An experience on wind hindcast to simulate a Wave Hindcast over the Irish Sea

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Abstract

The effects of global climate change have direct impacts on the environment and in particular with coastal and marine environment which are the scope of this paper. Nowadays people, living in the coastal areas, are concerned with impacts of erosion and flooding, and demand replies from the authorities of what can be done to predict them as well as what can be done in order to minimise them. In fact, due to the raising concerns, conferences and meetings in the ministerial level as well heads of state level are being frequently set up in order to evaluate and conduct studies of how to minimise this effect on the globe. Usually the driving forces that cause damages to coastal environment are the wave conditions and can be determined by utilising a wave model. In order to run a wave model, wave spectra and wind fields are required.

The paper discusses an experience with an ongoing EU (European Union) Framework 5 research project, whose objective is to produce a wind and wave hindcast for European waters including the Mediterranean, North East Atlantic and North Sea. The discussion will include the computational models used, validation of the wind fields as well as the present status of the wave hindcast.

Resumo

Os efeitos das mudanças climáticas globais têm impacto direto sobre meio ambiente e em particular sobre meio ambiente costeiro e da marinha que é o escopo deste artigo. Na atualidade, a população que vive nas regiões costeiras está preocupada com os impactos de erosão, enchentes e exigem informações das autoridades sobre como prever estes impactos além de soluções para minimizá-los. Com a crescente preocupação de tais efeitos, reuniões tem sido organizadas em níveis de ministros e até chefes de estado para realizar estudos sobre minimizar os efeitos negativos das mudanças climáticas. Geralmente os danos são causados pelas ondas e as condições de ondas podem ser determinadas utilizando um modelo de ondas desde que tenham as condições de contorno e ventos como entradas. O artigo descreve a experiência com um projeto em andamento e financiado pela União Européia, cujo objetivo é produzir a climatologia do passado de ventos e ondas das agues européias. O artigo também inclui os modelos utilizados, os procedimentos de validação dos campos de ventos e o presente estado do projeto em relação à climatologia de ondas.

Key words: Wind Hindcast, Wave Hindcast, HIPOCAS, Reanalysis, Validation, Coastal Environment

Introduction

Wave climate is an essential element to be considered for long-term coastal planning and management. Information on storm duration, wave heights and frequency are important assets in order to design breakwaters or seawalls. By evaluating the effects of different wave regimes and considering the type of coastline on which the waves will impact, it is possible to identify areas at risk of erosion. Warnings concerning climate warming in the 21st Century tend to focus on coastal and marine environments and outline the associated risk to human and wildlife populations according to [Gates et al, 1992]. This research paper is concentrated on coastal environments but it is expected that other related fields may find a use for the results that are generated. People living in coastal areas are now demanding that local authorities provide detailed information about the potential impacts of climate change. Recent reports for European coastal margins indicate increases in wind speeds, wave heights and heights of storm surges in recent years as pointed out by [Gunther et al, 1998]. For the Irish region, storm impact will be significant for coastal erosion and affect physical process as detailed in [Devoy, 1994] and [Lozano et al, in press].

It would be extremely valuable if coastal areas that are vulnerable and environmentally sensitive to changes in wave regime can be identified. The identification can therefore assess and predict risks of climate changes. This has been recognized at an international level and as a consequence the European Union sponsored a EU 5th Framework research project, Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe (HIPOCAS). This research project has an objective of obtaining a 40-year hindcast (from 1997 to 1958) of wind, sea level and wave climatology for European waters [Soares et al, 2002]. The approach of a hindcast is very interesting when knowledge of the prevailing wind and wave conditions is required for certain applications that need climate impact studies. Moreover, it is not very easy to get hold of such information mainly due to poor or incomplete observational records [Weisse and Feser, 2003].

In order to create the required wave conditions sea surface winds need to be generated from numerical models. These are obtained by usually downscaling the results obtained after initially running General Circulation Models (GCMs). The downscaling is necessary in order to increase resolution as well as to facilitate the imbedding of regional and local conditions. The reason for downscaling is due to the coarse-scale nature of these GCM and this is not adequate for conducting wave studies in coastal areas as pointed out by [Weisse and Gayer, 2000]. The downscaled output is then integrated with a separate wave model to produce of localised wave height, direction and frequency data.

The focus of the study presented in this paper is on coastal and marine environment, which are also of concern with respect to global climate change. In order to conduct studies on coastal environment, such as floods and erosion, wave conditions must be determined. Mathematical equations that can "determine" the future state of the wave conditions based on the present state of the atmosphere are very complex and are structured and coded into models known as wave models. However, these models require the wave spectra as well as wind fields in order to generate the information on wave conditions. The paper is based on a EU Framework 5 research project whose objective is to generate wind and wave hindcast for the European waters for the period of 1997 to 1958. First of all wind fields in a high resolution (both in space and in time) were generated by downscaling reanalysis models with regional models to be used to run the wave model. The discussion in this paper shows the computational models used to generate the wind fields as well as their validation and how they are being integrated into a wave model.

The paper is organised as follows. Section 2 discusses the hindcast project and the models employed. Section 3 describes the methodologies employed as well as data sources used to determine the reliability of the produced wind fields. Section 4 outlines the current status of the project with reference to the generation of wave conditions and discusses how requisite information on coastal environment can be obtained. Finally, Section 5 includes discussion and comments on the conclusions drawn from the research to date.

HINDCAST PROJECT FOR EUROPEAN WATERS

In 1999, a consortium was formed by several research institutes and organisations from countries such as Bulgaria, France, Germany, Ireland, Malta, Poland, Portugal and Spain. The consortium decided to undertake a research project HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) and received a grant from EU (European Union) Framework 5. The objective of the research project HIPOCAS is to produce a wind and a wave atlas for European coastal waters (North Sea, Mediterranean Sea, Black Sea, Baltic Sea and Irish and Celtic Seas) for the years 1958 to 1997 [Soares et al, 2002].

The potential of developing this type of atlas from numerical modelling of wind-wave dynamic processes has until recently been limited due to inhomogeneities as already indicated in [Gates et al, 1992] and [WASA Group, 1998]. These difficulties have now been, to some extent, overcome after gaining access to the 40-year reanalysis carried out by National Center for Environmental Prediction (NCEP), Washington, USA and the National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA [Kalnay, 1996]. This reanalysis has acted as a basis to the HIPOCAS research project. The reanalysis spatial resolution is coarse (200 KM) and the outputs were generated in 6-hour time slices. As this coarse resolution is not suitable for conducting studies on wave conditions, a downscaling process has been adopted so that high-resolution wind fields can be obtained. The process initially requires wind parameter data derived from large-scale models. The output from these is subsequently used in a downscaled localised atmospheric model to produce wind fields at a higher resolution. It is this final output from this localised model that is used by the separate Wave Model (WAM) to produce wave parameters such as height, direction and frequency.

Therefore, as mentioned above, the reanalysis is the initial database serving as boundary conditions for the HIPOCAS project. The initial downscaling has used the REgional MOdel (REMO) [Jacob and Podzun, 1997]. This model has a spatial resolution of 50 km and wind fields were generated in an hourly basis. For some areas, at this regional scale, a spectral nudging technique [von Storch et al, 2000] has been applied to enhance lateral boundary conditions by imposing time-variable large-scale atmospheric states on the regional atmospheric model.

For most of the European waters, the downscaling process terminated by employing REMO and the produced wind fields were then used to drive the Wave Model (WAM) [WAMDI Group, 1988] and [Gunther et al, 1992]. Besides the wind fields, in order to run the wave model, boundary conditions or wave spectra are also required.

WIND HINDCAST FOR THE IRISH SEA

Coastal and Marine Resources Centre (CMRC) from University College Cork (UCC) is the research institute that is responsible to produce the wind and wave hindcast for the Irish and Celtic Seas and adjacent North Atlantic area as shown in Figure 1.

Figure 1: Geographical extent of the Irish Sector

The process adopted for the Irish sector has been the same but with one exception. Instead of using the wind fields from REMO to drive the wave model, another limited area model has been utilised in order to further increase the spatial resolution. The model in question is HIRLAM (High-Resolution Limited Area Model) [Sass et al, 2000]. The output spatial resolution for HIRLAM is 10 KM and the time slices are hourly-based just like in REMO.

The 40-year dataset of wind fields from 1958-1997 has been generated over the last 18 months using a computer cluster consisting of 4 personal computers. Of these one has 2 Pentium III 886 MHz processors and other 3 have Pentium IV 2.2 GHz processors. As the HIRLAM code being used is not a parallel version the executable was installed in all machines in the cluster so that 4 model runs could be performed simultaneously. However in practice the primary PC was used to download the REMO boundary conditions (from GKSS Forschungszentrum Geesthacht GmbH-GKSS site in Germany) whilst the other three completed HIRLAM model runs for specific years in order to generate annual wind fields. Generation of a single year□s wind fields took approximately 5 days to complete.

All the boundary conditions generated from REMO for use by HIRLAM and the HIRLAM output were in rotated GRIB format:

http://www.wmo.ch/web/www/WDM/Guides/Guide-binary-2.html.

The authors also intend to extend the project to encompass 1998 □ 2002 but unfortunately the latest REMO data is stored in a different version of the GRIB format. Therefore a decoding methodology will have to be devised prior to integration of this extended data into the HIRLAM model.

Now that the wind fields from the HIRLAM model were generated the output has to be validated in order to ensure the reliability of the model prior to their inclusion in the wave model. Ideally any atmospheric validation model output would be conducted using known (real) observations. However, considering the Irish sector, unfortunately there is only very limited continuous meteorological and wave information available for the region [Vijaykumar et al, 2003]. This is mainly confined to data from 1990 onwards and information prior to this date tends only to be available from terrestrial sources. Even though such information is available, it tends to be spatially disjunct. However, it is important to stress that major improvements have been made in recent years and there are now numerous potential sources of continuously recorded observations, particularly through the deployment of weather buoys and in satellite imagery (http://www.ecmwf.int). In spite of these improvements model validation using real data remains difficult and a range of procedural options for validating atmospheric data have to be considered. The validation process is essential to the integrity of any conclusions derived from the output data. Unfortunately the process is restricted by the quality and duration of the available datasets (rubbish in = rubbish out).

For the data under consideration here, the validation indicators employed were well known statistical measures based on correlation coefficient and root mean square (rms). The data sources used included time series observations from ships and weather buoys for numerical comparison and satellite imagery, as linked to weather charts to visually assess wind patterns.

Figure 2 shows a plot that compares the HIRLAM model output of wind fields with ship observations. For the Irish Sea region, ship-based observations have been a traditional source.

Figure 2. Comparison of HIRLAM generated data and ship observations.

The plot covers observations for the month of January 1992. This offered a reasonably consistent ship position and observational time series. The comparison of wind speeds from both sources demonstrates a reasonable visual match. The obtained results were a correlation coefficient of 0.68 and an rms of 2.99.

The other source of observational validation data were UK Metrological Office weather buoys located at stations K2 (Latitude: 51.00o; Longitude: -13.30o) and K4 (Latitude: 54.54o; Longitude: -12.36o). These stations have observations of wind fields from 1993 to date and provided an overlapping period with the hindcast period of 5 years (1993-1997) with frequency varying from 3 hours in 1993 to every hour in subsequent years. The wind comparison between HIRLAM and data from the K4 station is shown in Figure 3 and revealed a correlation coefficient of 0.79 and an rms 1.004.

Figure 3. Comparison of HIRLAM and K4 Weather Buoy data

It has been noted that validation data, regardless of its inherent quality, is not always freely available or if available is not widely publicised. Some data is held by the commercial sector but the majority of data is held by government and therefore is subject to the laws of freedom of information held by a particular country. Regardless of location the information may be treated as proprietary or they may be considered sensitive (e.g. for security and commercial competition reasons) and, depending on the type of data, available only at commercial costs and in limited formats. Pricing policies may also vary greatly between the different providers although the provision of data for research and non-commercial purposes tends to be released at nominal costs as meteorological and linked state service are in general very helpful.

Due to the difficulties in obtaining observed/real data for long time series for offshore areas, particularly prior to the 1990s, other 'validation' options have had to be considered. One option is to use data, derived from a modelling reanalysis process (i.e. model prediction/output data), produced from other models. These may be specific oceanographic models or may include landmasses and usually resulted from previous research programmes (e.g. for ocean - offshore area meteorological data then NCEP, ECHAM4, REMO, ERA-15, ERA-40 model outputs can be utilised). The advantage of using such data is that they are often easily available and are in the majority free. These types of data are commonly stored in public domain databases, on websites, or in linked Geographic Information Systems. The negative aspects of these data sets are that they are not true observational records but outputs/reanalyses of previous model runs and that their resolution may be at much lower scale s than required. In addition these types of reanalysis data may or may not have been subjected to a rigorous validation process themselves and care needs to be taken to avoid producing erroneous results as a result of 'methodological circularity'

For the wind hindcast, reanalysis data from the ERA-40 project was considered (e.g., Gibson et al, 1997). The ERA-40 project's objective has been to define (parameterise) and analyse the state of the global atmosphere using satellite derived data sources. Data sets consist of 6-hour time slices with monthly mean data also available The ERA-40 project was developed through the ECMWF (European Centre for Medium-Range Weather Forecasts - http://www.ecmwf.int) and covers the period 1957 to 2001. The project was based on earlier work from ERA-15, for the years 1979 to 1993. Although developed for large-scale work the wind data sets were considered applicable to the Wave Atlas project and the results of the comparison were therefore included. Figure 4 gives an example of the wind results (for +10m sea level) from both the HIRLAM and ERA 40 model outputs. A coordinate node of □5.0^{0} (Longitude) and 55.0^{0} (Latitude) was selected and a time series with an interval of 6 hours between points was exported for the period between the 1st-7th September 1996. The correlation coefficient obtained for the wind speed was 0.78 whereas the rms obtained was 1.10.

Figure 4. Comparison of HIRLAM and ERA-40 reanalysis data.

In addition to the use of reanalysis/ model results the modelling methodology itself provides a further validation option (in essence an internal process check) to verify the accuracy of the model downscaling. A simple check to test whether the HIRLAM model outputs is working correctly is to compare the HIRLAM results with the initial REMO boundary parameters (Figure 5) and thus verify if the HIRLAM model was properly nested in the REMO simulations

Figure 5. Comparison of HIRLAM and REMO generated wind data.

As expected the trends and variations in the wind plots for the two models are similar. The difference in wind velocity is probably a result of the different elevations above sea level at which the model data are extracted, +10 metre for HIRLAM and between +20 and +40 for REMO. Another beneficial approach to test an atmospheric model is to check output with observed data during extreme events. Based on background information received from the national weather service, Met Éireann, it was decided to compare data for the period of 12th -19th December 1997 when wind velocities peaked at 54 knots. Figure 6 shows HIRLAM performance for this period compared with data at K4 station. Correlation coefficient of 0.77 and rms 1.49 were obtained.

Figure 6. Comparison of HIRLAM x K4 Weather Buoy data in Extreme Winds

The statistical measures utilised as part of validation process to date have been standard correlation coefficient and root mean square tests. It will be necessary in continuing work to use other types of test in order to make the verification methodology more robust. This is particularly important as only the wind and wave output statistics would normally be presented in a database and linked Geographic Information System.

One such statistical operation suggested [Weisse and Gayer, 2000] and used in assessing the quality of hindcast of wind fields is that of complex correlation. This operation is very practical and it determines the correlation between two vector time series, as is the case for winds. In short, complex correlation uses $u^{obs} + iv^{obs}$ and u^{mod} and iv^{mod} to calculate the coefficient. The superscript ^{obs} denotes observation values whereas ^{mod} denotes the results from a forecast model and i represents . Detailed information of this complex correlation operator can be found on the website http://storms.rsmas.miami.edu/~cook/thesis/node19.html and in [Kundu, 1976].

Just as an example of use, the complex correlation between wind fields from HIRLAM and ERA-40 reanalysis was determined. The correlation obtained was approximately 0.95 whereas the phase angle obtained was □23.0^{o}. The speed and direction of the wind fields from both the sources are shown in Figures 7 and 8 respectively. The very large magnitude of the correlation (~0.95) shows that the phase difference is fairly uniform throughout most of the occurrence. The phase angle gives the average angle of the second vector with respect to the first (positive if the second vector is counter-clockwise from the first). The result obtained was □23.0^{o}, indicating a clockwise mean displacement of HIRLAM vectors with respect to reanalysis data. A more extensive work using this operator will be conducted with other sources of data.

Figure 7. Time series of wind speed: HIRLAM x ERA-40 reanalysis

Figure 8. Time series of wind direction: HIRLAM x ERA-40 reanalysis

There is one more technique known as Gradient Pattern Analysis [Rosa et al, 1999], [Ramos et al, 2000] and will be applied to both the atmospheric and wave model outputs. This technique is innovative and has been developed to apply on non-linear spatial-temporal structures to estimate the gradient moment based on the asymmetries among the vectors of the gradient field of the scalar fluctuations. It is used to characterise the formation and evolution of extended patterns based on the spatial-temporal correlations between large and small amplitude fluctuations of the pattern-structure represented as a gradient field [Rosa et al, 1998], [Assireu et al, 2002] and [Rosa et al, 2003]. Unlike most of the statistical tools, GPA does not rely on the statistical properties of the series but depends solely on the local symmetry properties of the signal□s gradient pattern. Moreover, when considering complex variability, it takes into account the directional information contained in the vector field. This technique is based on two operators: Asymmetric Amplitude Fragmentation (AAF) [Rosa et al, 1999] and Complex Entropy Form (CEF) [Ramos et al, 2000]. AAF performs a global gradient asymmetry measurement by determining the symmetry breaking of a given dynamical pattern. The Complex Entropic Form operator is a measure of regularity and permits the quantification of the degree of phase disorder associated with a given gradient field. The idea here is to conduct a more rigorous study of how the application of such operators would help establish a valid verification methodology of weather related information before storing them in a GIS for future use. Further useful tests would concentrate on the accuracy of the model in predicting the occurrence of extreme events (timing and scale parameters), together with the testing of data homogeneity over time [Soares et al, 2002] and [Soares, 2003].

WAVE HINDCAST FOR THE IRISH SEA: PRESENT STATUS

Once the wind fields for the hindcast were generated and passed the initial validation they are to be used to drive the wave model. The wave model employed for the hindcast is a 4th generation version of the heavily tested and widely used wave model WAM, developed by [WAMDI group, 1988], and described in [Gunther et al, 1992]. The idea was to produce wave conditions for every 3 hours with a high spatial resolution of 0.083o (inner grid), 0.166o and 0.5o (outer grid). The required boundary conditions, (wave spectra), were produced by another HIPOCAS partner Instituto Superior Técnico, Portugal. The wave model for the Irish Sea has been successfully set up and some initial tests were run. An example output is shown in Figure 9 and presently the hindcast for the full 40-year period is being generated.

In addition to providing information about wave climate and behavior, the wave model can also provide the boundary conditions for wave refraction models. When used in combination these can used to assess the various levels of wave energy on the coast that can result from variations in deep water wave climate. This information can be invaluable to detect areas that are vulnerable to erosion, flooding and tidal surge damage. If this information is readily retrievable then policy decision makers such as urban planners and public bodies can utilise the information to alert the population when potentially dangerous situations arise.

Figure 9. WAM output

The same cluster used for running HIRLAM is being used and at the moment almost 10 years of wave conditions have already been produced. Again the validation procedures must be adopted in order to verify the reliability of the set up of the wave model for the Irish Sea. The observation data available are from K2 and K4 stations from the UK Meteorological Office and similarly as for HIRLAM, the period available is from 1993 to 1997.

CONCLUSIONS

Since the 1990s, evaluation of global climate change and its association with environmental processes have been in the spotlights. These topics are considered as major streamline research projects within several academic and commercial institutes around the world. In particular, for the areas of coastal science and coastal processes, several studies are being conducted to determine the effects of global climate changes to coastal regions, in terms of coastal flooding and linked river catchment functioning, erosion and many other coastal management concerns. These evaluations for the future depend necessarily upon the use of numerical modelling techniques and upon their accuracy in predicting the operation of environmental systems. In this work good model validation procedures are vital.

The work of the Wind and Wave Atlas project HIPOCAS is linked to the evaluation of coastal processes and to assessing the wider uses of ocean environments such as shipping, port management and others, particularly through the use of data incorporated into coastal GIS. It is important to highlight that the work requires the development of validation procedures before wind field data obtained from a high resolution atmospheric model (HIRLAM) can be incorporated into a wave model, together with the further validation of the wave data outputs. This validation though is inherently difficult because of the limited sources of good quality and readily available observational data from the offshore zone.

The paper illustrated the approach of combining atmospheric models in order to obtain high-resolution wind fields and integrating these fields with wave model to generate hindcast datasets for the Irish region. The atmospheric models selected (REMO and HIRLAM) to downscale the NCEP/NCAR reanalysis data performed well. However, some difficulties were found in finding out the proper decoding information to retrieve wind fields from REMO and HIRLAM output. The main concern is the format compatibility between models as long delays were encountered during the REMO / HIRLAM downscaling as a result of output / input incompatibility in GRIB formats. This experience was not repeated with the wave model as the version installed for this project deals with data in binary rather than GRIB format. Validation of the wind fields will continue as new source of data become available and new methods of validation such as Gradient Pattern Analysis and other techniques that deal with nonlinear phenomena will be explored.

This type of approach will be adopted when the generation of the wave data has been completed and adapted to reflect the differences in the type of data produced. By the end of this project, the Centre is expected to have a database consisting of 40-year wind fields and wave conditions for the Irish Sea. At the moment, a new research project is being set up in which efforts will be made to develop a web-based database system to store these obtained hindcast datasets. Moreover, operators will be also embedded so that one can visualise a required time series of the available datasets or even compare them with some other available source.

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