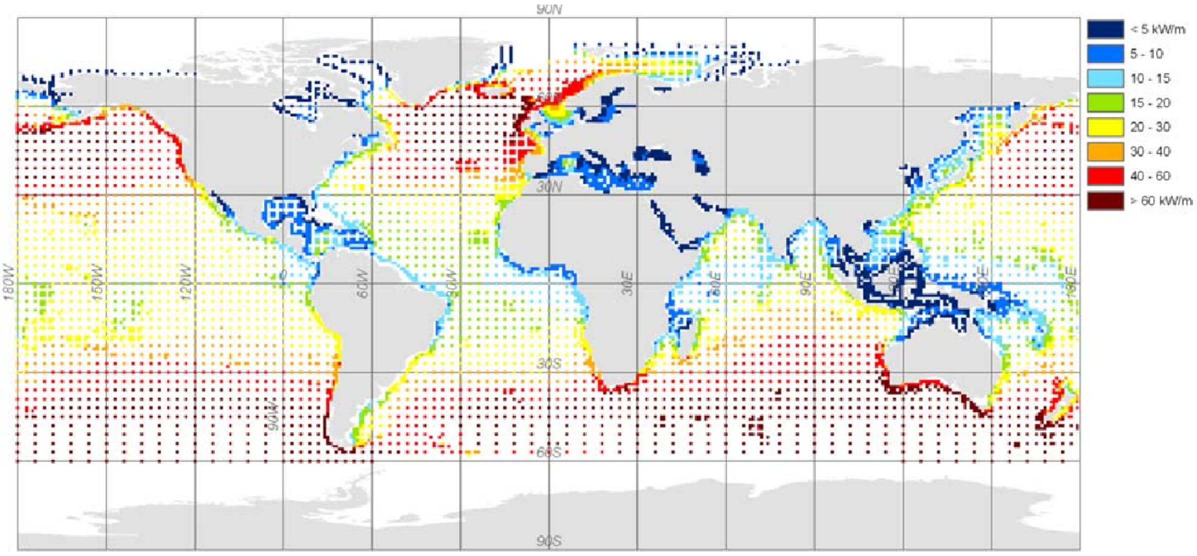

Figure 1.2: Annual theoretical wave power worldwide. Source: Mork et al. [2010]

By having a wave hindcast, the reconstruction of wave power facilitates the assessment of this renewable resource and its extraction. Therefore, it was decided to redirect the wave study towards an energetic assessment of such resource. In fact, the proposed wave energy assessment also responds to the current global necessities of reduce the Earth pollution, i.e., to produce cleaner energies avoiding the highest CO_2 load to the atmosphere [Aderinto and Li, 2019].

During the first half of 21^{st} century a growing global effort was shifted towards more sustainable power sources and reduce our reliance on fossil fuels. For instance, in Central America the continued growth of carbon dioxide emissions and greenhouse gases (GHG), has forced governments to adopt international policies and regulatory actions to pursue a sustainable pathway [Balsamo et al., 2023].

In this study, the wave power potential is particularly estimated in two marine regions with different meteoceanic characteristics. In first instance, the Pacific of Central America whose wave climate is conditioned by meteoceanic events over the entire Pacific Ocean, mainly the ENSO phenomenon [Hadley, 1735], Pacific decadal oscillation (PDO), ocean currents and tropical cell circulations, swells coming from the southwest Pacific basin, as well as seasonal and local wind events [Portilla et al., 2015, Hidalgo et al., 2020].

On the other hand, the Ligurian Sea corresponds to a permanent basin-wide cyclonic circulation involving both surface and intermediate waters. The Western Corsica current and the Tyrrhenian current flow northwards on the two sides of Corsica, which flows westward along the coast of Southern France, completing the cyclonic loop. Strong air–sea interaction processes greatly affect both atmospheric and marine circulation, determining a strong variability in the upper sea layers [Canepa et al., 2015, Besio et al., 2017].

Highest wave heights appearing during the late autumn and winter period (mainly from October to February) over the Ligurian Sea; whereas in the Pacific of Central America there is no marked difference from the lowest energy period to the highest energy period as presented in the tropical latitudes. The highest energetic period usually starts approximately at the middle of the year in this intertropical region. The wave environments categorization in both regions is presented in Figure 1.3. In this context, it follows that protected areas exhibit lower wave power than what is potentially present in the swells arriving on the coast.

Meteocean datasets coming from the wave hindcast in the Mediterranean Sea [Lira-Loarca et al., 2022], valid also for the Ligurian Sea, and the Pacific Ocean were employed in this thesis. In the case of the Pacific of Central America, the wave hindcasting dataset produced in the first part of this study was considered. Subsequently, the curiosity arose to assess both the wave energy exploitation and wave energy potential in the Pacific of Central American and Ligurian Sea.

A proper wave energy assessment considers analyses from the technical, economic, environmental and legal points of view. In terms of feasibility, as is applicable for other types of deployments and engineering projects, an economic analysis of the initial cost and periodic investments of energy converters gives greater confidence to the development and commissioning of these devices [Lavidas, 2020, De Andres et al., 2017, Lavidas et al., 2020].

Moreover, it is worth noting in this regard one difference between wave energy potential and wave energy exploitation: although the Earth's inter-tropical regions offer lower wave energy potential, wave energy exploitation can be more feasible in regions as the Pacific of Central America or at the Mediterranean sea than the higher latitude marine regions in terms of converter survivability and longer operation throughout the year [Portilla-Yandun and Guachamin-Acero,

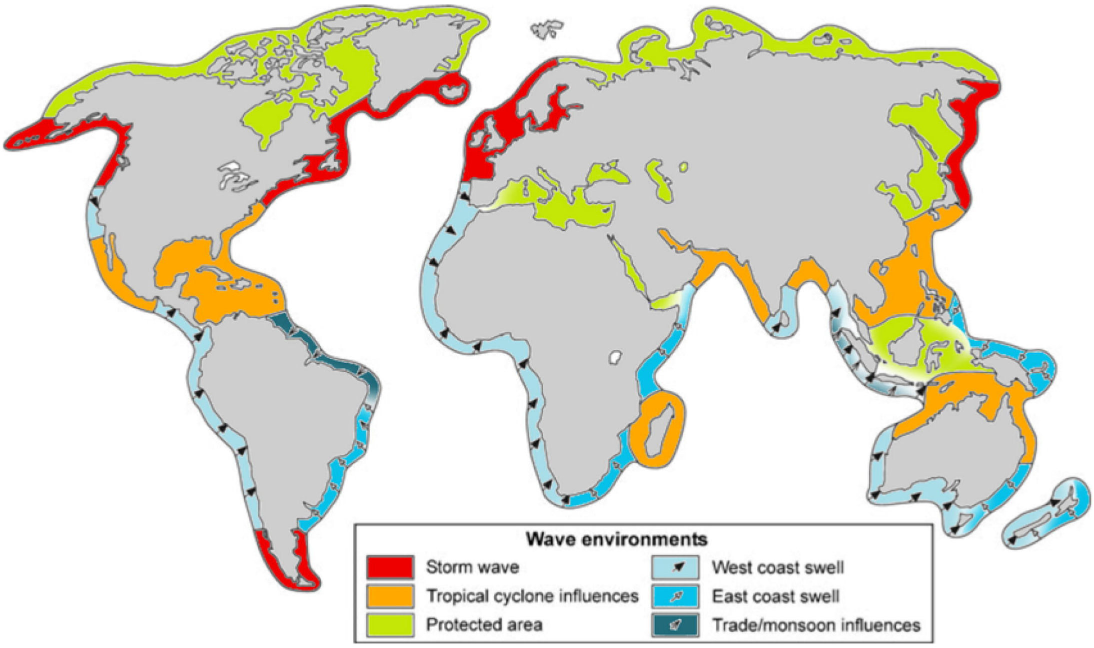

Figure 1.3: Global coastal wave environments. Source: Bergsma et al. [2022]

2023].

One route to achieve the aforementioned is through the WEC size optimization by adjusting their capabilities to the wave conditions at a given location. Nevertheless. special attention must be paid to preserve the scaling similarities, in this case it is particularly required to maintain the balance of inertial and gravitational forces, or the Froude number (Fr) between the prototype and the scale model [Hughes, 1993].

On the other hand, literature reports varies methodologies related to WEC sizing and design. One of these scaling methods is based on the preservation of the capture width ratio (CWR) of scaled device respect to the prototype WEC, as demonstrated in various studies, some examples of them are the investigations developed recently by Martić et al. [2024], Jin et al. [2022], or Orphin et al. [2022]. These studies correlated the wave power (P_w) and the extracted wave energy by the Power Take Off system of the converter (P_{WEC}). Thus, P_{WEC} by the converter would vary depending on the converter resizing. In the first approach P_{WEC} depends on a characteristic wavelength, or characteristic wave period obtained from the assessed wave time series, whilst the second approach considers the harvested wave power by the joint occurrence H_{m0} and T_p of the wave times series.

Besides, a holistic approach to resize the wave power harvesting capabilities is based on the adaptation of the power matrices. Evaluations performed by Martić et al. [2024], Bozzi et al. [2018], Beatty et al. [2017]. Zanuttigh et al. [2016], O'Connor et al. [2013] and Sinden [2005] have employed such technique based on the Froude's similarity law to size the power matrix of a WEC.

Respect to scientific basis on the WEC scaling approach, Falcão and Henriques [2014] derived the scaling rules (based on Froude similarity) through dimensional analysis; then, Sheng et al. [2014] conducted a similar study in which they conclude that this type of scaling is appropriate but the validity for high Reynolds numbers. Moreover, Schmitt and Elsäßer [2017] indicated that Froude similarity laws can be employ to scale device geometry but the PTO (Power Take Off) scaling is based on the device forces and velocities (as opposed to the device characteristic length and stream velocity for Froude similitude), indicating that the two subsystems do not scale in the under the same similarity law.

However, conclusions on WEC sizing-related studies [Orphin et al., 2022, Zabala et al., 2019, Zanuttigh et al., 2016] indicate that to achieve a reasonable model-prototype requires the experimental validation in order to quantify the scale effects.

To mention concrete examples, the study on a scaled OWC converter by Dai et al. [2019] indicates that a difference of around 30% of the capture width radius was found for reduced scale models due to deficiencies in the Reynolds similarity; or, through the study by Viviano et al. [2018], in which the smaller models offered approximately 20% relatively smaller loads in the largest wave conditions. In contrast, other experiments, e.g.[Orphin et al., 2022], indicate not to have faced significant scale effects when scaling the WECs based on Froude similarity.

Moreover, a theoretical methodology allows to estimate the energy captured by any wave energy converter exposed to irregular waves such as the sounded Boundary Element Method (BEM) [Isaacson and Nwogu, 1987]. This approach employed in the WEC design, considers the three-dimensional inertia and its damping as well as the degrees of freedom of the device [Cruz et al., 2010]. In this way the P_{WEC} can be directly estimated for any WEC. The advantage of this method is that it does not really scale down the converter characteristics as the previous approaches; however, in order to be projected to advanced TRL stages there are certain assumptions that need to be validated later on [Budal and Falnes, 1982]. The proper WEC design processes involves the physical modelling previous to launch the converter to the real wave conditions.

Whilst not belittling the importance of the capabilities of the generating devices, the economic aspect is decisive for the definition of the type of converter to be implemented, even considering extreme events, and the resulting operation shutdowns. Leading economic indicators in the evaluation of marine exploitation technologies are the Cost of Energy (COE), Levelised Cost of Energy (LCOE), the Value Adjusted Levelized Cost of Electricity (VALCOE), and the Payback Period (PBP) [Lavidas, 2019].

However, the current still premature state of the consolidation of energy converters has led to a lack of confidence in the indicators that are still under investigation today but which are necessary to quantify with a certain degree of uncertainty the magnitude of the investment that must be made for their development [Trueworthy and DuPont, 2020]. In fact, in 2015, Astariz and Iglesias [2015] indicated that the exploitation of wave energy was still not economically feasible.

There are certain factors obstructing marine energy development, which are classified in subgroups such as complex planning processes, administrative procedures, Environmental Impact Assessment process, or Interactions with other marine uses and stakeholders. As indicated in the literature review by O'hagan et al. [2016], these barriers will be solved by as the number of developments increase and there is greater familiarity with, and knowledge of, the technology.

Following such indication, and based on economic assessment studies such as those developed by Lavidas et al. [2020] in the Ligurian Sea, Langer et al. [2021] in the Indonesian archipelago, the evaluation of economic indicators applied to WECs carried out by De Andres et al. [2017], or the technical-economic evaluation of converters in the North Sea by Lavidas and Blok [2021], it was proposed to analyse the costs in the WEC assessment over one of the studied regions in this work.

Moreover, several guidelines e.g. Sustainable Development Goals established by United Nations [2022], the standards dictated by the European Marine Centre (EMEC) [EMEC, 2009], the technical rules IEC-TC 114 dictated by the International Electro technical Commission (IEC),[IEC, 2023], the Regulatory Frameworks for Marine Renewable Energy issued by the Pacific Northwest National Laboratory [2021], are leading the regulatory field in the pursuit of sustainability, however, there is no official worldwide regulation for marine renewable energy deployment.

As already mentioned, the wave energy resource evaluation and its exploitation by means of converter devices commonly requires integral wave parameters for the estimation of the energy potential, however, such information do not capture the variability of different wave systems during multi-modal sea states, i.e., those seas encompassing both wind seas locally generated and swell waves that already left their area of generation.

Spectral information over the full range of wave frequencies and directions is most appropriate for evaluations aimed at propagation of multiple wave systems along different directions; indeed, such condition could give origin to crossing seas that are particularly dangerous for the safety of navigation. In this framework, a novel methodology for the detection of relevant directional wave patterns was developed as a complementary study, as explained in Section 1.3..

1.3. Analysis of wave energy density spectra: Wave systems

During a specific period an important quantity of individual waves of different characteristics, i.e. wave heights, wave periods, and wave directions occur. Then, a representation of that period, or sea state, gathers the distribution of wave energy density along the wave frequencies and wave directions, in the so-called wave energy density spectrum [Holthuijsen, 2007].

The wave energy density spectra therefore condense more wave information than an integral parameter can yield for regarding the sea state over a period of time, and this in turn allows groups of waves with similar energy packages to be properly identified [Hasselmann et al., 1973].

For instance, a wave hindcast integral parameters can be used to construct power matrices useful for wave energy assessment, however, they may fail to describe the single features of full wave energy density spectra.

Particularly, if multimodal energy spectra exist, i.e, wave energy density spectra with more than one waves packet with similar energy density content, it may result in loss of relevant information from low frequency or high frequency waves. To tackle such issue, spectral partitions can be referred to.

Instead, by splitting up into spectral partitions: wind-sea waves (shorter waves) and swells (longer waves), it would allow the flourishing of a plethora of applications [Li and Zhao, 2012]. Coastal morpho-dynamic patterns, reliability of structures characterized by strength anisotropy, and the analysis of crossing seas, they all closely depend upon waves direction.

A wave system is defined as wind-wave climate feature which contents an important wave energy density content in a determined pair wave direction and wave frequency [Portilla-Yandún et al., 2015]. Thus, a differentiation of the several (or unique) wave systems can be distinguished in a sea state.

Among the methods to identify the wave systems into the wave energy density spectra there exist some of them classified as topographic partitioning methods that leverage watershed algorithms [Hasselmann et al., 1996], while other based on the analysis of the bi-variate frequency matrix. A bi-variate frequency matrix contains the pairs of wave period and direction. The selection of T_m is usually employed owing to it distinguish different type of waves [Munk, 1951].

Besides, the detection of the wave systems also has positive implications on the design of structures characterized by strength anisotropy [Wu et al., 2015, Bruns et al., 2011, Bitner-Gregersen and Toffoli, 2014], the assessment of littoral drift patterns [Sierra and Casas-Prat, 2014], the assessment of wave power for energy production [Robertson et al., 2016], and the safety in navigation as the maritime routes determination [Xu et al., 2020, Mayer et al., 2018, Leone, 2017], considering that in the Mediterranean Sea is transited by different types of vessels and cruisers, wherein some marine locations present more than 1200 route per square kilometer per year [EMSA, 2023].

Consequently, navigation in the Mediterranean Sea is therefore susceptible to experiencing crossing seas, since most ship accidents occur due to mixed sea states characterized by oblique waves [Toffoli et al., 2005, Zhang and Li, 2017]. Crossing seas occur when multiple wave systems propagating from different directions coexist; usually, when a wave system still in the generation and growing phase crosses one or multiple swells, i.e., long waves that have already left their generation area [Semedo et al., 2011]. This scenario can produce the existence of rogue waves larger than those in unimodal seas [Toffoli et al., 2011, Petrova and Guedes Soares, 2014, Vettor and Soares, 2020, Davison et al., 2022].

1.4. Objectives and outline of the thesis

This study was motivated by the pursuit of answers to three questions: first, could a more accurate wave database be developed for use in maritime and coastal engineering in the Pacific nearshore of Central America? second, it would be possible to feasibly harness wave energy at the Pacific of Central America and Ligurian Sea? and third, could a wave system detection methodology based on image segmentation be applied to determine the interaction of different wave systems?

Certainly there are previous studies that provide strategies to address these issues and there are preexisting methodologies to find answers of the previous premises, in particular for the wave systems detection. However, with a detailed research approach, a new high-resolution wave hindcast in a scarce explored region is produced in first instance. In general, this project was conceived with the idea of producing a new optimised and validated wave hindcast database focuses on the Central American Region of the Pacific coast, specifically from longitudes -92.7° to -76.6°, and latitudes -4° to 16°, from 1980 to 2021 along the Pacific of Central America by employing the spectral numerical wave model WWIII.

Secondly, the pioneer evaluation of WECs along the Pacific and Ligurian Sea, and finally, a image segmentation method applied as application in the maritime engineering was implemented. Moreover, the evaluation of the exploited wave energy through several wave energy converters in several locations along the studied region as well as the implementation of a novel methodology for detecting the wave systems based on pixel image segmentation and a further determination of the permutations of the wave systems occurring in the Mediterranean Sea. A schematic chartflow of the proposed work in this thesis is presented in Figure 1.4.

This thesis is organized as follows:

Chapter 2: Wave hindcasting in the Pacific of Central America

The development of a wave hindcast database is explained in this chapter. The employed wave model corresponds to the WWIII model [WAVEWATCH III Development Group, 2019]. The wave modeling was carried out along the Central American Pacific region, in which several model parametrizations were tested in order to get higher correlations respect to the satellite records [Busswell et al., 2010].

Correction methods for the wave integral parameter significant wave height were applied [Albuquerque et al., 2018]. Subsequently, a validation process was carried out by comparing the corrected results against in-situ wave records. The chapter ends with a series of final remarks.

Chapter 3: Wave energy resource assessment

The wave energy was estimated at several locations over the Pacific of Central American and the Ligurian Sea. In the case of the Central American Pacific region nine wave energy converters were assessed at 16 locations, whereas eight wave energy converters were evaluated at 36 locations. The wave energy converters were evaluated as a single unit instead of a WEC farm. Several performance indexes of wave energy converters were evaluated in both regions and afterwards WEC scaling based on the Froude similarity law applied to the WEC power matrices, allowing to determine a scaled converter with the highest efficiency.

In addition, an economic evaluation was carried out in the Ligurian Sea using the indicators COE, LCOE, PBP to establish the optimum converter in terms of the economic and technical aspects.

Chapter 4: Wave systems in the Mediterranean Sea

A complementary assessment on wave systems over the Mediterranean Sea was carried out. In first instance, the determination of wave systems through the image segmentation method [Otsu, 1979] was performed.

Subsequently, the existing occurrence among the different wave systems was estimated. the main findings of this study are highlighted in the conclusions. As part of the outcome a website was created to visualize the results of this section.

Finally, Chapter 5 gathers the main conclusions of this doctoral thesis.

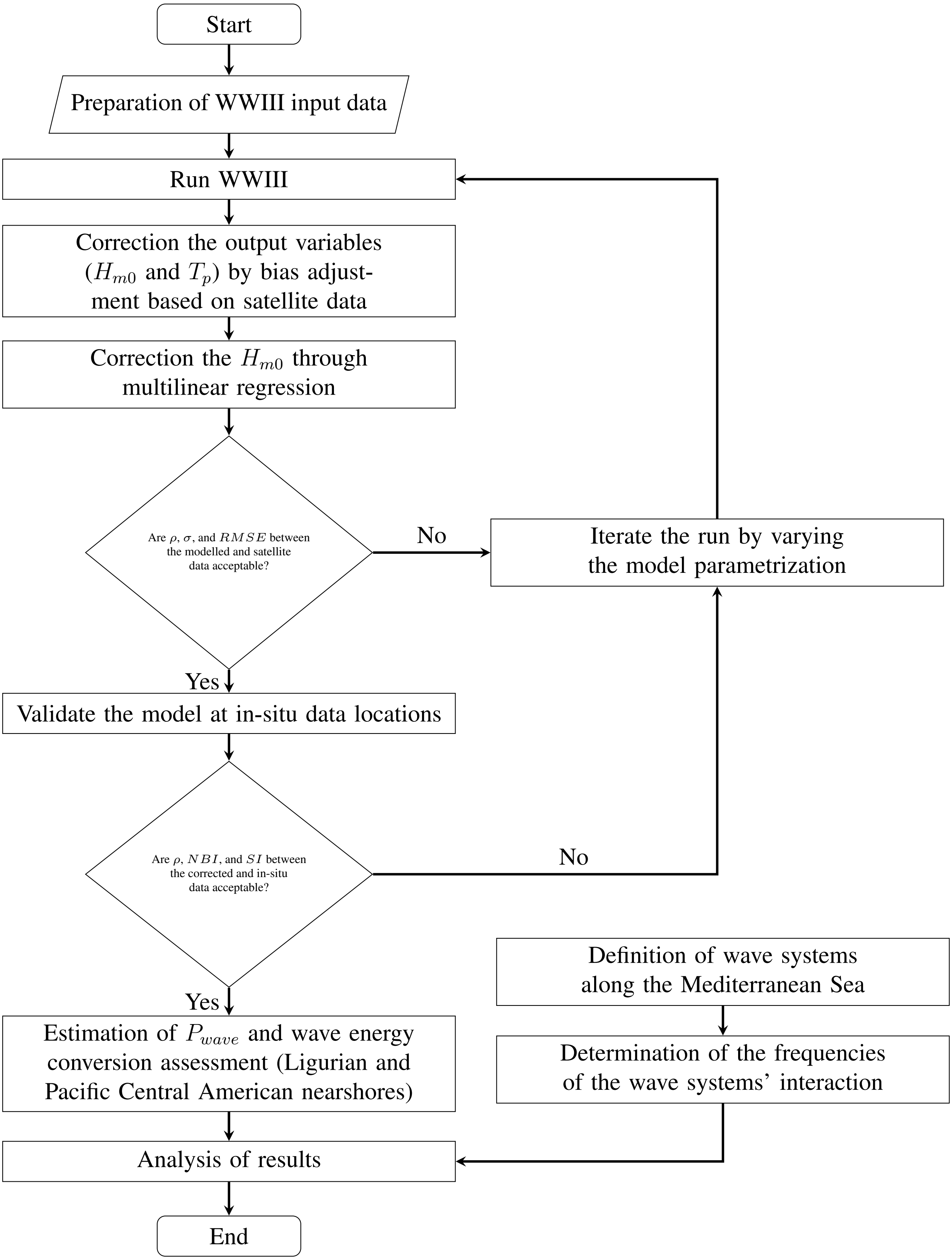

Figure 1.4: Representative flow chart of the methodology followed in this thesis.