Computational Modeling of Environmental Processes: A Hindcast of Wind Atlas over Irish Waters

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Abstract: Numerous research projects are currently being conducted to establish a link between global climate change and the risks to coastal and marine environments. As part of a wider European 5th Framework Project, *HIPOCAS*, an attempt is being made to establish this link for the Irish and Celtic waters. To facilitate this a wind hindcast was conducted for this region for subsequent integration with a wave model. This paper outlines the experiences of using the computational models selected for this project and the necessity of evaluating the reliability of the atmospheric model before integrating it into the wave model.

***Keywords**:* Hindcast; Wind atlas; Global Reanalysis; Regional High-Resolution Area Model

1. INTRODUCTION

Consideration of wave climate is essential for long-term coastal planning and management. For example, in order to design breakwaters or seawalls it is essential to have data not only on wave height and frequency but also, on storm duration, severity, wave heights and frequency of occurrence, amongst others. By evaluating the effects of differing wave regimes and considering the type of coastline that the waves will impact on 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 is also 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].

In assessing the predicted risks of climate change, it is extremely valuable to be able to identify coastal areas that are at potentially high risk and environmentally sensitive to changes in wave regime. This has been recognized at an International level and the research detailed here forms part of an ongoing EU 5th Framework research project, *Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe (HIPOCAS).* The background of this project is provided in Soares et al [2002] and its objective is to obtain a 40-year hindcast of wind, sea level and wave climatology for European waters from 1997 to 1958.

To create the required wave statistics sea surface winds need to be generated from numerical models. These are usually initially generated from General Circulation Models (GCMs) and downscaled to increase resolution and to facilitate the imbedding of regional and local conditions. The downscaled output is then integrated with a separate wave model to produce of localised wave height, direction and frequency data.

This paper is concerned with the computational modeling involved in generating the wind atlas for the Irish and Celtic Seas. The paper describes the models utilised and the validation procedures employed prior to integration into the wave model. In addition to this introductory section four additional sections are included. Section 2 discusses the hindcast project and the models employed. Section 3 describes the validation methodology and verification 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.

2. MODELLING: HIPOCAS PROJECT

The primary output from HIPOCAS is a Wave Atlas for European coastal waters for the years 1958 to 1997. The potential of developing this type of atlas from numerical modelling of wind-wave dynamic processes has until recently been limited due to inhomogeneities already indicated in Gates et al [1992] and WASA Group [1998]. These difficulties have now been overcome and this paper sets out to describe the processes required to generate a wave hindcast atlas for the Irish and Celtic Seas and adjacent North Atlantic area (Figure 1). 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 (hourly output on 0.12^0 grid). 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.

The data that forms the basis of the HIPOCAS project is derived from a 40-year global atmospheric reanalyses dataset as described in Kalnay et al [1996]. The reanalysis was carried out by the National Center for Environmental Prediction (NCEP), Washington, USA and the National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA. The spatial resolution of the GCM output is coarse spatially 200km and temporally every 6-hour intervals. The coarse-scale of the GCM and associated regional models is inadequate for wave studies in coastal areas as discussed in Weisse and Gayer [2000]. Therefore the GCM output is used as a starting point for a downscaling process to derive data at the higher spatial and temporal resolution. The initial downscaling is completed using a regional model for the North Atlantic REgional MOdel (REMO) and details can be referred to in Jacob and Podzun [1997]. This model has a spatial resolution of 50km and wind data can be generated at hourly time scales. For the Irish sector (Figure 1) this data was further downscaled using the High-Resolution Limited Area Model, (HIRLAM -Sass et al [2000]), in order to increase the spatial resolution to 10km. This output provides both the wind fields for inclusion in the actual HIPOCAS project and the input for the WAM wave model (WAMDI Group [1988] and Gunther et al [1992]).

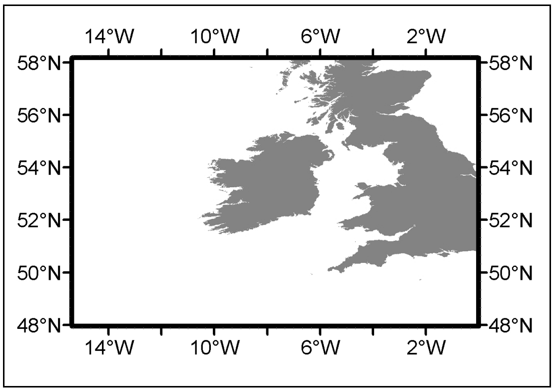

Figure 1. Geographical extent of the Irish Sector

The 40-year dataset 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 the 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 the 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 REMO data for this period is not stored in the requisite format, making it incompatible with HIRLAM. Therefore a decoding methodology will have to be devised prior to integration of this extended data into the HIRLAM model.

3. VALIDATION

Once the HIRLAM wind fields were generated the output was subjected to validation. This process was essential in ensuring the reliability of the model and the subsequent wind results prior to their inclusion in the wave model. Ideally validation of the HIRLAM model output would be conducted using known (real) observations. 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. Any information that is available also tends to be spatially disjunct. 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 validation 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.

For the data under consideration here, the validation indicators employed were 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.

A traditional source of 'real' data for the Irish Sea region has been from ship-based observations and for this project ship-based data covered for a single month (January 1992) was utilised. This offered a reasonably consistent ship position and observational time series. The comparison of wind speeds from both sources is shown in Figure 2 and demonstrates a reasonable visual match. In addition, the correlation coefficient for the wind speed obtained was 0.68 and the rms obtained was 2.99.

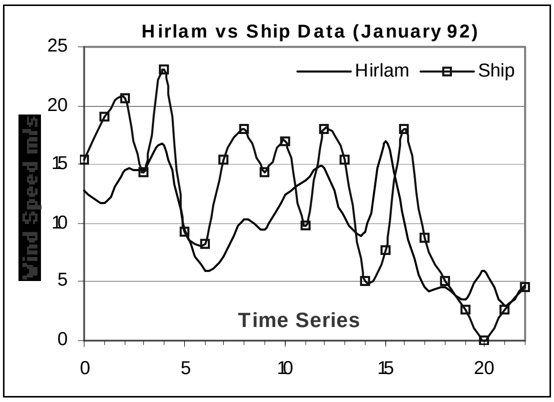

Figure 2. Comparison of HIRLAM generated data and ship observations.

The other source of observational validation data were UK Meteorological Office weather buoys located at stations K2 (Latitude: 51.00°; Longitude: -13.30°) and K4 (Latitude: 54.54°; Longitude: -12.3°). These stations have observations of wind fields from 1993 to date and provided an overlapping period with the model 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 are shown in Figure 3 and revealed a correlation coefficient of 0.79 and rms 1.004.

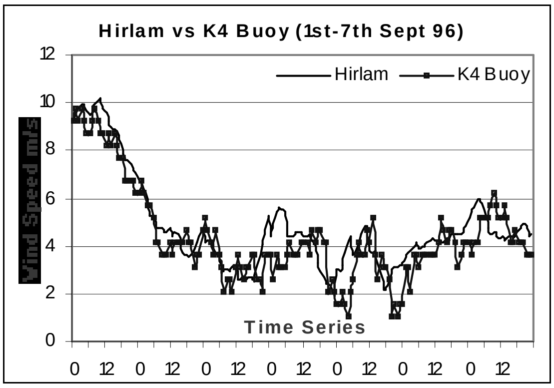

Figure 3. Comparison of HIRLAM and K4 Weather Buoy data

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 (>months) 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 scales 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 Wave Atlas (HIPOCAS- Irish Sea region) 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.

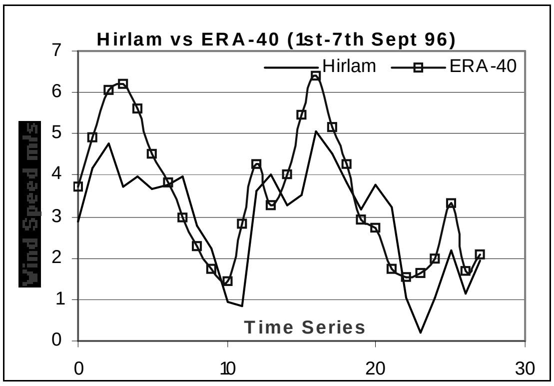

Figure 4. Comparison of HIRLAM and ERA-40 reanalysis data.

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

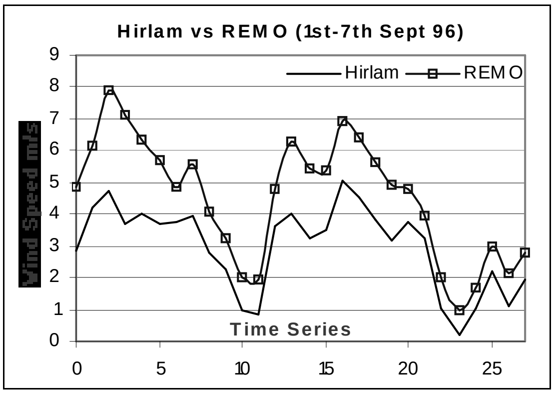

Figure 5. Comparison of HIRLAM and REMO generated wind data.

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, +10m for HIRLAM and between +20 and +40m 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.

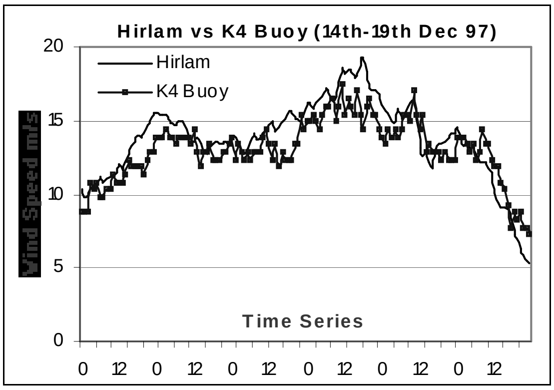

Figure 6. Comparison of HIRLAM and K4 Weather Buoy data in Extreme Winds

The statistical measures utilised as part of validation process to date have been standard correlation coefficient and root mean square tests. However the authors realise that a more robust series of tests will need to be employed in the future to fully assess the quality of the HIRLAM output. Therefore, other validation methods such as complex correlation (Kundu [1976)] and Gradient Pattern Analysis (Rosa et al [1999], Ramos et al [2000]) will be applied to both the atmospheric and wave model outputs.

4. WAVE HINDCAST

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 4^{th} generation version of the a 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 hourly wave conditions with a high spatial resolution of -0.25^{o}. 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 7 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.

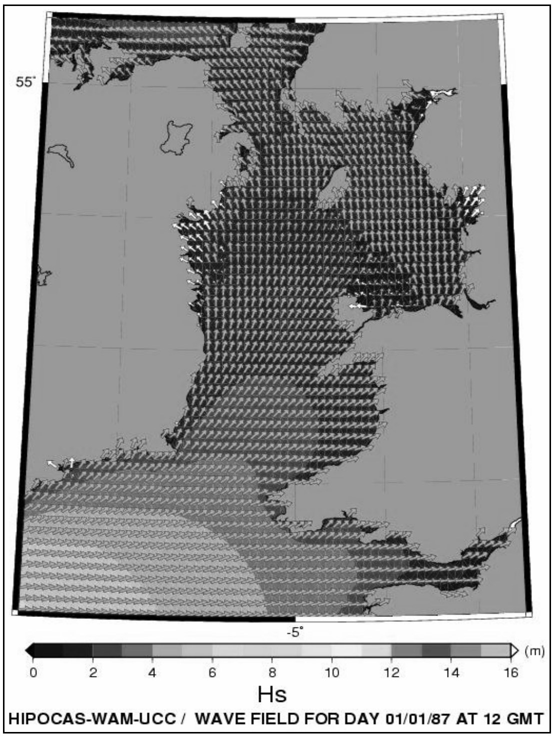

Figure 7. WAM output

5. CONCLUSIONS

The paper illustrates the approach of combining atmospheric models and integrating them with wave model to generate hindcast datasets. The atmospheric models selected (REMO and HIRLAM) to downscale the NCEP/NCAR reanalysis data performed well. 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 model 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 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.

In addition, refinements need to be made whereby better quality data is made available to end users thus stressing the importance of validating results from atmospheric models.

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