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Application of Numerical Wave Models at European Coastlines: A Review

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Abstract

Significant advancements have been made in the past few decades (since the 1980s) on detailed evaluation and quantification of wave resources globally. Larger availability and advances of computational resources have contributed to the utilisation of numerical wave models as powerful tools in climatic and energy studies. This review presents current state-of-the-art numerical tools and their status in the process of wave power assessments. We focus on the evolution of studies undertaken at the European coastline regions and the Black Sea.

Although, a number of studies have been successfully developed and implemented in the past contributing to our understanding of the resource, this paper discusses the benefits, limitations and potential for improvement of numerical tools. From the literature, it is evident that different applications and scale may require different models, however, it is also the experience and knowledge of the user, applied in the tuning of a number of parameters that govern the process of wave generation, propagation, and the quality of input parameters that are the cornerstones of a successful model. This review depicted that the use of numerical wave models, depending on specific region and application, offers significant benefits on quantification of coastal zone wave resources which benefit multiple offshore applications and the energy industry.

Keywords: Numerical Wave Models, Wave Energy, Resource Assessment

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1. Introduction

The wave climate is highly variable across the globe on spatio-temporal scales, local bathymetry, coastlines, and winds greatly influencing formation and propagation of waves. Currently third generation numerical wave models are utilised for historical (hindcast) and forecast studies. A properly calibrated, validated wave model is the basis to reduce uncertainties both for long and short term resources examination. Developments in our understanding of wave theory, and improvements of infrastructure in computer advancements, have allowed significant enhancements in understanding of waves. This has put the use of numerical models at the forefront of climatic research, climate change and energies [1, 2, 3, 4, 5, 6]. With accuracy improved, numerical wave models have found utilization within the research and energy communities [7, 8, 9].

A key component for the accuracy and confidence in a model is user experience and expertise. Proper set-up of a numerical wave model is a cumbersome process that comprises of many inputs and careful consideration on physical tuning solutions. Indicatively, models are highly sensitive to winds which are driving the evolution/propagation of waves, tuning of physical properties, and propagation schemes. Current numerical models have different solutions which may affect their applicability.

Estimations of wave resource with higher accuracy and at the same time covering entire regions or global domains was not always possible. Some of the limitations were in our understanding of wave evolution and computational limitations. Although, robust wave theories have been in development since the 1950's and wave energy converters (WECs) since the 1970's [10], verification of various theories concerning waves were limited to localized studies and experimental observations [11, 12, 13, 14, 15], which laid the foundations for improvements and incorporation of wave theory into numerical models.

It was not until the early 1980's that an increase in computational strength and initial efforts from researchers such as the WAMDI group [16] paved the way for the creation of a dedicated group concerned with evolution of numerical wave models. This attempt led to the development of the Wave Modelling Group which within ten years managed to evolve the application of wave theory from 1^{st} and 2^{nd} to the state-of-the-art 3^{rd} generation [7]. This rapid development allowed global historical studies (hindcasts) that are being extensively used in the fields of climate change, meteorology, weather forecasting and many more.

This review presents the applicability of such efforts, providing an up-to-date literature review on majority of hindcasts dedicated to wave power quantifications through numerical wave models. Section 2 discusses the status, methods and classification of numerical wave models. It also provides description and information concerning current state-of-the-art wave models, their strengths, weaknesses, opportunities and threats (SWOT).

Section 3 offers a detail record of main hindcast studies around European and Black Sea coastlines. They are classified according to location, duration of hindcast, model used, spatial resolution and outputs delivered. While, many European institutes are currently active in continuous mapping of the offshore environment, focus here is given predominantly at wave energy hindcasts. Thus, the review presents studies that have contributed, but are not limited, to quantification of wave energy resource. We also have included seminal early studies which laid the foundation and increased the confidence in numerical wave modelling.

Section 4 discusses the important considerations, and potential limitations that users have to take into account. It also presents the current issues and considerations with regards to wave modelling. Section 5 offers the conclusions that resulted from this review study, and supports the growing demand of high-quality data for wave environments. Application of wave models have proven that it can reduce uncertainties and enhance human activities in offshore regions.

For review studies concerning the evolution of physical solution and improvements in numerical models, the reader is diverted to the seminal works of Komen et.al. [7], Cavaleri et.al [8], Holthuijsen [17], Tolman [18, 19] and Janssen [9], which discuss the state-of-the-art aspects of wave theory and its physical formulations in specific wave models.

2. Numerical Models

From first generation models to the current third generation [7, 9] significant advancements have been made in our understanding and knowledge of wave mechanics. Currently investigations and examination of wave resource, wind wave interactions and forecast of extreme events is predominately performed with use of spectral models. Several institutions and organizations around the world couple wave models with atmospheric models [9, 20, 21, 22, 23].

In the late 1980's with computational resources increased the WAMDI Group developed a fully functional wave model. Its verification allowed the examination of hindcast at a much larger scale for areas or regions without recording mechanisms [16]. This proved a significant step in the investigation of climate change factors concerning wave environments, and allowed to study the effects for different climate scenarios. From this standpoint, many studies have proposed and promoted the use of wave numerical models for historical years, and most importantly providing information for areas where no site measurements or wave recording devices exist [7, 24, 17, 25, 26, 27].

Wave models can be separated into two distinct categories, oceanic and coastal. While, most wave models can be applied to both large and small domains, their computational demands, efficiency, and accuracy determines their preferred use. The popular well known ocean scale models are WAve Model (WAM) [7] and WaveWatch 3 (WW3) [18], coastal or shelf-sea models are Simulating WAves Nearshore (SWAN) [28], MIKE21-SW[1] [29] and TOMAWAC [30]. Except MIKE21, majority of wave models are open sourced. Although several limitations exist, developments to alleviate inaccuracies continue. It is important to note that this separation is not deterministic, and in fact all models can be used for ocean and/or smaller domains, however the intricacies behind source terms, numerical solutions schemes, and computational requirements contribute to this classification.

One major difference of the models lay in the way they resolve the action balance density equation, with a range of available source terms. The nature of a model is also a distinguishable part, with varying options whether they are deterministic, probabilistic, using phase resolving or phased averaged approaches. Their ability to reproduce wave conditions and provide spectral information for shallow or deep water locations, depends on the physical approaches used in the solvers within a specific wave model. While commonalities exist in some source terms, available options, and parametrisations differ significantly within the models.

2.1. WAve Model (WAM)

With the introduction of wind interaction theory for wave generation [11], attempts to incorporate the knowledge of wave theory into numerical models for wave analysis was spurred. Miles [11] theory was the basis for initial

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[1] MIKE21 can be also classified under oceanic

development of 1^{st} and 2^{nd} generation numerical models but were limited in their interactions and physical terms they accounted for. They were mostly limited to wind-wave generation without any additional complex non-linear terms accounted for.

The first simplistic wave numerical code was developed early in the 1970 (1^{st} generation), and in 1984 the WAve Model (WAM) [16] was introduced by a team of leading authorities in the field. With previous attempts like the SWAMP project [31], the introduction of several numerical techniques led to the creation of this advanced model. Initially, hindcasts of extreme events i.e. storm or past wave conditions were examined, with promising results about the overall accuracy of the model [16].

WAM introduced initially a linear solution for resolving the wave (or density) action equation. Improvements allowed the model to simulate two dimensional wave spectra in spherical coordinates, with consideration over a large number of frequencies and directions. Currently the model is operated by various organizations and agencies such as the European Centre for Medium-Range Weather Forecasts (ECMWF) [32, 20, 33]. The current version accounts for wind generated seas, swells propagation, quadruplets (deep non-linear interactions), bottom interaction at deep waters, and a simplified modelling of non-linear coastal interactions [34].

WAM is predominately used for global predictions and oceanic (large area) simulations. WAM offers a wide variety of wave parameters such as significant wave height, mean-zero crossing period, and peak direction etc. [7]. Governing equations of WAM were innovative and set the foundation for development of forthcoming models. Its resulting wave fields can be coupled with most existing, coastal or shelf-sea models, providing necessary boundary conditions information and initial conditions. WAM is available as open source under restrictions[2] in a FOTRAN distribution compiled.

2.2. WaveWatch 3 (WW3)

Another ocean scale wave model is WaveWatchIII (WW3), and its first version was developed by Hendrick Tolman [18]. Currently it is updated and optimized predominately by the National Oceanic and Atmospheric Administration (NOAA) group on Waves and Oceanic research [21]. The model's primary deep water source terms are similar to the WAM model, however

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[2] Permission needed and restricts use for academic and/or research purposes

alterations in the way of calculating non-linear interactions by an alternative scheme are offered to the user. Further, wind-wave generation and some different shallow mechanics have been introduced by the developers. WW3 has active continuous parametrisation packages, offering differentiations on their solution compared to the WAM model [19, 18].

WW3 offers an extensive manual with several initial proposed test case files provided. The manual provides insights of important physical parameters that have to be taken into account depending on the area of implementation [18]. WW3 is available in open source under registration[3] in a FOTRAN distribution.

2.3. Simulating WAves Nearshore (SWAN)

SWAN is a coastal and shelf seas numerical model developed and maintained by the Hydraulics Department at Delft University [28]. As in the case of WAM and WW3, SWAN is also a phase averaged numerical model that resolves the energy density equation with the help of Eulerian methods. It can account for many source terms that provide a final solution on the energy density of waves. The use of an Eulerian solution was chosen based on the fact that a Lagrangian approach failed to resolve the non-linear components of shallow water mechanics [35].

The model was developed out of the necessity for nearshore models as indicated after the development of WAM [16]. The reason was that although oceanic models can assess wave conditions, they are based mostly on explicit empirical schemes to account for coastal non-linear terms, with a certain spatial resolution as limitation. SWAN is a state-of-the-art model with a probabilistic phase averaged approach, that allows both deep water and nearshore non-linear components to be activated.

SWAN was primarily based on WAM formulations for the numerical model solution, although the user is exposed to many different formulations and options that can be tuned. All of the numerical aspects included in wave mechanics can be altered in accordance to the specifications and experience of the user. This proves particularly useful, in comparison to other models whose ability to change physical schemes, numerical, and iterative solvers is somewhat limited.

SWAN is an open source model, with two distinct distributions, one in

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[3] Permission needed, obtain by NOOA after declaring purpose of use

FOTRAN available for user compilation and a pre-compiled version for Windows. SWAN shares similar configurations throughout its distributions, with the user being able to alter and tailor the model. Limitations though exist in both distributions, the Windows executable allows only a serial implementation to the user, which inherently restricts speed of computations, and the amount of available resources to be used, e.g., restrictions on the use of memory for larger runs.

2.4. TOMAWAC

TOMAWAC model was developed for coastal areas, its capabilities include mostly shallow water mechanics and wind generated waves. TOMAWAC uses finite element method to resolve the energy density equation in a simplified spectro-angular method. Although focused on coastal areas, only major non-linear interactions are accounted, such as dissipation and refraction from bottom friction and currents.

Complex resource assessments are not advised [30] and although is mostly suitable for calculations of flows and sentiment transports, since its coupling with TELEMAC provides it with this advantage. Distribution of the code includes pre-compiled Window's version and a UNIX/LINUX source code freely available [30].

2.5. MIKE21-SW

MIKE21 Spectral Wave model was developed in Denmark by DHI and is a commercially available software [29]. Model solutions consider similar source terms to WAM cycle 4 and wind input based on the formulation of Janssen's [36, 37]. Abilities of the model include non-linear interactions according to Discrete Interaction Approximation (DIA)[38], wind generation, and can also account for sentiment transport interactions.

The software is user friendly, with pre and post processing graphical user interface in Windows. Unstructured meshes are used for computational grids, enhancing its calculation for shallow water regions. Source sink terms account for every component of wave resource, but the model allows limited alterations to significant source terms [29], in contrast to the openly available models. MIKE21 requires user specific information such as wind, bathymetry and boundary information. Distribution of the model comprises of a Windows based commercial software, with parallel computing options.

2.6. Strength, Weakness, Opportunity and Threats (SWOT) for numerical wave models

Numerical wave models have proven powerful tools in the evolution of climate studies. Although currently the numerical models are at the 3^{rd} generation, many problems still have to be resolved. Some of the issues are not directly focused on numerical models, but are inherit dependencies associated with the input/output quality. Table 1 provides a SWOT analysis for numerical wave models. It has to be noted that some parameters can share both positive and negative aspects at the same time.

Table 1: SWOT analysis for Numerical Wave Modelling

Strengths	**Weaknesses**
Global and/or Local coverage	Experience of User
Computing Speed	Data for calibration, validation
Accuracy	Storage requirement
Historical data	Computing requirements
Forecast data	Tuning of physical properties
Results for multiple industries	Improvements for physical terms
Multiple nesting	Quality of inputs
Physical solutions of complex terms	
Timescale of results	
Tuning of physical properties (customisation)	
Data Assimilation	
HPC multi-threading (computing)	
Opportunities	**Threats**
Data assimilation	User Experience
Multi-model communication	Instability of propagation schemes
HPC multi-threading (computing)	Allocation of computing resources
Quality of Inputs	Processes based on empirical formulations

Amongst obvious strengths of numerical wave modelling is its wide range of applicability. Wave models can be applied in global, shelf seas and coastal regions. Resolutions may vary from coarse $1-10^o$, or finer spatial resolutions of ≤ 10 meters with the use of unstructured, structured and curvilinear grids. Wave simulations/estimation can be either backwards in time (hindcast) or forwards in time (forecasts). Current advancements in computing speed and resource allow such studies to cover wide temporal scales, with recordings offer for highly discretised times i.e., results can be output for every 10 min or lower or higher. Historical studies can go back to 100 years or more. Reliable forecasts can be derived for up to 7-15 days; their results are not advised far ahead into the future due to increased uncertainties [39].

Numerical model results are useful for a wide range of human and environmental monitoring activities, such as Climate Change, climatic patterns, naval routes (shipping), offshore construction (platform, harbour), maintenance and operation, coastal defences, fisheries etc.

Threats and weakness are quite similar to each other, while the capability of models and numerical scheme have evolved significantly, accuracy in output parameters are highly dependent on user expertise. Experienced users can modify complex physical solution to deliver a customised model applicable to an area. Customisation of the model includes mesh construction, wind inputs, specific tuning of physical terms, ensuring stability of propagation schemes, and time integration.

User input is significant to a model, since many physical terms require specific tuning. For example some level of non-linear theories included in these models are not fully resolved and are based on explicit solution by so called "Rule of Thumbs" coefficients [9] derived through innovative investigations [15, 40, 41]. Such terms include whitecapping [42], quadruplet interaction [43, 44, 19], triad wave interactions, spectrum parametrisation, and wind related parameters [45, 46].

Another vital consideration in the application of numerical models is the computing and storage resources. Advancements and more powerful configurations have increased the speed, however long-term ocean simulations often require dedicated computing facilities. Especially for so-called oceanic models, High Performance Computing (HPC) access is vital to ensure a cost-effective study. On the other hand smaller domain models can operate in conventional powerful personal computers, however when we are to consider spatial resolution of just a few meters over a long temporal duration, the use of HPC is highly desirable. Availability of storage resources is also advised; when considering high resolution temporal solutions, adequate storage is required to facilitate output data of the simulation, and storage of final variables. Numerical wave modelling studies usually result in several TeraBytes (TB) of spectral and spatial data, especially when long-term studies are conducted (for example in Agarwal [47] 6TB of storage were required). In wave modelling, spectral data output over the computational domain are amongst the most significant findings. Storing full scale two dimensional spectral information demands large storage. Use of high Common Data Format (CDF) files, and Gridded Binaries (GRIB) alleviates some of these issues, but in large hindcast storage availability is crucial.

Final considerations of threats and weakness is the quality of inputs. Numerical wave models can be used for idealised cases and for the validation of a particular theory. Although, an operational model depends on specific inputs such as wind, currents, boundaries, bathymetry etc., quality of inputs plays an important role in the output results. Different spatio-temporal resolutions of wind, bathymetry affects outreach of the models and can result in under/over-estimations. While, several products of wind are available in the public domain, they have their own limitations in terms of time and resolution [48, 49, 50, 51, 52]. Alternatively, the user may choose some of the current wind datasets and perform temporal linear (or non-linear) regression to achieve a higher temporal wind driver, or use mesoscale models to obtain increased spatio-temporal wind datasets. First option is not always advised, as it entails proper cross-reference and validation of the interpolated dataset. While the latter often requires collaboration of experts in atmospheric models operation for proper results. Coupling of numerical models does not only benefit wave related operations, but also contributes to the continuous development of atmospheric models. Assessing the performance between models, enhances indirectly the quality of wind products, by cross-comparison of modelled data and the effects (ocean feedback), waves have on wind accuracy [5, 53].

Additionally, bathymetric information depends on certain databases such as the ones found in [54, 55], but for specific regions and coastal zones higher resolution data are necessary. The spectral boundary conditions are not often available increasing the dependency of smaller domain runs from larger models. The above de-efficiencies are not directly attributed to wave models, but to the estimate of resources. In has to be noted that several national agencies may have high resolution data, although they are not often in the public domain or accessible.

Finally, opportunities include prospects which are being implemented in numerical wave models and can significantly improve their performance. In the last decade satellite data and statistical techniques have contributed in model accuracy of forecast and reliability [22, 34, 33]. Statistical corrections and data assimilation techniques that take into account satellite, buoy measurements, forecast runs, and use them to ”correct” wave parameters produced by numerical models, will contribute in the minimisation of errors and improve predictions [56, 57, 58, 59, 60, 61].

3. Model Application

Majority of wave models, presented in Section 2 have been used throughout the years to provide significant information for the wave environments. Currently, many European institutes and research groups are operating wave hindcast and forecasts, e.g., ECMWF [32], NOAA [21], Hellenic Centre for Marine Research (HCMR) [62], University of Athens-Physics Department [20], ISPRA [63] and Ifremer [23] to name a few. Focusing on wave energy resources, Tables 2-9 provides an overview of the models implemented. The resulting datasets and studies are divided according to study region, model used, outcomes of the study, and most importantly range of hindcast in years (see Tables 2-9).

Table 2: Implementation of Global Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Global	[1]	WAM	15	$3^o x 3^o$	Waves
Global	[64]	OWI-EG	40	$0.625^o x 0.83^o$	Waves
Global	[65]	WW3	10	$1.25^o x 1^o$	Wave Power
Global	[66]	WAM-SWAN	50	$1.5^o x 1.5^o$	Wave Power
Global	[67]	WAM-SWAN	10	$0.5^o x 0.5^o$	Wave Power
Global	[68]	WW3	31	0.5^o & 0.06^o	Waves
Global	[69]	WW3	20	0.5^o	Waves
Global	[4, 6]	WW3	60	$1.5^o x 1^o$	Wave Power
Global	[70]	WW3	10	$1.25^o x 1^o$	Wave Power
Global	[71]	WW3 [1]	6	$0.5^o x 0.5^o$	Wave Power
Global	[5, 53]	WW3-WAM [2]	31[3]	variable[4]	Waves

Producing long temporal historical data over the global domain has a somewhat limited history. Use of early second generation models [1, 64] allowed the identification of intra-annual and decadal variations in the wave environment. After 2008 many projects showed interest in knowledge of the global wave resource, its long term variability, climatic changes and cycles. Most appropriate models for such scale are considered the oceanic models (see Table 2 and Section 2).

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[1] Results are obtained from NOAA re-analysis datasets

[2] Results are obtained from NOAA and ECMWF re-analysis datasets

[3] Depending on the dataset used

[4] Depending on the dataset used

At the same time developments in the wave energy community, [72, 10], spurred a necessity for continuous quantification of wave energy resource levels [65, 66, 67]. Up to that point datasets were limited to ≤ 10 years duration, with hindcast spatial resolution around $1-3^o$ in latitude and longitude. Recent studies have increased the spatial and temporal resolutions of databases allowing further improvements of wave climate records [4, 70]. Several research institutes are operating models that are constantly updated and re-analysed. These hindcasts serve as a rich repository of information that can be used in wave power studies (with considerations of applicability due to coarse domains) [71], but also provide the necessary benchmarks for the comparison-evaluation of other atmospheric models (i.e wind models) [5, 53].

Table 3: Implementation of Atlantic Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Europe-Atlantic	[73]	WAM	8 [5] & 3 [6]	$3^o x 3^o$ [5] & $0.5^o x 0.5^o$ [6]	Waves
Europe-Atlantic	[74]	WAM	10	$0.05^o x 0.05^o$	Waves, Extremes
Europe-Atlantic	[75]	WAM	45	$1.5^o x 1.5^o$	Waves, Climate Analysis, Extremes
Europe-Atlantic-UK	[76]	SWAN	7	$0.16^o x 0.16^o$ & $0.04^o x 0.04^o$	Waves, Wave Power
Europe-Atlantic-UK	[47]	WW3	140	$1^o x 1^o$ & $0.25^o x 0.25^o$	Waves, Climate Change, Extremes
Europe-Atlantic-UK	[77]	MIKE21	1	Unstructured	Wave Power
Europe-North East Atlantic	[78]	WAM	44	$0.25^o x 0.25^o$	Waves
Europe-North East Atlantic	[3]	WW3	57	$0.5^o x 0.5^o$	Waves, Wave Climate

Application of models at Atlantic European coastlines contributed significantly to the identification of wave climate patterns, quantification of extreme values, and climate change analysis. In the seminal work of [75], the Atlantic extreme return periods were quantified, with authors underlining limitations of oceanic models to nearshore coastal environments.

In order to quantify and increase confidence in the results, especially for climate studies, very long datasets are required. This was noted in several studies [75, 78, 3]. In terms of climate change, even longer records are required to assess the levels of change throughout a long-period of historical events. In the work of [47] the focus was on the identification of Climate Change in the offshore environment and corresponding extreme value levels. This extensive dataset of 140 years, allowed investigation of Climate Change trends in the Atlantic and UK coasts. The work utilised continuous development in the wave field, and offered a customised model for the region, with

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[5] Atlantic

[6] Mediterranean

improved indices when compared with buoy data. The validation of that work [47] included use of buoys with different annual recordings. After the selection of the optimal configuration the model expressed biases as low as 0.39% and high correlations.

Higher latitude regions of the United Kingdom (UK) benefit from significant high resources of waves [79, 80, 81]. This is also evident by the numerous ocean energy companies founded and operated in the UK, alongside with a state-of-the-art test facility for scale and real-time testing [82]. The need for a detailed resource quantification was thus initiated a while back, with the UK government issuing the first wave power map [83] in 2007. While at the time of publication, the map offered information, concerning areas with high concentration of wave power. Considerations must be taken by the use of a second generation model and a coarse resolution as discussed in [76] and [84]. Onwards, significant and continuous effort are made to improve the quantification of resource knowledge especially at coastal areas. This approach was utilised in the [76, 77, 84], in which wave modelling was applied to estimate the resource energy levels.

Table 4: Implementation of UK-Ireland Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
United Kingdom	[83]	WAM	7	$0.25^o x 0.25^o$	Waves, Wave Power
Isle of Lewis-Scotland	[85]	MIKE21	0.5	Unstructured	Wave Power
Isle of Lewis-Scotland	[86]	SWAN	1	Unstructured	Waves, Wave Power
Isle of Lewis-Scotland	[87]	SWAN	variable	Unstructured	Waves, Wave Power
Scotland-North Sea	[88, 89]	SWAN	1	$0.025^o x 0.025^o$	Waves, Wave Power
Scotland-North Sea	[84, 90, 91]	SWAN	11	$0.025^o x 0.025^o$	Waves, Wave Power, Extremes
Cornwall	[92]	SWAN	n/a	$0.05^o x 0.05^o$	Waves, Wave Power
Cornwall	[93]	SWAN	23	$0.05^o x 0.05^o$	Waves, Wave Power
Cornwall	[94]	SWAN	23	Unstructured	Waves, Wave Power
South UK	[95]	WW3	19	Unstructured	Waves, Wave Power
Ireland	[96]	WW3	10	$0.125^o x 0.125^o$	Wave Power
Ireland	[97]	WW3	14	Unstructured	Wave Power

Studies can be classified in three ways, first as the UK based, medium area studies and limited area studies (covering a small coastline), see Table 4. Transitioning from deep water to nearshore locations, also prompts the use of different numerical models most appropriate for nearshore mechanics [98, 99].

A study by Gallagher et.al. [96] produced wave resource maps for the greater areas of the UK and Ireland using an oceanic model. Subsequently, studies of medium and limited areas [86, 87] focused at the Scottish and North Sea regions, and produced wave energy quantifications. Limited areas, include smaller coastlines or regions, often for a dedicated wave site such as the Isle of Lewis [85, 77], or the WaveHub/Cornwall location [94] in which wave energy converters are also currently tested.

Majority of the studies are restricted by their temporal outcomes and hindcast duration. Concerning wave climate and energy studies dedicated in the region, long hindcasts are limited. Neil et.al. [76] used a nested mesh approach for the Mid-Atlantic and then several smaller domains, and their results showed small under-estimations when compared with buoys. Smith et.al. [94] produced a high-quality long-term hindcast for the area of Cornwal for 23 years at high resolution, the study utilised a mixture of inputs and achieved high correlation with small wave height under-estimation for recording by six buoys. Lavidas [84] utilised a high resolution spatial mesh examined the wave climate, power resource, WECs energy performance, and extreme conditions around multiple locations of the Scotland for 11 years.

Although, different models were used similar results were obtained, pending on the customisation of the model the accuracy was affected. For instance when comparing two studies of the same region and with common buoy for validation, Venugopal et.al. [77] results shows small over-estimations of biases in wave heights and correlation coefficients from 88% to 96%. In Lavidas and Lavidas et.al. [84, 90, 91] for the same buoys and same years the results are quite similar, with the same performance in correlation coefficient, though with under-estimation instead of over-estimation. In the latter studies the nearshore model was also compared with over 7 years of buoys recordings and multi-model analysis, the results were in very high agreement with correlation coefficients from 87% to 97%, but most of the time significant wave heights were under-estimated.

Table 5: Implementation of France Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
North France	[100]	TOMAWAC	24	Unstructured	Waves, Wave Power
Iroise	[94]	SWAN	23	Unstructured	Waves, Wave Power
West France	[101]	SWAN	3	1.5^o & 0.5^o	Waves, Wave Power
France	[102]	WW3	19	Unstructured	Waves, Wave Power
France	[87]	WW3	variable [7]	Unstructured	Waves, Wave Power
France (Sea of Iroise)	[103]	SWAN-TOMAWAC	8	Unstructured	Waves, Wave Power

Neighbouring to the UK are the French, Dutch and Belgian coastlines. With various institutes offering hindcast and forecasts, particularly for lim-

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[7] variable domains and spatial resolution used under different areas

ited area studies are also increasing for the region. As mentioned, nearshore environments require higher resolution models [104, 95]. Boudiere et.al. [102] produced a high resolution and accuracy databased (HOMERE) for the French region. In the validation of this dataset the authors used a WW3 model with unstructured grid and for selected locations their model performed very well with correlation from 89%-97% and a mixture of over and under-estimation of wave heights depending on location. The benefits of spectral databases for wave energy and availability are discussed in [104, 95].

Table 6: Implementation of Mediterranean Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Mediterranean	[105]	WAM	10	$0.5^o x 0.5^o$ & $0.25^o x 0.25^o$	Waves, Wave Climate
Mediterranean	[106]	WAM	44	$0.5^o x 0.5^o$	Waves, Wave Power
Mediterranean	[107]	WAM	10	$0.1^o x 0.1^o$	Waves
Mediterranean	[108]	WAM	2	$0.1^o x 0.1^o$	Waves
Mediterranean	[109]	WAM	10	$0.625^o x 0.625^o$	Wave Power
Mediterranean	[110]	WW3	35	$0.12^o x 0.09^o$	Wave Power
Mediterranean	[111]	SWAN	35	$0.1^o x 0.1^o$	Waves, Wave Power
Mediterranean	[112]	WAM	29	$0.25^o x 0.25^o$	Waves, Wave Power

Moving away from mid towards lower latitudes the Mediterranean Sea is encountered. The basin is known for its complexities, sharp bathymetric changes, volatile wind environment, and long complex coastlines. Many countries are exposed to the wave environment of the Mediterranean both North and South, with offshore human activities (i.e fishing, naval, marine etc.) highly active. Interest by the neighbouring countries has spurred for better understanding and forecasting of wave conditions for the Basin. A significant buoy network exists [113] with measurements dating back to ≈ 10 years and longer, predominately dispersed in Italy [63], Spain, France [23, 114], Greece [62].

Due to complexity and number of studies in the Mediterranean Sea, the studies can be sub-divided into country specific and limited area specific. The observation and historical evaluation of the Mediterranean Sea has produced numerous studies. In 2004, the Wave Atlas delivered by a high-quality consortium of regional agencies and research groups [105] predominately focused on wave resource. Recently interest has moved into the domain of wave energy quantification using numerical wave models.

Majority of the studies in the Mediterranean examined and delivered wave parameter data [106, 107]. Since 2010 interest on the examination of the wave energy resource, has spurred numerous dedicated studies for wave power [109, 110, 111]. With models both large and coastal scale, at high resolution and delivering long-term records with usual time duration of data $\approx 10 - 35$ years, there is now a plethora of useful datasets.

Complementing the usual coarse maps, dedicated country and limited domain area are also available. The quantification of wave energy in the area, is offered at higher detail both in spatial resolution and hindcast duration. Models such as SWAN and MIKE21 are used [109, 115, 116, 117]. Country and regional applications offer significant information on wave energy for the Italian and Spanish coastlines, by utilising high resolution models that are in a position to quantify the resource at coastal and shallow locations. In addition, unstructured grids and multiple nesting options helped to that enhance the applicability of results. This was the case in Monteforte et.al. [116], where a unstructured high-resolution model was used and its results were cross-compared with the ECMWF model (as no buoys were available). The results showed that the unstructured model was in very close agreement with the international accepted database of ECMWF, with very small underestimation by the Italian unstructured model.

Table 7: Implementation of Spain-Italy-Portugal Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
North Italy	[115]	SWAN-ROMS	15	$0.004^{o}x0.004^{o}$	Waves, Wave Power
Italy	[116]	SWAN	11	Unstructured	Wave Power
Balearic Islands (Spain)	[118]	WAM	17	$0.25^{o}x0.25^{o}$	Wave Power
Spain	[117]	SWAN	19	n/a	Wave Power
Spain	[119]	WAM	23	$0.25^{o}x0.25^{o}$	Wave Power
Balearic Islands (Spain)	[112]	WAM	29	$0.25^{o}x0.25^{o}$	Waves, Wave Power

Table 8: Implementation of Aegean Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Aegean	[120]	WAM	1	$0.06^{o}x0.06^{o}$	Waves
Aegean	[121]	MIKE21	15	Unstructured	Wave Power
Aegean	[122]	SWAN	1	$0.1^{o}x0.1^{o}$ & $0.025^{o}x0.025^{o}$	Waves, Wave Power
Aegean	[123]	WAM	42	$0.1^{o}x0.1^{o}$	Waves, Extremes
Aegean	[124]	MIKE21	15	Unstructured	Wave Power
Aegean	[125]	WAM	10	$0.05^{o}x0.05^{o}$	Waves, Wave Power
Aegean	[126]	SWAN	35	$0.025^{o}x0.025^{o}$	Waves, Wave Power
East Mediterranean	[127]	WAM	10	$0.016^{o}x0.016^{o}$	Waves, Wave Power

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[8] Multiple Domains nested

Recent years have also seen an increasing number of studies for the Aegean and East Mediterranean Sea (i.e Cyprus). Also, in this case long-term studies are found. Recently Zacharioudaki et.al. [123] delivered a comprehensive database of climate patterns and extremes found in the Aegean via the use of an oceanic model. Two studies used MIKE21 to quantify the wave power potential in the Aegean, utilising an unstructured mesh approach [121, 124], enhancing the results around coastal island areas and assessing the wave energy distribution in potential areas of interest. Emmanouil et.al. [125] used a high resolution oceanic model to assess wave energy levels and identify "hot-spots" sites. Lavidas et.al. [126] applied a two way nested model to the Aegean, identifying "hot-spot" areas, variations, and power performance by potential WECs in different depths and environments.

Results from these studies are quite comparable and similar even thought different models were used. Both Lavidas et.al. [126] and Zacharioudaki et.al. [123] studies have similar scatter indices, correlation coefficients, biases and rmse values are similar for all locations with some improvements in the Athos. Jadidoleslam et.al. [124] used an unstructured domain and when compared to the aformentioned studies, their work produced similar mean values with high correlation coefficient. Zacharioudaki et.al., Jadidoleslam et.al. [123, 124] had less biases for wave heights. Lavidas et.al. [126] showed a better performance in peak periods with lower biases.

The Eastern Mediterranean and lower Southern regions, do not have much information or buoy network as the rest of the Mediterranean countries, thus wave studies are necessary to enhance information. Zodiatis et.al. [127] produced a comprehensive hindcast map of the climate and wave energy for the Eastern Basin. Valuable results on the variability, distribution levels have been produced by [127], however the analysis was based on a oceanic model and results have to be extended to shallower regions with caution.

Table 9: Implementation of Black Sea Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Black Sea	[128]	WAM	41	$\approx 0.065^{o}x0.065^{o}$	Waves
Black Sea	[129]	SWAN	Limited	$0.07^{o}x0.07^{o}$	Waves
Black Sea	[130, 131]	SWAN	15	$0.0167^{o}x0.0167^{o}$	Waves, Wave Power
Black Sea	[132]	MIKE21	13	*unstructured*	Wave Power
Black Sea	[61]	SWAN	15	$0.07^{o}x0.07^{o}$	Waves, Wave Power
Black Sea	[48]	SWAN	Limited [9]	$0.067^{o}x0.067^{o}$	Waves
Black Sea	[49]	SWAN	Limited [10]	$0.067^{o}x0.067^{o}$	Waves
Black Sea	[133]	SWAN	31	$0.067^{o}x0.067^{o}$	Waves, Waves Power

Similar to the Mediterranean, the Black Sea is an enclosed basin with high wind and surrounding coastlines, posing a difficult and interesting case. The interest for wave energy resource and potential utilisation has increased with increasing numbers of studies delivering resource and climate maps [128, 131, 61, 133] for the Black Sea. Starting with Cherneva et.al.[128] an oceanic model was coupled and calibrated by using the regional atmosphere model (REMO). Subsequently, a 41 year hindcast delivered amongst the first most comprehensive resource assessments for the region.

However, resolution and limited physical solutions for the nearshore environments prompted long-term studies, both for waves and energy assessments [129, 130]. Akpinar et.al.[131] utilised the SWAN nearshore model to produce highly spatio-temporal databases of wave power spanning for a period of 15 years. Aydogan et.al. [132] used an unstructured mesh and estimated wave power potential across the Black Sea Basin for 13 years, and the results included wave power levels associated with directionality, as well as multiple investigation of bivariate distribution. These information can be used to select operational ranges for potential wave converter application. Rusu [61] enhanced a nearshore model by applying data assimilation method, presenting a high accuracy dataset. Most recently Akpinar et.al. [133], ran a nearshore model for 31 years, tuned against multiple physical solutions and wind components [48]. The results comprise a long-term database whose results are expected to undergo thorough examination in the future time.

One conclusion drawn from the investigation of the above studies is that depending the on application, different scale models are required. It has to be noted, that when nearshore coastal assessments are required, the model used must have the ability to estimate the shallow water mechanics, thus oceanic scale models are not always advised by their physics, spatial resolutions, and explicit schemes.

4. Discussion

Sections 2-3, offered an overview of the wave models that are currently being used and an extensive list of model results in relation to wave energy application. With continuous development and extensive studies the predictability of wave models' accuracy for offshore applications is increased.

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[9] Limited duration for the selection of appropriate wind dataset

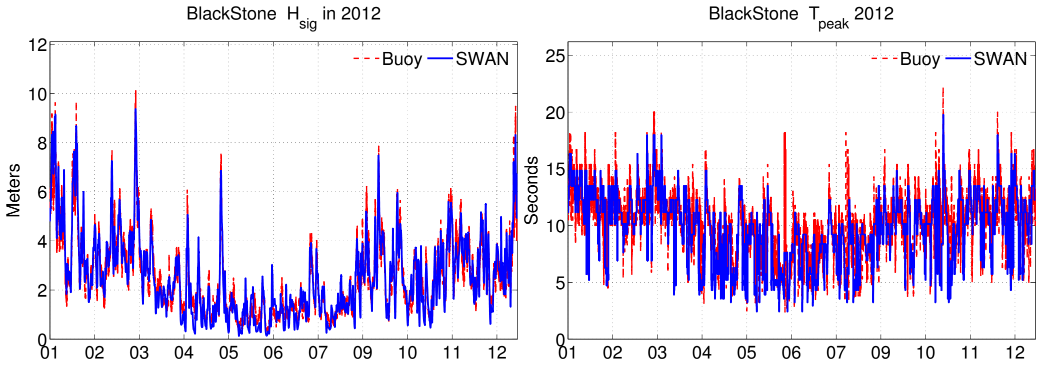
[10] Limited examination of storm duration extremes under scenarios

Application of numerical wave models is not straightforward, and it requires knowledge of the wave theory, insights on potential implications that coefficient tunings have, proper selection of inputs, boundary conditions, and scale of application. Calibration/validation of numerical models is done primarily with buoy recordings, with some limitations discussed in Cavaleri et.al. [134]. Although, often the limited application area and relatively small record length of measurements make them not so useful for generalised studies. For that reason the use of numerical models is advised in order to extent offshore analysis [26, 99]. Satellite data can also be utilised for calibration/validation purposes, but they are restricted in their temporal recordings. Usually their recordings are comprised of gaps between passing of the satellites, $\approx 10-30$ days apart, and recordings for wave parameters initiate $\approx 20Km$ off any coastline [24, 134, 135].

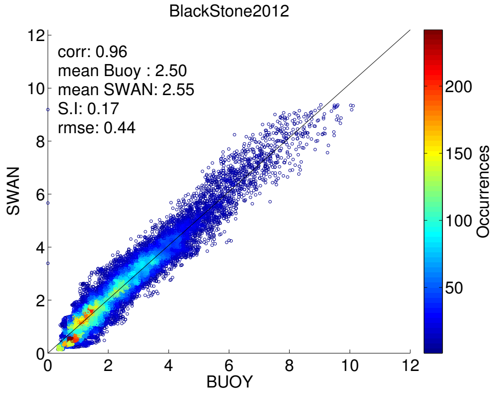
Results from numerical wave models are not without limitations, and have inherit uncertainties by our lack of exact solutions for several wave theory problems such as whitecapping. Calibration of a wave model involves "random errors", such as deviations from the site measurements due to the dependency of components (i.e wave heights, wave period) on wave spectrum and solutions applied [7, 26, 18, 35]. While alterations are usually not major, they are affected pending on the model [136, 98], set-up [136, 89], coefficients and solvers for physical process [136, 137, 138, 139, 44], spatio-temporal quality of inputs and boundaries [136, 137, 48, 49, 52].

One major disadvantage of numerical wave models is the missing of the "peaks" phenomenon [137]. Most models have a tendency to under-estimate wave heights at low frequencies and over-estimate at higher ones. Another driver is the quality, of the wind input and the scheme for wave generation and propagation [137, 53, 48, 52]. Wind datasets are also derived by larger atmospheric models which exhibit different performances depending on their area of application [5, 53],such irregularities propagate into the estimation of spectra by wave models.

Replacing a low temporal wind component with higher resolution one, may alleviate some of the under-estimations, but physical tuning is required to ensure that an optimal performance of a wave model with regards to the wind input, bathymetry, location, physics and solving approaches. Several physical problems are resolved within the wave models by "suggested" coefficient, which the user has to bear in mind that they may not have universal applications for optimal results [140, 141, 139, 19, 44]. Several of the models presented, offer significant parametrisation options which can improve the results after calibration. As example in Figure 1, the comparison of a calibrated–validated coastal model against buoy measurements is given. The generation trend and correlation coefficient (96%) of the model against the buoy is good for both period and wave height. This leads to bias of 0.05 meters indicating that the results of the model can be confidently used.



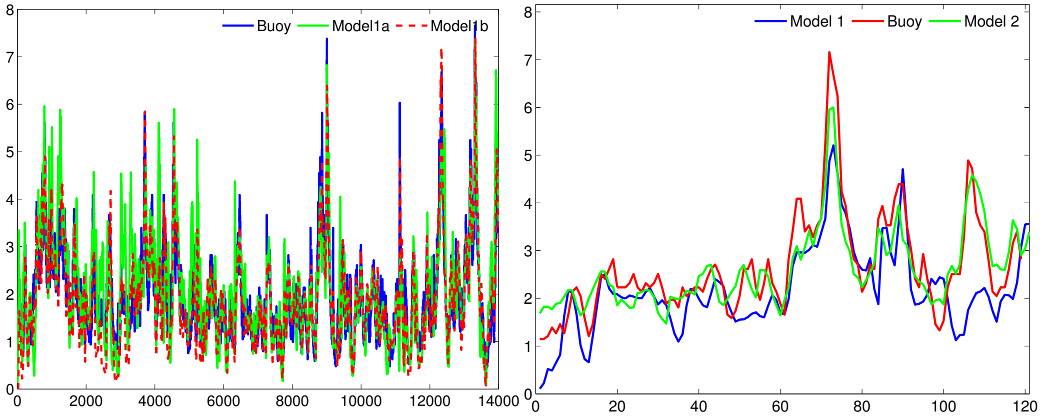
(a) Wave Height (b) Peak period



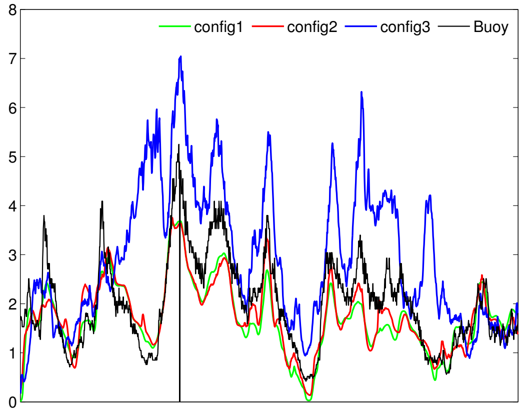
(c) Scatter diagram

Figure 1: Numerical models results of a calibrated–validated model, data analysed by the authors based on the dataset of [84, 91]

In Figure 2 some results from test cases (calibrations) are presented to show the effect of inputs (panel a), different models (b), coefficient tuning and propagation schemes (panel c). This shows that the performance of a numerical model can be sensitive to the parametrisation and inputs used. The level of sensitivity may vary accordingly, with physical alteration (coefficient, schemes) proving to be most sensitive, although they are able to improve or reduce accuracy.



(a) Winds (b) Models



(c) Physical Configuration

Figure 2: H_{sig} results by numerical model application with different inputs (a), models (b), and physics(c) applied by [52, 84]

Another parameter is to determine the duration for which a model will run (i.e. for how long). This is highly dependent on the desired analysis, and the user has to design the ”experiment” in a way that it will provide adequate and useful information. Depending on the application, the duration of a hindcast is vital to determine the validity of a study. The models presented in Section 2 offer numerous output parameters, and some models provide the parameters directly, others may require further analysis.

Based on the suggestions from previous studies and other guidelines, the duration of wave data for a high confidence level in the wave power estimation must have at least a 10 year minimum duration [99, 142]. In the case of studies for the estimation of return periods, the dataset should should not be less than 20% of the desired return period. The quantities should include the minimum one-dimensional wave spectra (1-D), and if adequate storage requirements exist this should be extended to two-dimensional (2-D) for every location [99, 142]. Indicatively, parameters needed for a wave energy resource applications are Significant Wave Height ($H_{sig/m0}$), Mean wave period(T_{m01}), Energy wave period ($T_{e/m10}$), Peak Direction (P_{kDir}) and Directional Spreading (D_{spr}) for minimum 3-hours intervals.

From Tables 2-9 it is obvious that not all studies are suitable for resource assessment, and climate characterisation based on time duration criteria. If a long-term dataset is not used then uncertainties increase, and intra-annual and/or decadal variations are not properly represented in the analysis. However, one year studies are still important, as they often provide significant insights for calibration and scoping of locations, that can be expanded upon by a more extensive study.

Final component that has to be taken into account is the computational efficiency, and parallelisation of the numerical model. Most models included in this review do offer a compilable source code, that is based either on Open Multi-Processing (OMP) or Message Passing Interface (MPI). Models that utilise an MPI approach can have cores and RAM memory allocation, thus contributing to fast and efficient model runs. Each wave model might have specific restrictions/requirements for minimum/maximum set up, core usage and memory requirements. For example in some instances, a model is more efficient when utilising 1-4 cores for limited study areas, than by using a higher number. On the other hand for larger domains some models have the ability to utilise a large number of cores to accelerate their solution, for example 20 cores. However, the same high number of cores for a smaller domain will not provide a faster solution. Thus, investigation of dependencies must also be taken into account and can actively contribute in minimising over/under usage of computational resources, which can be prove ”expensive” in use for wave modelling applications.

5. Conclusions

This review presented the state-of-the-art numerical wave models that are currently used in various institutions, underlined the constant evolution of numerical modelling of waves, and the significant outcomes that can be gained by their application. A brief outlook of the popular numerical wave models were presented and classified based on their characteristics and availability.

Also, a detailed record of global, regional and limited area studies focused on wave energy resource hindcasts was presented. The classification was based on the domain reach, duration of the dataset, models used, resulting outputs and resolution. The literature sources selected offer a comprehensive and up-to-date information on the range and applications of numerical models specific to several regions in Europe. Further this review pointed out potential areas that require further investigations, based on models limitations. The presented studies can also be used as a starting point for regional configuration of the models, based on the successful hindcasts in the past.

Selection of most appropriate numerical wave model depends upon the intended use, region, type of study, storage and computational resources. The review also illustrated that the numerical hindasting is a cumbersome process which requires detail preparation, dissemination of data, model construction and thorough validation. The intricacies of numerical wave models are numerous but are powerful tools in providing with high long-term spatio-temporal information on metocean resources, that are not otherwise feasible. Further, "building" and utilising a generic model for different regions, will not going to produce the best results; and with a plethora of options customised solutions can deliver high-quality results useful for the wave energy sector.

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