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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.

1. Introduction

The wave climate is highly variable across the globe on spatio-temporal scales with local bathymetry, coastlines, and winds greatly influencing the 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 [1–6]. With accuracy improved, numerical wave models have found utilisation within the research and energy communities [7–9].

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 [11–15], 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 the 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 1st and 2nd to the state-of-the-art 3rd 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

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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, tothe 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 [9,20–23].

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 [7,24,17,25–27].

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 development of 1st and 2nd 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 (1st 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 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 alterations in the way of calculating non-linear interactions by an alternative scheme are offered to the user. Furthermore, 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.

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[1] MIKE21 can be also classified under oceanic.

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

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