

Department for Business, Enterprise
& Regulatory Reform

Atlas of UK Marine Renewable Energy Resources: Technical Report

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Report No: R.1432



Department for Business, Enterprise & Regulatory Reform

Atlas of UK Marine Renewable Energy Resources: Technical Report


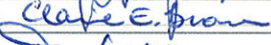
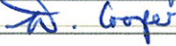
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Summary

The Atlas of UK Marine Renewable Energy Resources (hereafter called 'the Atlas') was first published in September 2004 and has since become widely recognised as the main reference for regional scale descriptions of offshore renewable energy resource. In response to the initial high interest in the Atlas a freeview GIS version was released in July 2005 and has since given the industry a primary tool to screen for potential development sites. It is understood that over 300 CD-Roms of the Atlas GIS have now been distributed. This document supersedes ABPmer Report No. R.1106 which accompanied the previous Atlas release.

Early in 2007 it was recognised that Department for Business, Enterprise and Regulatory Reform's (BERR) continuing progress with Strategic Environmental Assessment (SEA) for potential wave and tidal energy schemes would directly benefit from an update to the Atlas to ensure best available and reliable data combined to underpin the SEA process. Additionally, any future plans for wind energy developments, including Round 3 licence calls, would similarly draw extensively from the Atlas. It is on this basis that the BERR commissioned a consortium led by ABP Marine Environmental Research (ABPmer), to update the Atlas from its present form with a combination of new data and enhancements of presentation to ensure that the forthcoming initiatives of BERR remain supported with the best available information.

The study team included partners from the original project and was led by ABP Marine Environmental Research Ltd, with support from two additional leading UK organisations in marine science and offshore resources:

- ABP Marine Environmental Research Ltd;
- Met Office; and
- Proudman Oceanographic Laboratory.

The Atlas update was tested against user requirements (Section 1.3) to ensure that enhancements are relevant to the marine renewable sector. Two key changes have been made, namely the:

- Improvement of the underlying resource datasets; and
- Enhancement of the dissemination methods.

The wind and wave datasets have been derived from an increased archive of data (from 3.5 years to 7 years) which has improved confidence within the models and enabled inter-annual variability statistics to be included within the results. The wave resource assessment now includes statistics that differentiate between the energy that can be exploited by focusing a device on the primary component of energy in the wave field, as compared to the energy available to devices that can capture the total energy from sea-states comprising distinct wind-wave and swell components (crossed-seas). The tidal dataset benefits from improved model calibration and enhanced vertical data resolution provided by five independent layers of model



outputs. The tidal current dataset also has an improved accuracy through the implementation of a new ocean turbulence model.

The datasets are available through a new webGIS dissemination tool (<http://www.renewables-atlas.info>) which provides resource mapping as well as access to additional information and the underlying GIS datasets.

The original Atlas was well received by the marine renewable community and still provides a valuable reference for the regional scale analysis of UK offshore wind wave and tidal resources. The Atlas, through end user engagement, has proved that there is a continuing demand for updated versions of the datasets, which, will initially be fulfilled by the publication of the latest Atlas outputs including the pre-prepared Atlas maps and interactive webGIS. As the UK offshore renewable industry matures it is suggested that this interest is likely to be maintained and therefore the project has developed several recommendations for future Atlas products to support a full range of stakeholders within marine renewable energy projects. These include data updates, additional constraints data layers and tool enhancement.



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Project Team:

ABP Marine Environmental Research Ltd:	Bill Cooper Chris Jackson Jamie Moore Claire Brown Rebecca Russell David Petrey Mike Elmes Paul Lacey
Met Office:	Andy Saulter
Proudman Oceanographic Laboratory:	Colin Bell
Royal Haskoning:	Nick Brockie
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Abbreviations

ABPmer	ABP Marine Environmental Research Ltd
AEY	Annual Energy Yield
AMM	Atlantic Margin Model
ASL	Above Sea Level
BERR	Department for Business, Enterprise and Regulatory Reform
BODC	British Oceanographic Data Centre
BWEA	British Wind Energy Association
CS3	Continental Shelf Model
CIRIA	Construction Industry Research and Information Association
DEAL	Free, public, web-based service, designed to promote and facilitate access to data and information relevant to the exploration and production of hydrocarbons on the UKCS.
D_p	Principal wave energy direction
DTI	Department of Trade and Industry
EC	European Community
EMEC	European Marine Energy Centre
GEBCO	General Bathymetric Chart of the Oceans
GIS	Geographical Information System
GW	Gigawatt (1,000,000,000 watts , 1,000 megawatts)
HRCS	High Resolution Continental Shelf Model
H_s	Significant wave height
HV	High Voltage
HW	High Water
JONSWAP	Joint North Sea Wave Project
K_1	Lunar solar diurnal constituent of the tide
km	kilometre
LW	Low Water
MAWS	Marine Automatic Weather Station
MNR	Mean Neap Range
MNPC	Mean Neap Peak Current
MSPC	Mean Spring Peak Current

MSR	Mean Spring Range
MW	Megawatts (1,000,000 watts)
M ₂	Main lunar semi-diurnal constituent of the tide
NAO	North Atlantic Oscillation
NEA	North-East Atlantic Model
NWP	Numerical Weather Prediction
O ₁	Main lunar diurnal constituent of the tide
PML	Plymouth Marine Laboratory
POL	Proudman Oceanographic Laboratory
P _w	Wave power
REZ	Renewable Energy Zone
RMS	Root mean square
RPA	Renewable Power Association
SAC	Special Area of Conservation
SAR	Synthetic Aperture Radar
SD	Standard Deviation
SEA	Strategic Environmental Assessment
SWRDA	South West Regional Development Agency
S ₂	Main solar semi-diurnal constituent of the tide
T _e	Wave energy period
The Atlas	Atlas of UK Marine Renewable Energy Resources
TW	Terrawatt (1,000,000,000,000 watts, 1,000,000 megawatts, 1,000 gigawatts)
TWh/y	Terra-watt-hours per year
T _z	Zero- upcrossing period
UKCS	United Kingdom Continental Shelf
WAM	Wave Analysis Model
WAsP	Wind Atlas Analysis and Application Programme

Atlas of UK Marine Renewable Energy Resources: Technical Report

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1. Introduction

1.1 Overview

The Atlas of UK Marine Renewable Energy Resources (hereafter called 'the Atlas') was first published in September 2004 and has since become widely recognised as the main reference for regional scale descriptions of offshore renewable energy resource. In response to the initial high interest in the Atlas a freeview GIS version was released in July 2005 and has since given the industry a primary tool to screen for potential development sites. It is understood that over 300 CD-Roms of the Atlas GIS have now been distributed. This document supersedes ABPmer Report No. R.1106 which accompanied this previous Atlas release.

The key concept of the Atlas is to present a reliable and spatially coherent description of the marine renewable energy resources (offshore wind, wave and tidal). At the time of first publication the source datasets were provided by the Proudman Oceanographic Laboratory (POL) High Resolution Continental Shelf Model (HRCS) for tidal and by the Met Office UK Waters Wave Model for offshore wind and wave. These are the primary organisations responsible for developing regional scale marine datasets in the UK and underpin the key principle of the Atlas that of ensuring that it is based upon the best available data resources, which would stand scrutiny at the highest level. These features are extremely important in a tool to be used in strategic level decision making for UK energy development.

Early in 2007 it was recognised that Department for Business, Enterprise and Regulatory Reform's (BERR) continuing progress with Strategic Environmental Assessment (SEA) for potential wave and tidal energy schemes would directly benefit from an update to the Atlas to ensure best available and reliable data combined to underpin the SEA process. Additionally, any future plans for wind energy developments, including Round 3 licence calls, would similarly draw extensively from the Atlas. It is on this basis that the BERR commissioned a consortium led by ABP Marine Environmental Research (ABPmer), to update the Atlas from its present form with a combination of new data and enhancements of presentation to ensure that the forthcoming initiatives of BERR remain supported with the best available information.

The study team included partners from the original project and was led by ABP Marine Environmental Research Ltd, with support from two additional leading UK organisations in marine science and offshore resources:

- ABP Marine Environmental Research Ltd;
- Met Office; and
- Proudman Oceanographic Laboratory.

1.2 Report Structure

This report provides a technical description of the Atlas and describes the data sources, methods of analysis, structure of the interrogative database and finally provides an overview of the resource maps provided, webGIS and the use of the database to assist future decisions on strategic areas for marine renewables.

- Chapter 1: Provides an introduction to the project, including the study rationale and study area, what's new and dissemination methods.
- Chapter 2: Describes the information sources used in the derivation of the tidal, wave and wind resources.
- Chapter 3: Lists the parameters used to describe the wind, wave and tidal energy resources and specific equations used to calculate the power variable for each resource are provided. Details the process undertaken to derive a consistent mapping framework for the resource data.
- Chapter 4: Provides an outline description of the validation of the data used in the Atlas.
- Chapter 5: Describes the spatial database developed within the GIS system and the resource assessments that have been developed.
- Chapter 6: Suggests recommendations to maintain the Atlas as the state-of-the-art database of marine renewable resources.

1.3 Study Rationale

The update process was split into two distinct stages:

- Stage 1. The implementation of data retrieval from archives and the requisite processing and analysis, reported separately; and
- Stage 2. The Atlas dissemination by means of a hardcopy document, a technical project report and GIS; the distribution of the GIS through to the large number of present end-users will be facilitated using a webGIS application (detailed in this report).

The work carried out in Stage 1 included the following:

- Formalisation of the project specification and agree end-user requirements;
- Implementation of data retrieval for wind, wave and tidal stream archives;
- Agreement of additional data analysis methodologies to apply to retrieved data;
- Analysis of supplied data;
- Checking and approval of the additional Atlas outputs; and
- Reporting on findings.

At the outset of the study a process of rapid end-user engagement was implemented to validate that the planned refinements of the Atlas were endorsed by and would provide the expected benefits to the marine renewable industry. This was undertaken in the form of an online Web survey of the previous Atlas end-users. The range of participants consulted during the survey included the project funder, SEA programme managers, government agencies and representatives of the marine renewable industry; including technology developers and energy suppliers who are known to be presently working with the existing Atlas GIS database. The results of the survey indicated that the underlying project specifications for the Atlas update were in line with the marine renewable energy sector's current requirements for the identification of suitable sites, and provided a robust endorsement of project objectives (see Appendix A for detailed breakdown of results).

The aim of the present study is therefore to update the Atlas with the spatial quantification of wave, tidal and offshore wind at a regional scale over the area of the UKCS. The approach taken to deliver this work has been to identify and review any new datasets collated by the project team, and provide a more detailed and consistent description of the marine resource to better match the needs of the regulators and developers.

To ensure the information provided to the Atlas is managed and maintained most effectively, all the derived marine resource parameters have been captured in a structured database, within a Geographical Information System (GIS), so enabling data presentation and interrogation.

1.4 Study Area

The study area covers the marine waters extending across the entire UKCS, including the territorial sea around the Channel Islands, as shown in Figure 1. The proposed development of the Renewable Energy Zone (REZ) will allow the exploitation of renewable marine resources out to the 200 nautical mile limit. Thus the coverage provided by the Atlas will enable informed decisions to be made for the entirety of the REZ. Within the study area, the marine renewable energy resource has been quantified and described at a regional scale according to a number of principal components:

- **Tidal Resource:** The tidal resource is identified by the horizontal spatial variation in amplitudes of water levels and currents, with the current further subdivided into thirty-two evenly spaced layers in the water column, of which five layers are presented in the Atlas.
- **Wave Resource:** The wave resource is determined from the amplitude of wave heights and wave period propagating across the sea surface.
- **Offshore Wind Resource:** The offshore wind resource is derived from wind speed values taken at a consistent height above the sea surface related to present hub heights being designed for offshore wind farm installations.

1.5 What's New

The Atlas update was tested against user requirements (Section 1.3) to ensure that enhancements are relevant to the marine renewable sector. Two key changes have been made, the:

- Improvement of the underlying resource datasets; and
- Enhancement of the dissemination methods.

The wind and wave datasets have been derived from an increased archive of data (from 3.5 years to 7 years) which has improved confidence within the models and enabled inter-annual variability statistics to be included within the results. See Sections 2.3, 2.4 and 4.3.1 for further details. The wave resource assessment now includes statistics that differentiate between the energy that can be exploited by focusing a device on the primary component of energy in the wave field, as compared to the energy available to devices that can capture the total energy from sea-states comprising distinct wind-wave and swell components (crossed-seas). The tidal dataset benefits from improved model calibration and enhanced vertical data resolution provided by five independent layers of model outputs. The tidal current dataset also has an improved accuracy through the implementation of a new ocean turbulence model. See Section 2.5 for more detail.

The datasets are available through a new webGIS dissemination tool which provides resource mapping as well as access to additional information and the underlying GIS datasets.

1.6 Dissemination

The Atlas information is available in two formats, as a series of pre-prepared GIS maps and as a webGIS. The pre-prepared Atlas is available for download as a PDF document from <http://www.renewables-atlas.info> or <http://www.offshore-sea.org.uk> and provides updated maps of the following parameters:

Diagram 1. Parameters included in the pre-prepared Atlas

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The Atlas webGIS is available for viewing at <http://www.renewables-atlas.info>. The release of the original hardcopy Atlas in 2004 generated interest in making available the underlying resource datasets, this led to the creation of the Atlas Freeview GIS CD to disseminate relevant data layers. WebGIS technology has significantly advanced over the last few years and not only provides advanced tools for delivering maps over the internet but also offers the ability to query the underlying GIS datasets. The Atlas webGIS has been designed to provide straightforward access to the Atlas maps and underlying datasets for all potential users, without the requirement for any proprietary software applications. The key features of this system include:

- Allowing users to remotely interrogate GIS data layers from the Atlas database from a standard web browser without installation of any specialist software;
- Enabling the user to interrogate attributes stored in the underlying GIS database to create selections based on the Atlas parameters or spatial queries;
- Provide the facility for users to download the Atlas datasets for inclusion in their own GIS applications;
- Disseminating data from a single central resource has several additional benefits including the ability to efficiently offer instantaneous updates to a wide audience, allowing additional GIS mapping layers to be added to the database in the future, and tracking users who download the Atlas datasets; and
- All information supersedes previous versions of Atlas.

1.7 Primary Uses

The Atlas provides regional information about the potential offshore wind, wave and tidal resources within the UK REZ. This represents the best available continuous dataset for this area and provides valuable information for planning offshore renewable energy projects as well as ongoing activities within the BERR SEA programme. The recently published CIRIA guidelines for the '*Use of metocean data through the life cycle of a marine renewable energy development*' (Cooper *et al*, 2008) draws attention to the Atlas as an important information resource and it is anticipated that the forthcoming EMEC standards for '*Tidal stream resource assessment*' and '*Marine renewable project development*' (both currently in draft) will also highlight the importance of the Atlas project outputs.

These guidance and standard documents all outline phases of project development that include a *Regional Site Selection Screening/Assessment* to help identify potential development opportunities. The Atlas datasets are deliberately structured for this stage of project development and to provide a good level of consistent detail without generating an onerous volume of information. Interrogation of the wind and wave datasets provides information about resource magnitude and available power split into annual, seasonal and monthly averages. Tidal resource data can be interrogated over spring, neap and annual averages as well as relevant depths for specific user interests. All of the energy resource information is placed in a spatial context by other mapped layers which provide administrative boundaries, water depths and distances to landfall.

2. Information Sources

The rationale for the Atlas design has been to compile sets of marine renewable energy resource information that provide complete and consistent data coverage over the extent of the study area. The main data providers to the project are the Met Office and Proudman Oceanographic Laboratory (POL) who each operate regional scale models which, in combination, provide the required definitions of offshore wind, wave and tidal parameters. Other base mapping details have been sourced from the (US) Naval Oceanographic Office and the UK DEAL data registry.

The Atlas tidal parameters are based on the POL High Resolution Continental Shelf (HRCS) model that has 367,395 grid points of which approximately 170,000 fall within the study area. The original Atlas was the first project to make use of this state-of-the-art model which still provides the best tidal model data around UK waters and includes detail around nearshore locations, headlands and narrow tidal straits. This is of particular importance when considering the tidal regime as it is more spatially confined, unlike the wave and wind resources which tend to be more spatially consistent.

Wind and wave resource information are both sourced from the same model suite operated by the Met Office. The UK Waters Wave model presently offers the best source of detailed wave information around UK waters. This model came into operation in June 2000. At the stage of data extraction from the model archive a total of 7 years (inclusive) was available (June 2000 to May 2007). This model was used in preference to the European Wave Model, which contains a longer data archive, as there was a need to balance the longest available time-series of wave data with the high spatial resolution needed to best resolve geographical variations in wave resource over the UKCS. The length of the archive used for this version of the Atlas represents more than a doubling of the archive length used for the original Atlas (3 years and 3 months) and serves to improve the robustness in the statistical deviation of average annual, seasonal and monthly parameters.

2.1 Data Limitations

The work presented here is based on the best available regional scale data at the time of publication, however the following limitations are acknowledged in the present mapping and relate mostly to the nearshore and shallow water coastal areas:

- **Tidal Resource:** The resource parameters are derived from a 15-harmonic tidal model alone to ensure derivation of typical conditions, however therefore no meteorological, wave or steric (thermal expansion) effects are not taken into consideration and hence sensitivity to these effects is not taken into account.

- **Wave Resource:** The transformation of deepwater offshore waves towards shallower, nearshore areas is not robustly represented in the present numerical scheme. In addition, the statistical derivation of typical annual, seasonal and monthly parameters is only based upon 7 years of archived data, although the validity of using this period has been tested through the comparison of other, longer databases.
- **Wind Resource:** The modelling of nearshore wind may not robustly address coastal effects. In addition, the statistical derivation of typical annual, seasonal and monthly parameters is only based upon 7 years of archived data, although the validity of using this period has been tested through the comparison of other, longer databases.
- **General Comments:** The Atlas does not consider the resource available within smaller estuaries. Latitude and longitude values refer to the centre of model cells and therefore data is averaged over a cell dimension and not precisely calculated at that location.

As stated, the Atlas provides resource information on a regional scale over the extent of the UKCS and is suited to strategic level or regional considerations. If a specific area is taken forward for development, then site specific measurements will be required for local validation purposes.

2.2 Bathymetry

Bathymetric information has been obtained from two main sources, which together provide attribute coverage of the entire UKCS and visual information beyond.

The first dataset is from the (US) Naval Oceanographic Office. It is a single consistent dataset quoted to a standard Mean Sea Level (MSL) datum and WGS 84 projection. This dataset was interpolated to create the visual bathymetry backdrop utilised in the Atlas products.

The second dataset was sourced from POL's HRCS model, which was constructed from a variety of sources and covers all data areas. The underlying bathymetry originates from the General Bathymetric Chart of the Oceans (GEBCO) 1 minute digitised bathymetry. This is a high quality data source, having been produced through an initiative to assist the numerical modelling of surges studies in the North Sea. This dataset was interpolated onto the model grid and the coastline guided (but not defined) by the World Vector Shoreline. Where possible, the bathymetry has been improved by the replacement of the GEBCO depths with bathymetry from higher resolution datasets available to POL. This has provided significant improvements over GEBCO bathymetry in near-shore inter-tidal regions. It is noted that for all resource layers bathymetric information is supplied at the same resolution as the underlying model cells.

The coastline used in the Atlas is sourced from the DEAL Data Registry. Both the coastline and US Naval Oceanographic Office bathymetric data are fully in the public domain.

Figure 1 illustrates the bathymetry across the UKCS using a variable depth scale that classes values to allow visualisation across shallow nearshore zones (<5 to 50m depth), intermediate depths (50 to 500m), and deep water locations (500 to 5000m).

2.3 Tidal Data

The POL HRCS model has been used to derive the tidal parameters for the Atlas (Figure 2). This model has a resolution of $1/60^\circ$ latitude by $1/40^\circ$ longitude and a horizontal resolution of approximately 1 nautical mile (1.8km). The domain of the model covers 12°W to 13°E ; 48°N to 63°N within the 200m depth contour and is 3D with tidal data available at 32 evenly spaced sigma levels through depth. The results for the 2008 Atlas have been derived from run 011 of this model compared to run 005 for the 2004 Atlas project. This has introduced several improvements into the results, namely:

- Higher resolution in the vertical - the original Atlas used just depth-averaged currents. The revised model has been run with 32 sigma levels of which 5 independent levels have been used to create the data for the Atlas. Data has been included from the 50% layer and then at 10% intervals towards the bed at depths where tidal technologies are likely to be deployed. This lower 50% has a large variation in tidal flows due to near bed effects.
- Run 11 used an improved vertical mixing scheme, the general ocean turbulence model (Umlauf, L. *et al*, 2005). This gives more accurate tidal currents, although it tends to have higher friction and therefore marginally slower currents in many regions. Vertical profiles are determined by how the bottom friction is transmitted through the water column by turbulent mixing (hence the importance of the turbulence model).
- Some of the grid cells in the HRCS model used in run 005 of the model are not part of the latest HRCS model runs. These are in wetting and drying (inter-tidal) areas and have been removed so as to improve the accuracy of the nearby model grid cells which are outside of the wetting and drying zone.

The governing equations that are represented within a hydrodynamic model are the equations of momentum (effectively Newton's 2nd law), and continuity of mass (or volume). Both are based on hard physical principles and are central 'planks' of fluid dynamics. Wetting-drying algorithms, which might be employed to allow for a moving coastal boundary have a less physical basis. A plethora of approaches exist, and all are eminently sensible and based on good logic (e.g. if this cell is full, but its neighbours are empty then allow the cell to empty according to some modified friction

law) but none have the same solid foundation as the governing equations. Consequently, wetting and drying can, in some circumstances, produce unphysical behaviours in models in very shallow areas (e.g. see-saw oscillations) and impact on the accuracy of surrounding grid cells. It was for this reason that some very shallow areas were removed from the HRCS model in run 011.

The original Atlas presented depth averaged current statistics and the Atlas now includes this along with information for specific model layers. These two parameters are not directly comparable even for the 50% layer, which is an average of the water between 51.56% and 48.44% (i.e. 1/32nd of the water column) as the 3D model was split into this is many layers. The depth averaged currents from the original Atlas are an average for the whole water column. It is not advisable to compare depth averaged with mid-depth (50%) as the depth average is going to be affected by differences at any point in the vertical profile whereas the mid-depth (50%) is only going to reflect any localised changes e.g. if the near sea bed currents are much slower than in a typical profile due to higher friction, then this will bring down the depth-averaged currents, but will not affect the 50% current.

For some locations, improvements in the model combined with the move to currents computed at individual depth levels rather than depth-averaged have resulted in slightly lower for the Mean Spring Peak Current (MSPC) when compared to the original Atlas. However, it is noted that the spatial distribution of areas of good tidal resource remains consistent with the original Atlas. The peak current of a mean spring tide only occurs at one instantaneous point during a tidal cycle, and relative current speeds and overall power do not show the same trend of reduction as MSPC.

For the purposes of this project, the domain has been limited to the UK REZ. The tidal current parameters have been computed independently for the 5sigma levels closest to the depths of 50%, 60%, 70%, 80% and 90% from the sea surface. It is also generally understood that there is less tidal variation in the top 50% of the water column than in the bottom 50%.

Information for the Atlas has been developed from a prediction of a complete representative annual tidal event (and assuming that year to year variations are insignificant). These predictions are based on operating the models with 15 tidal harmonics to generate standard outputs of water level, current speed and current direction. For further details see Appendix B1.

2.4 Wave Data

The main source of wave information has been made available from the Met Office and is developed from the UK Waters Wave Model (spatial resolution 12km) and Global Wave Model (spatial resolution 60km) (Table 1). These models maintain a realistic simulation of wave conditions shelf-wide by being run on a regular basis (four times daily for UK Waters, twice daily for the Global model) forced by wind data from an

atmospheric model which includes assimilation of observations of actual weather conditions.

Table 1. Data used to describe the wave resource

Model	Spatial Resolution	Period
UK Wave	12km	1 June 2000 to 31 May 2007
Global Wave	60km	1 June 2000 to 31 May 2007

The wave models are based on a 2nd generation spectral scheme (Golding, 1983) which can typically resolve waves with periods between 3 and 25 seconds, and deep-water wavelengths from 15 to 975m. The models are forced using the wind field 10m above mean sea-level derived by the Met Office atmospheric models, which assimilate observational data from satellite, ship and met buoy networks. It is the wind strength, duration and direction that defines the frequency and directional bins in which energy is transferred to the wave model through the process of 'wind-sea' growth. Parameterisations of the wind-sea spectral peaked-ness and peak frequency are used to select an appropriate member of the JONSWAP family of spectra to represent the growing wind-sea.

Wave energy falling outside of the wind-sea frequency and direction range is treated as swell, and advected through the model domain. Further physical changes to the wave field can occur through energy dissipation from bottom friction and wave breaking, or energy redistribution through the frequency band due to non-linear inter-frequency interactions. All are treated through parameterisations which modify the appropriate bins of the wave model spectrum. In shallow water, the wave group speed depth dependency and refraction are represented in the model physics.

The UK Waters Wave Model additionally includes the effects of time-varying currents. The wave model output has previously been verified using the available network of Marine Automatic Weather Station (MAWS) wave buoys to provide information on wave height and period which is compared directly with model output.

The UK Waters Wave Model provides coverage over the major part of the UKCS, with the exception of outer shelf areas and has a resolution of 1/9° latitude by 1/6° longitude (approximately 11km in mid-latitudes). The UK Waters Wave Model became operational in June 2000 and has an archive of results stored at hourly intervals from the last 7 years, approximately.

Areas outside of the UK Waters Wave Model are described by the Global Wave Model which provides a resolution of 5/9° latitude by 5/6° longitude (approximately 60km square grid at mid-latitudes). Figure 3 presents the layout of grid cells adopted by the Atlas from these two wave models.

Since year to year variations may occur in wave data, it has been necessary to sample from the entire archive of the UK Waters Wave Model to produce a 'synoptic' description of representative wave parameters. Matching data over this period has been added from the Global Wave Model for outer shelf locations. Standard model output developed from the archives includes resultant significant wave height, zero up-crossing period and wave direction.

In order to assess temporal variations, this version of the Atlas provides additional synoptic data parameters that report on year to year variability in mean wave height and mean power, and point series that show the change in mean wave height and mean wave power on a month by month basis. See Appendix C for further details.

2.5 Offshore Wind Data

The primary source of the raw data for the wind resource has been made available from the Met Office Numerical Weather Prediction (NWP) system, a description of which is provided in Appendix D.

Operationally, the Met Office runs two configurations of this model:

- The NWP global model. Prior to December 2005 this model had a resolution of 5/9° latitude by 5/6° longitude (approximately 60km in mid-latitudes), and 30 vertical levels with humidity calculated on the lowest 27 levels. Post December 2005 the model horizontal resolution changed to 3/8° latitude by 9/16° longitude (approximately 40km in mid-latitudes) and vertical resolution increased to 50 levels; and
- The NWP mesoscale model, which is a regional model centred on the UK, which has a resolution of 1/9° latitude by 1/6° longitude (approximately 11km in mid-latitudes), and has 38 vertical levels with additional levels in the boundary layer to provide extra detail for forecasting over the UK.

Forecasts for the global model are updated 8 times per day, and for the mesoscale model four times per day. Until September 2000, the data used was from pressure level 1, which, although variable, approximates to 19.5m ASL (Above Sea Level; assuming neutral atmospheric stability). In 2000, the NWP model was changed to produce wind data at constant 10m ASL height. However, in order to preserve consistency in the wind used to force the wave models, the data from the NWP from 2000 onwards was scaled back to 19.5m. The scaling equation used is: (wind speed at 10m) = 0.94 * (wind speed at 19.5m). All wind data in the Met Office wave model archives are therefore scaled at a height 19.5m ASL.

For this version of the Atlas the simple linear scaling has been removed, so that the Atlas native wind data is taken at the original (and more standard) height of 10m ASL.

Since the wind data calculated by the NWP model are used as boundary conditions into the Met Office wave models, the wind data used within the Atlas originates from (Figure 4):

- The UK Waters Wave Model is used for the continental shelf and nearshore areas. It provides data over a shorter period of time than the global model, but it has a higher resolution, which is essential in giving more detail and is believed to be more accurate for the UK waters. Because of changes mentioned earlier, the global model is in any case consistent over the long term; and
- The Global Wave Model is used for the outer western and northern extremes of the UKCS not covered by the UK Waters Wave model. For consistency, duration of data provided is the same as that available from the UK Waters Wave model.

In addition, a set of representative data points from the European Wave Model has been used for the extraction of long-term (approximately 15 years) data for a comparison test with the 7 year Atlas analysis period. The data used to describe the wind resource is summarised in Table 2.

Table 2. Data used to describe the wind resource

Data Specification	Period	Model
1 hourly wind speed and direction time histories for each grid point.	1 June 2000 to 31 May 2007	UK Wave (12km)
3 hourly wind speed and direction time histories for each grid point.	1 June 2000 to 31 May 2007	Global Wave (60km)
3 hourly wind speed and direction time histories for 9 representative points (see Appendix C3).	June 1992 to May 2007	European Wave

Whilst the Met Office models provide the best available information for the UKCS, the predications for the shallow nearshore areas may not be robustly described and are subject to the limitations outlined in Section 2.

3. Derivation of Marine Resource Parameters

A set of principal marine resource parameters has been derived for the Atlas to quantify the envelope of spatial and appropriate temporal variations, these used accepted methodologies as published the Proceedings of the Institution of Civil Engineers (Cooper *et al.*, 2005). The following sections describe those relating to tidal, wave and wind respectively.

3.1 Tidal Resource

The main tidal resource parameters included in the Atlas are:

- Mean tidal flows;
- Tidal range; and
- Annual tidal power estimates.

3.1.1 Details of Parameters

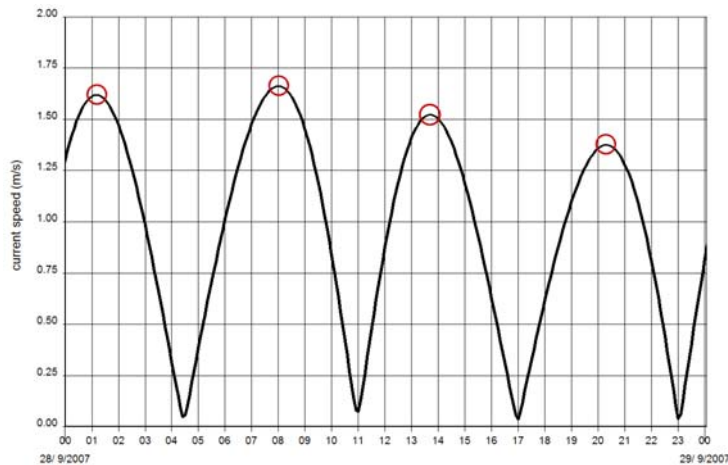
The parameters included in the Atlas have been selected to give a good overview of the tidal conditions that are most relevant to someone working in the field of offshore renewable energy. They have also been selected to provide average conditions so that meaningful comparisons can be made between different sites. It should be understood, however, that being an average means that there will be variations across the tidal cycles, and from one tidal cycle to the next. For example mean spring peak current will give an average that the current speed will peak at during an average spring tide, however there can be $\pm 20\%$ variation on this value across the course of a year for other spring tide events.

Some of the parameters are derived from 2 or 4 tidal harmonics and it is often asked why more harmonics are not used. The additional harmonics create a more temporarily specific description of the tide which moves the parameters away from the average which is attempted to be captured in the Atlas. For example M_2 and S_2 can give an accurate average of the spring and neap tidal range. Inclusion of further harmonics will not make the average tidal range any more accurate, however they would show up differences between one spring range and the next.

3.1.2 Mean Spring Peak Current (MSPC) and Mean Neap Peak Current (MNPC)

The MSPC (Figure 6) and MNPC (Figure 7) parameters give the average value for the peak flow of the current (this is the current equivalent of the Mean Spring/Neap Range for levels given below), and are computed using the semi-major axes from the M_2 and S_2 ellipses. It is important to remember this is the average of the peaks (shown in red in Diagram 2) and when working out power potential, the whole tidal cycle would need to be considered.

Diagram 2. The peaks of a 24 hour current curve - averaged to give the mean spring/neap peak current parameters



3.1.3 Mean Spring Range (MSR) and Mean Neap Range (MNR)

The mean spring and neap ranges (MSR and MNR respectively) are computed directly from the two principal semi-diurnal harmonic components M_2 and S_2 . These are the two components that govern the timing of the spring neap cycle and their amplitudes can be used to compute the average tidal range at springs and neaps. At spring tides, the lunar and solar tides reinforce each other and therefore the MSR (Figure 5) can be computed using the formula:

$$MSR = 2(H_{M_2} + H_{S_2}) \quad (1)$$

H_{M_2} is the amplitude of the M_2 harmonic constituent;
 H_{S_2} is the amplitude of the S_2 harmonic constituent.

At neap tides, the solar tide partially cancels out the lunar tide and therefore the MNR can be computed using the formula:

$$MNR = 2(H_{M_2} - H_{S_2}) \quad (2)$$

Typically the amplitude of S_2 is about 35% the size of the amplitude of M_2 , thereby making the neap tidal range typically around half the size of the spring tidal range.

The Atlas database contains complete quantification of MSR and MNR conditions. Figure 5 presents data for the mean spring tidal range using standard metric units of metres vertical height and with a linear scale from 0 to 12m, in increments of 1m.

This type of data has direct relevance to any marine renewable technology, which operates on the principle of converting energy from a rising and falling tide, such as a low head hydro tidal impoundment device.

Standard tidal typology would class the tidal range into the following terms:

Tidal Range (m)	Typology
<2	Micro-tidal
2 to 4	Meso-tidal
4 to 8	Macro-tidal
>8	Mega-tidal

It is expected that mega-tidal range conditions and above are of particular interest to tidal impoundment devices. It can be seen that, from Figure 5, these conditions are restricted to the Irish Sea, Bristol Channel, the eastern English Channel and the Channel Islands.

3.1.4 Annual Tidal Energy Yield

The general equation for power available from tidal currents is given by:

$$P_{\text{cross-section}} = \frac{1}{2} \rho A_{\text{cross-section}} U^3 \quad (3)$$

where:

ρ is the density of water (kg/m³);
 $A_{\text{cross-section}}$ is the cross sectional area (m²), and
 U is the instantaneous current velocity (m/s).

The average value throughout the year gives the mean power potential at the site. The figures in the Atlas are given for a one square metre cross sectional area, therefore the formula is:

$$P = \frac{1}{2} \rho \langle U^3 \rangle \quad \rho = 1027 \text{ kg/m}^3 \text{ and } \langle \rangle \text{ indicates the averaging period. (4)}$$

The reality is that no device will ever be 100% efficient and so power extracted will be less than the theoretical maximum given by these equations.

The power figures are also based on current speed only, and therefore for a fixed axis device, the type of flow and the devices efficiency for off-axis currents will have an impact on the power available across the tidal cycle.

Three values are given for the tidal energy yield these are all based on average power per square metre of vertical cross section:

- Average power obtainable over a complete year taking into account the complete tidal curve (i.e. not just the peak current values);
- Average spring power (Figure 8) - taking into account the peak only of the spring tidal curve; and
- Average neap power (Figure 9) - taking into account the peak only of the neap tidal curve.

Appendix B2 provides further details on tidal parameters.

3.2 Wave Resource

Variability of the wave resource around the UK, and consequently the amount of wave energy, can be related to:

- The exposure conditions of any site;
- The amount and distance of open water over which the wind blows to generate the waves (the fetch); and
- The strength of the winds generating the waves.

It is generally regarded that the UK is geographically well suited to exploit the wave resource, lying at the eastern end of a long fetch (the Atlantic) which has a prevailing wind blowing from the west. Earlier studies (prior to the original Atlas) have attempted to quantify the wave resources around the UK and include work previously undertaken for DTI (Whittaker, 1992) and other more recent studies for the EC (Pontes *et al*, 1997). Resource estimates derived by these previous studies were sourced from the Met Office European Wave Model (1/4° latitude and 2/5° longitude) and the WAM model (3° latitude and longitude resolution), respectively, and for a small number of discrete sites in water depths generally greater than 50m.

The rationale in the present study has been to develop a consistency in estimating the wave resource aligned to these previous studies but to use a higher resolution dataset that can provide complete coverage across the UKCS. The data source applied to the Atlas is described in more detail in Section 2.4.

The wave spectrum (i.e. the envelope of wave activity in a sample) characterising the conditions at a given site can be summarised quite accurately by a small number of basic statistical parameters. The most important parameters are:

- Significant wave height, H_s ;
- Wave energy period, T_e ; and
- Mean wave direction of the power flux.

Wave conditions around the UK generally exhibit two components; a locally generated wind-wave (generated across the fetch where the wind has blown), and a swell-wave which propagates into the area from a remote source and characteristically has longer periods. It is important to note that the direction of the swell-wave is not necessarily aligned to the direction of the wind-waves. Such conditions are given the term 'crossed-seas'.

For reference, the archive of the UK Waters Wave Model contains hourly records from June 2000 when the model first became operational, with data stored as significant wave height, zero up-crossing period and mean direction for each of wind-sea, swell and resultant wave components. Storing data in both its resultant form and as wind-sea and swell components allow the analysis described above.

The spatial and temporal scales used to describe the variation in the wave resource are:

- Annual: These calculations include adjustment for any seasonal bias inherent in the 7 years input data period;
- Seasonal: Where the seasons are defined as:
 - Winter: December, January, February;
 - Spring: March, April, May;
 - Summer: June, July, August; and
 - Autumn: September, October, November.
- Monthly: These calculations provide the range of values for each month.

3.2.1 The Wave Spectrum

Met Office operational wave model spectra are calculated over a domain of 13 frequency (25 to 3 seconds) and 16 directional bins (covering 0 to 360 degrees). Total energy in the spectrum can be represented using a set of simple parameters that describe wave height (energy) and predominant wave periods and direction. Specifically, the parameters maintained in the Met Office archives are:

$$H_s \quad \text{Significant wave height (m)} \quad H_s = 4\sqrt{m_0} \quad (6)$$

$$T_z \quad \text{Zero-upcrossing period (s)} \quad T_z = \sqrt{\frac{m_0}{m_2}} \quad (7)$$

$$D_p \quad \text{Principal wave energy direction (degrees)}$$

where :

$$m_n \quad = \text{the } n^{\text{th}} \text{ moment of the spectrum.}$$

In the original Atlas, these values were assumed to be representative of the entire wave spectrum (i.e. the wave spectra are assumed to be uni-modal). However, for this version of the Atlas the effect of those circumstances, where the spectrum describes wind-wave and swell components that are both distinct and significantly energetic (crossed-sea) is assessed.

The analysis has been undertaken to two sets of power data statistics, namely:

- 'Primary Component' analysis provides statistics from the most energetic (principal) component (wind-wave or swell) in a 'crossed-sea'; and
- 'Full Wave Field' analysis provides statistics from all energy in a 'crossed-sea' (i.e. wind-wave and swell) assuming that the energy is additive.

In each case the wind-wave and swell components of the resultant wave field are tested in order to define whether a 'crossed-sea' has occurred. In the instances where a 'crossed-sea' has not occurred wave parameters associated with the resultant wave field are applied to the power calculations. Where a 'crossed-sea' has occurred, the Primary Component analysis calculates power using the most energetic component ('wind-sea' or swell) only, whilst the Full Wave Field analysis assumes that both component power values can be added to yield the total output (wind-wave and swell). For further details see Section 4.

3.2.2 Significant Wave Height

Significant wave height, H_s , is a standard expression that can be used to rapidly identify the variability in wave conditions across the UKCS. The parameter is important to all offshore resource exploitation, since it provides a clear measure of potential difficulties for vessel operations at a given location. The overall significant wave height data, which is held in the database, describes the (long-term) annual mean wave height, see Figure 10. This value has been derived from the whole archive to average out any a typical year of data. This version of the Atlas also provides point specific significant wave height distribution tables that can provide further detail with respect to specific operating thresholds.

3.2.3 Wave Power Estimation

The quantification of the power transmitted by a wave moving across the sea surface was calculated using methodology similar to that described in Tucker and Pitt (2001) and consistent with the original Atlas. It is based on the following expression (for more details see Appendix D1):

$$P_w = 0.0623 \rho g H_s^2 c_g \quad (8)$$

where:

- P_w = Wave power (W) per metre wave crest;
- ρ = Water density (kg/m^3);
- g = Acceleration due to gravity (m/s);
- H_s = Significant wave height (m);
- C_g = Wave group speed (m/s).

As previously stated, the archived wave model statistic for wave period is zero-upcrossing period (T_z). This statistic is derived using the spectrum second moment and as a result may be sensitive to high-frequency low energy variations in the wave spectrum. A more generally accepted statistic for wave power calculations is the energy period (T_e) which represents lower frequencies better. This parameter is defined using:

$$T_e = \frac{m_{-1}}{m_0} \quad (9)$$

Whilst T_e is not directly computed by the wave model an approximation can be made based on T_z . The approximation assumes that a standard JONSWAP spectrum is representative of the average wave conditions over time, and from this spectral form the ratio between T_z and T_e can be calculated. The ratio is found to vary between 1.0 and 1.17 for a spectrum based on standard design values for the North Atlantic (NORSOK, 1999) and with peak periods between 3 and 20 seconds. For this version of the Atlas a table of values was created for application to given values of T_z , such that T_e is determined across the UKCS using:

$$T_e \approx C_{TR} T_z \quad (10)$$

where:

C_{TR} , which is a constant applied as the ratio between T_e and T_z is taken from:

	T_z Period Range		
	< 6 seconds	< 10 seconds	> 10 seconds
Wind-wave C_{TR}	1.06	1.12	1.14
Swell C_{TR}	1.05	1.10	1.14

The conversion from these values to annual output in TWh/y can be achieved by integrating in space and time (e.g. multiply mean power by approx. 12000 metres per Atlas grid box, and 365 days x 24 hours x 60 minutes x 60 seconds). It is important to note that values determined in this manner do not directly provide a realistic quantification of practical output production as the scale of any energy converter and efficiency rating and consequential downstream energy losses would all need to be considered.

The temporal variation in the wave power is described in the Atlas in terms of monthly, seasonal and annual variation in the mean wave power estimates (Figure 11). It is important to recognise that the annual mean energy yield has strong seasonal bias with peaks during the winter and calms during the summer, see Figure 12.

3.3 Offshore Wind Resource

The wind characteristics experienced at a given site can be described quite accurately using a small number of basic statistical parameters. The parameters which have been described within the Atlas, in addition to the associated temporal resolutions, are listed in Table 3 and shown in Figures 13 and 14.

Table 3. Summary of wind resource parameters

Parameter	Height (ASL)	Temporal Resolution	Data Source
Mean wind speed (m/s) (*)	10m, 80m and 100m	Monthly; seasonal; annual	UK Waters Model and Global Model
Mean power density (W/m ² of rotor swept area)	80m and 100m	Monthly, seasonal; annual	UK Waters Model and Global Model
(*) Refer to Appendix C.			

As with the wave resource the seasons are classified according to the groups of following months:

- Winter: December, January, February;
- Spring: March, April, May;
- Summer: June, July, August; and
- Autumn: September, October, November.

Data points were supplied by the Met Office, and covered time histories in hourly (UK Waters Model points) or three hourly (Global Model points) intervals from 1 June 2000 to 31 May 2007. The required parameters were derived from this substantial volume of data by using the following steps:

- Transform wind speeds to 80m and 100m ASL. The choice of heights was made to reflect future trends in hub heights for offshore wind turbines. A power law relationship was assumed to represent the atmospheric boundary layer; and
- Calculate mean wind speed and mean wind power density statistics for monthly, seasonal and annual periods.

3.3.1 Offshore Wind Power Density

Offshore wind power density was calculated using previous methods detailed in the European Wind Atlas, (Troen and Petersen, 1989), and it represents the average for the time series at each point and as such gives a value of wind power density of the rotor swept area. This parameter is calculated using:

$$P_{\text{wind}} = 1/2\rho V^3 \quad (11)$$

where:

P_{wind} = offshore wind power density (W per m² of rotor swept area)
 ρ = air density (1.225 kg/m³ - normal atmospheric pressure at sea level);
 V = mean wind speed (m/s)

(N.B. this expression is entirely comparable to the equation used to estimate the tidal stream power density. The fundamental change is the density of the respective fluid from water to air).

Annual average wind power density across the UKCS is shown in Figure 15.

4. Validation of Data Sources

4.1 Introduction

Validation of the data sources used in the Atlas is an important and integral component in maintaining the best available operational system. The validation of the two main data sources, the POL tide model and the Met Office wave and wind models are treated separately in the following sections.

4.2 POL Numerical Schemes

During construction the HRCS model outputs were compared with 257 coastal and offshore tide gauges and 278 current meter measurements from the British Oceanographic Data Centre (BODC) databank. During this task the model tidal parameters were interpolated to the exact longitude, latitude and depth of the observation selected. The parameters of tidal elevation and currents continue to be assessed with each new model run (original Atlas was run 005 and the new Atlas is run 011) and are discussed in Appendix B4. In summary:

- There is overall good agreement between observed and computed tidal elevations over the UKCS; and

- The model is, in general, in good agreement with the observations of most tidal components. The spread, which in general increases with current speed, shows the variability in bathymetry which might be expected within a grid cell. This indicates that care should be exercised when comparing observed data with model data.

In addition to comparing the HRCS model output with observation data, during construction comparisons were also made with the older CS3 model output and the output provided within the Seapower South West study. A good correlation can be observed within these data sets, and in summary:

- Areas of flow speed hot spots (i.e. around headlands) and low spots (i.e. middle of the North Sea) are observed in similar locations over the UKCS;
- There was a good spatial and temporal correlation between HRCS data and the CS3 model, although as expected, some of the HRCS depth levels used in the Atlas are near the sea bed and will therefore show slower current speeds due to bed friction; and
- The HRCS provides an improved, higher resolution of data than both the CS3 and Seapower South West models.

4.3 Met Office Numerical Schemes

Ordinarily the Met Office performs meteorological forecast validation. These procedures focus upon forecast performance and skill at various lead times. In the context of the Atlas database however, the data validation requirements are different as the source data used is from a model hindcast, i.e. forecast skill should not be an issue. Therefore, the main issues to be addressed are:

- Over the defined climate period, does the distribution of model data represent a measured spread of wind and sea-state conditions well?;
- Does the sourced data broadly represent long-term variations in wave climate?; and
- Is the performance of the sourced model data better or worse for specific regions of the UKCS?

The validation exercise was undertaken in two parts. To test validity against a measured source and geographic variation in performance, the UK Waters Model and observation time-series data from in-situ wave and meteorological measurement platforms were compared. Observation time-series data were selected from sites comprising the Met Office Marine Automatic Weather Station (MAWS) Network (Appendix C, Figure C23) in order to undertake the validation exercise. These sites provide direct observations of both marine wind and wave parameters, specifically wind speed, wind direction, significant wave height and wave period. Locations were

chosen to provide a spread of representative sites around the UKCS and in as many SEA areas as possible, and are summarised in Table D5. The observations were tested against the UK Waters Model data underpinning the Atlas, and over the 7 year period of the Atlas analysis.

To determine how the sourced data compare to longer term assessments in the climate over the UKCS the archive of Met Office European Wave Model data was utilised. This data source extends over 15 years, and comparisons were made between the whole 15 year period and the Atlas' specific 7 year analysis period.

4.3.1 Validation of Wind and Wave Model Data

For full details of the comparison and a detailed discussion of the results obtained, the reader is referred to Appendices C3 and D3. Conclusions from the comparison were that:

- Modelled mean statistics are generally within 5-20% of the observations; which is a favourable comparison when it is considered that observation accuracy is likely to be of the order of 5-10%;
- The model data performs best at 'open sea' sites, i.e. away from the near coastal zone; and
- The short term (7 year) and long-term (15 year) analysis periods showed a very close match. This implies that the Atlas has realised the maximum benefit from its use of the shorter term highest spatial resolution Met Office archive.

These conclusions, plus the use of the UK Waters Model climate dataset and long term experience in running the Met Office wave models operationally means, generally, that these data should be considered as a reliable qualitative resource for comparing both wind and wave power resource over the UKCS regions. The minor shortcomings of using this data have been given in Section 2. The ability of such a short term dataset to fully represent the wave climatology at any given location will depend on exposure to individual storm conditions, both in terms of geographical location and the season examined.

For summer and the least exposed regions of coastline the number of storm events experienced will be fewer than in winter months at the most exposed sites. As a result the probability of obtaining a near complete range of possible wind and wave conditions over a short period will be smallest at sheltered sites. For example, in the data presented here, it is suggested that the full range of seasonal variations in significant wave height may not be incorporated into the Atlas climatology in the most sheltered areas (e.g. English Channel). Conversely, in areas directly exposed to wave energy (e.g. Northwest Approaches) the time-series used is likely to be very similarly

populated in terms of differing wave conditions compared to the long term climate. As a result, the wave resource climate is best represented in the Atlas for regions where the wind and wave resource is most consistent.

On this basis, whilst the recommendation for any site specific study of wind and wave resource is that a long term measured dataset be considered in addition to that presented here, for the decision making purposes the Atlas is intended for, the time-series used are believed to provide acceptable estimates of wind and wave climate in addition to being the best available resource in terms of spatial coverage. Any effects derived from the North Atlantic Oscillation (NAO) are also discussed in Appendix D2.

The following points should be noted when using the Atlas data:

- For open sea sites, Atlas wave data is reliable, but it is useful to consider whether the region is likely to regularly include a significant swell component in its sea-state (e.g. Atlantic facing regions). This check can be made in the first instance by comparing the Primary Component and Full Wave Field power outputs; and
- In coastal zones, wind resource data should be compared with local understanding of prevailing wind conditions and topographic features given due consideration. Wave resource data should be compared with bathymetric charts to gain an understanding of likely local wave refraction and sheltering effects as waves travel into shallower locations. An appreciation of the general wind-wave versus swell climate should also be gained where appropriate.

4.3.2 Further Comments on Wind Data

An examination of the resource map for wind highlighted one unexpected feature occurring to the north-west of Scotland, i.e. at strip of slightly higher wind speeds running south-west to north-east along the boundary of the Outer Hebrides (Figure 13). Although of academic interest, this is not considered to be of any practical significance for the Atlas. The feature was reviewed by the Met Office and two possible explanations proposed:

- The result is physical. Storms approaching on a track from south-west to north-east tend to be steered by land topography, passing between UK and Iceland and flanked to the east by Norway. This leads to an average storm centre, with associated slightly lower wind speeds, running along a track centred at approximately 60N, 10W; and
- The slightly lower wind speeds in what is in effect the north-western boundary area of the UK Waters Model may be a result of the numerical scheme used at the Global Model/UK Waters Model boundary, i.e. it is a model artefact.

5. Atlas Resources

The marine resource parameters held within the Atlas database can be viewed as 'maps', similar to pages in a book. However, it is also important that marine renewable stakeholders are able to interrogate the resource database. Two resources have been developed to make maximum use of the Atlas datasets (1) by as wide an audience as possible and (2) by the client, BERR:

1. Atlas website including an interactive webGIS; and
2. Full desktop GIS

5.1 Atlas Website

The Atlas website (<http://www.renewables-atlas.info>) is designed to provide supporting information and downloads from the project as well as interactive webGIS maps of the wave, wind and tidal resource parameter. The other supporting website pages offer more generic project information and also allow the user to download items such as the technical report, pre-prepared Atlas maps, underlying GIS layers and associated metadata. The website is designed to be viewed using standard web browsers without the requirement for any proprietary client-side software.

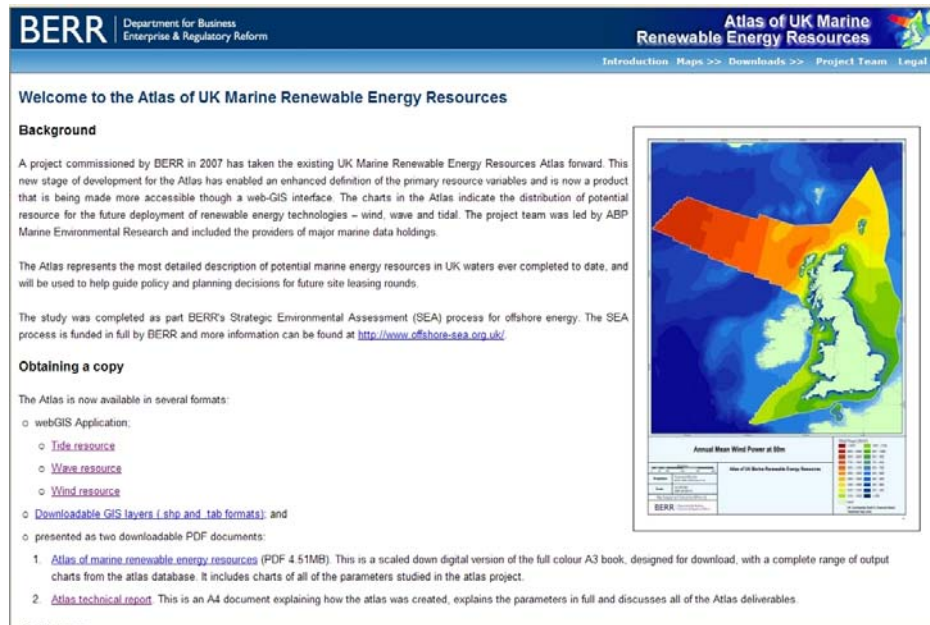
The basic sitemap structure for the website is shown below and further details are given in the following sections:

- Introduction
- Maps
 - How to Guide
 - Tide
 - Wave
 - Wind
- Downloads
 - Download Data
 - Download Metadata
 - Download Documents
- Project Team
- Legal

5.1.1 Introduction

The introduction provides a brief background of the Atlas and offers some quick links to key deliverables of the project including the technical report and pre-prepared Atlas PDF maps.

Diagram 3. webGIS front page



5.1.2 Maps

Each resource parameter has a dedicated Atlas webGIS map selectable from the main menu under 'Maps', which allows the user to view the key resource data layers with supporting baseline reference layers. Each layer's symbology has been constructed to maintain consistency with the pre-prepared Atlas maps. Several layers are available to view on the different map pages as summarised in Table 4.

Table 4. Available web data layers

Data Layer Group	Individual Layer Name
Baseline (Available each resource map)	<ul style="list-style-type: none"> ▪ Land ▪ UK Continental Shelf ▪ Bathymetry
Annual Mean Wave	<ul style="list-style-type: none"> ▪ Height ▪ Power (Full Wave Field)
Mean Tide	<ul style="list-style-type: none"> ▪ Annual power ▪ Neap <ul style="list-style-type: none"> - Peak flow - Power - Range ▪ Spring <ul style="list-style-type: none"> - Peak flow - Power - Range
Annual Mean Wind (100m)	<ul style="list-style-type: none"> ▪ Speed ▪ Power

The webGIS maps all have a standard layout and the following diagram highlights the different parts of the application that the user may interact with.

Diagram 4. Figure layout of Atlas webGIS application

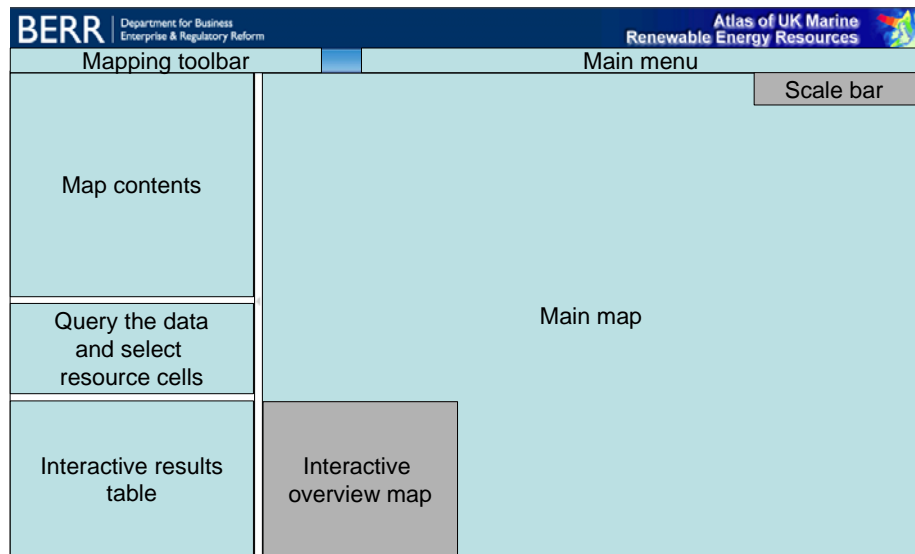
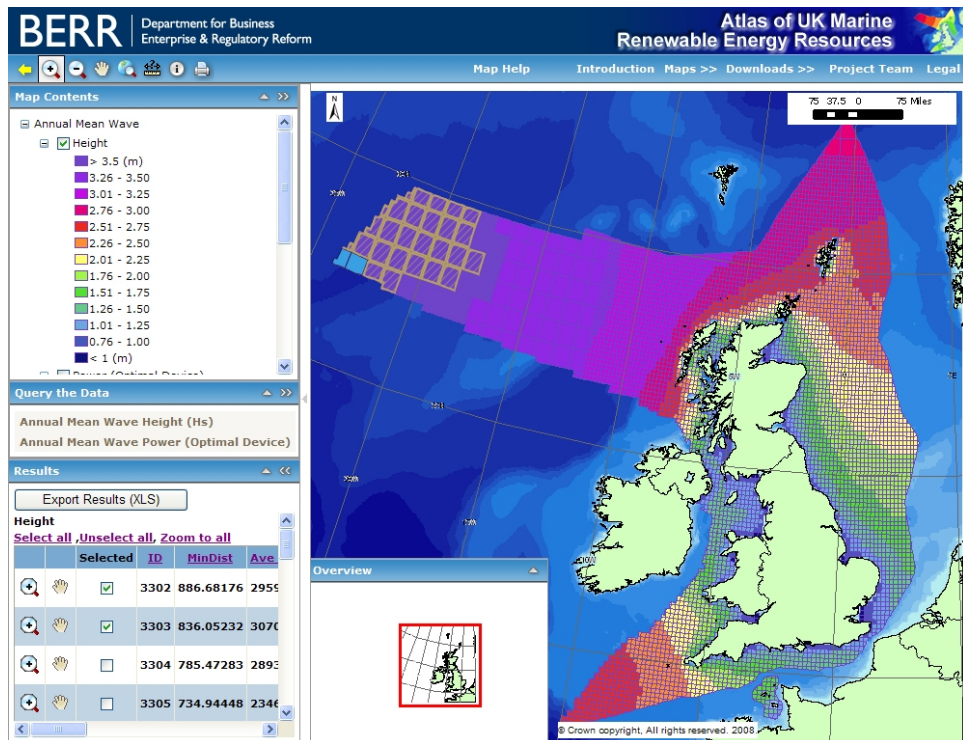


Diagram 5. webGIS screen shot



Within this layout the user can navigate around the map content by clicking on tool icons in the mapping toolbar at the top of the page and then interacting with the main map display. Layers can be turned on and off in the map contents window on the left of the page and expanded to view the key for the colours displayed (Diagram 5). There is an overview map in the bottom left of the main map, this displays, where in the main map, the view is located. It is possible to expand and drag the red rectangle in the overview map and this will dynamically refresh the view in the main map display.






The resource layers can be interrogated by GIS tools found on the left of the screen and results will appear in a results table in the bottom left of the screen. This table can be undocked by the user (as can other menu applets) and expanded or dragged as required. The user can interact with the table of results and execute tasks like select, unselect, and zoom to all of the features in the table. By clicking on the column headers the user can sort data in the table. The data can then be exported into an Excel spreadsheet (*.xls) by clicking on the 'Export Results (XLS)' button located above the table of results.

If the user requires full access to the resource datasets, for example to undertake custom queries and outputs (result tables or printing) then the underlying resource data layers are available for download and can then be loaded into a dedicated desktop GIS application for further manipulation.



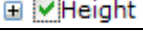
Summary of functionality

Mapping functions:

Navigation:




Function	Icon
Zoom in	
Zoom out	
Full extent	
Previous extent	
Pan the map	


Other:






Function	Icon
Interactive overview map	
Print to new window	
Turn layers on and off	

GIS functions:

Measure tool (click on  icon):

Function	Icon
Return coordinates of any point	
Measure distance by custom line	
Measure area and perimeter by custom polygon	

Select data tool (click on  icon):

Function	Icon
Select cell by point	
Select cells by rectangle	
Select cells that intersect by a custom line	
Select cells by custom polygon	
Select cells by circle	

Query the data:

Select cells by defining lower and upper range for a specific resource parameter combined with depth and distance from nearest land, see Table 5.

Table 5. Available queries

Resource	Layer
Wave	Annual Mean Wave height (H_s)
	Annual Mean Wave Power (Optimal Device)
Tide	Mean Spring Peak Currents
	Annual Tidal Power
Wind	Annual Mean Wind Speed (100m)
	Annual Mean Wind Power (100m)

Running one of these queries will take the user entered values (or defaults) and then return all cells with attributes that meet those criteria. The underlying logic of each of these queries can be summarised in the following statement:

Return all cells that have attributes that are > than minimum resource parameter AND < maximum resource parameter AND > minimum depth AND < maximum depth AND > minimum distance from land AND < maximum distance from land.

5.1.3 Downloads

This section of the Atlas website contains all available outputs for the current version of the Atlas. From a GIS perspective this includes all resource data layers (excluding baseline layers) used in the online webGIS in both Mapinfo (tab) and ArcGIS (shp) formats (N.B. basic user data is required to be entered to generate statistics of key user groups that are utilising the data) and the metadata (xml) for all key datasets. It is also possible to obtain a copy of the pre-prepared Atlas maps (reduced in quality for downloading off the web) and this technical report.

5.1.4 Project Team

A list of project partners involved in making this version of the Atlas possible is provided in this section.

5.1.5 Legal

Legal terms regarding use of the website are provided under this heading.

5.2 Desktop GIS

When considering the potential locations of the UKCS for certain technologies/rounds of development, it is also important that decision makers, such as BERR, are able to interrogate the resource database. A suite of desktop GIS tools have been developed in ArcGIS Version 9.2 and these enable BERR to analyse detailed wave, wind and tidal resource parameters.

The GIS system allows Atlas data interrogation to give a regional-scale assessment of resource potential. A detailed guide for using the desktop GIS tools can be found in Appendix E1.

The GIS tools are split into two separate functions namely;

- Graph Manager; and
- Criteria Selector.

The graph manager has been implemented to provide visualisation of data parameters that are not easily conveyed using traditional two-dimensional maps. These include variations over depth and time and directional components such as wave and wind roses as well as tidal ellipses.

5.2.1 The Graph Manager

The Graph Manager employs all of the parameters found in Table 6, allowing the user to choose a position on the map and return a graphed result. For some of the graphs more than one location can be plotted on the same axes for comparison.

Table 6. The graph manager parameters

Resource	Parameter	Temporal Resolution	Units
Tidal	Tidal Range	Spring and neap	m
	Current speed	Spring and neap	m/s
	Current speed exceedance	Spring and neap	% frequency
	Ellipse Semi-major axis	Spring and neap	non-dimensional
	Ellipse Semi-minor axis	Spring and neap	non-dimensional
	Ellipse Orientation	Spring and neap	deg. clockwise
	Phase of ellipse	Spring and neap	±
Wave	Tidal power density	Annual, spring and neap	kW/m ²
	Significant wave height	Monthly, seasonal and annual	m
	Wave period	Monthly, seasonal and annual	sec
	Wave direction	Seasonal and annual	deg. N
	Wave power	Monthly, seasonal and annual	kW/m
	Significant wave height exceedance	Monthly, seasonal and annual	Cumulative %
Wind	Wave power exceedance	Monthly, seasonal and annual	Cumulative %
	Wind speed	Monthly, seasonal and annual	m/s
	Mean power density	Annual	W/m ²
	Direction	Annual	deg. N

5.2.2 The Criteria Selector

The Criteria Selector enables rapid identification of locations that meet specific tidal, wind or wave resource thresholds as well as other parameters including both and distance from land. The tool offers the user a standard form to input constraint values of certain parameters (Table 7) which are both generic (e.g. distance from shore) and resource specific (e.g. wave height). The results of the selection are highlighted on the map and key statistics such as number of selected cell and area are also returned. The tool also include an export function wish allows the user to export the selection to a new layer which can be stored for future use.

Table 7. The criteria selector parameters

Resource	Parameters
Tidal	Water column position, water depth, distance from shore, tidal power, current speed, tidal range
Wave	Season, wave height, water depth, distance from shore, wave power
Wind	Season, device height, water depth, distance from shore, wind speed

Further information regarding the desktop GIS tools as well as a detailed User Guide can be found in Appendix E1.

6. Recommendations

The original Atlas was well received by the marine renewable community and still provides a valuable reference for the regional scale analysis of UK offshore wind wave and tidal resources. The Atlas, through end user engagement, has proved that there is a continuing demand for updated versions of the datasets, which, will initially be fulfilled by the publication of the latest Atlas outputs including the pre-prepared Atlas maps and interactive webGIS. As the UK offshore renewable industry matures it is suggested that this interest is likely to be maintained and therefore the project has developed several recommendations for future Atlas products to support a full range of stakeholders within marine renewable energy projects.

6.1 Data Updates

The new Atlas provides an enhanced description of the wave, wind and tidal resource parameters by incorporating the latest available information from the Met Office and POL. These core datasets will continue to develop and over time it is likely that the Atlas product will benefit from future updates to these parameters. It is likely that in the future there may be a need to improve the spatial resolution of the resource layers to provide refined predictions in near coastal and other topographically challenging areas. It is noted that the development of the new webGIS application enables data updates to be delivered to all users as a single efficient process.

6.2 Additional Constraint Data Layers

The Atlas provides information about the potential wind, wave and tidal energy resources within UK waters however it makes no reference to potential constraints for development or how exploitable these energy resources may be. The GIS architecture that underlies the project database can easily be developed to incorporate additional data layers, which often already exist, providing information on a range of potential constraints to deployment. Suggested layers include existing infrastructure (cables, pipelines, oil and gas installations, implemented renewable developments, aquaculture), activities (navigation, leisure, fishing), geophysical (detailed bathymetry, seabed sediments/geology), and environmental considerations (designations, flora and fauna). This information would enhance understanding of potentially exploitable resource areas, and if combined with information about renewable technologies has the potential to deliver quantitative analysis of the relative merits of deploying different technologies in specific spatial locations.

6.3 Tool Enhancement

The desktop GIS tools have been designed to use the advanced parameters within the Atlas database to provide more detailed information for the regulatory bodies, including BERR. Several of these tools could be disseminated to a wider audience using the webGIS technology developed as part of the current project. This would enable remote users to generate graphs of temporal, directional and vertical parameters to visualise information that is difficult to convey using traditional two-dimensional mapping. Additional functionality could also be implemented allowing advanced data queries to deliver cross-parameter analysis that would inform further development phases such as likely conditions for installation activities and working windows for operation and maintenance schedules.

7. References

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Figures

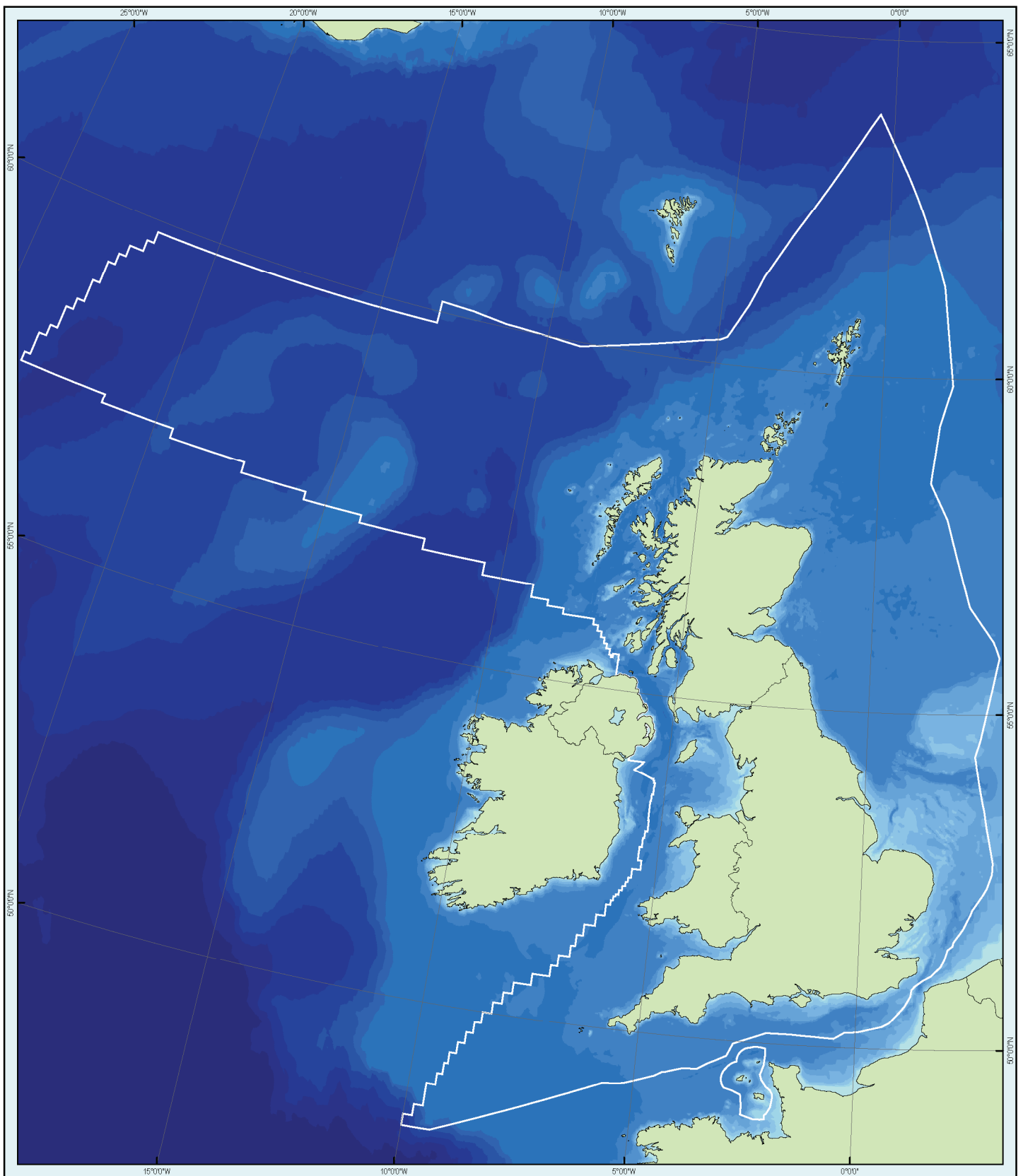
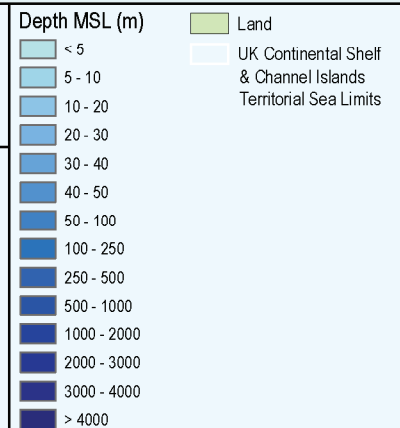


Figure 1 - Bathymetry



Projection	Transverse Mercator WGS 1984 UTM Zone 31 N
Scale	1:6,250,000 when printed A3

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Notes

1. Derived from US Naval Oceanographic Office DBDB0-V Version 4.2 bathymetry.
2. Bathymetry recorded to Mean Sea Level (MSL) in metres.
3. Coastline obtained from the DEAL Data Registry.
4. March 2008, Version 2.0.
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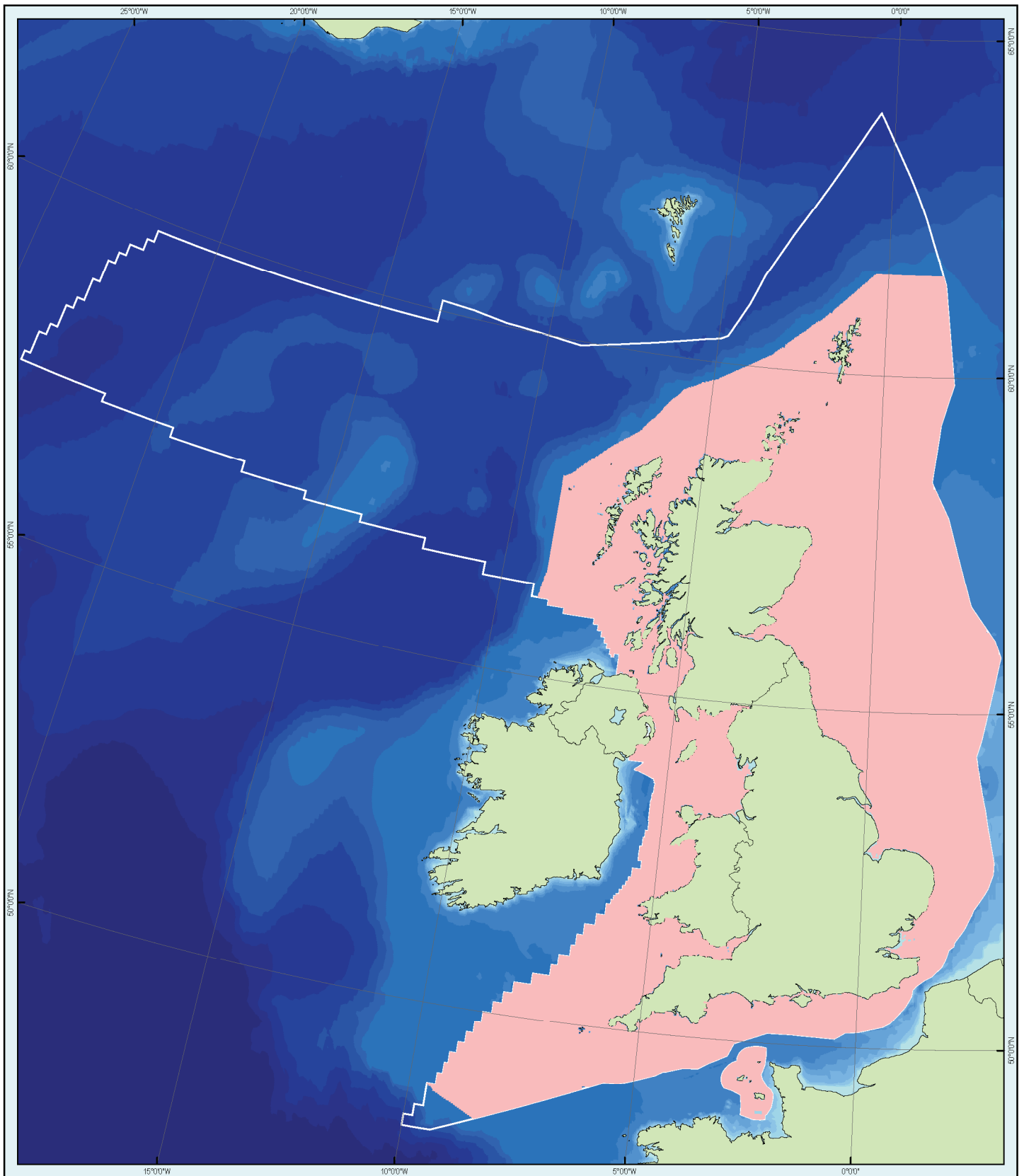


Figure 2 - Location of Tidal Model Grids

Model

- HRCS (approximately 1.8km)
- Land
- UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
when printed A3

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Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model data sourced from the Proudman Oceanographic Laboratory (POL) High Resolution Continental Shelf (HRCS) model.
3. Tidal model based on data derived for an average tidal year.
4. March 2008, Version 2.0.
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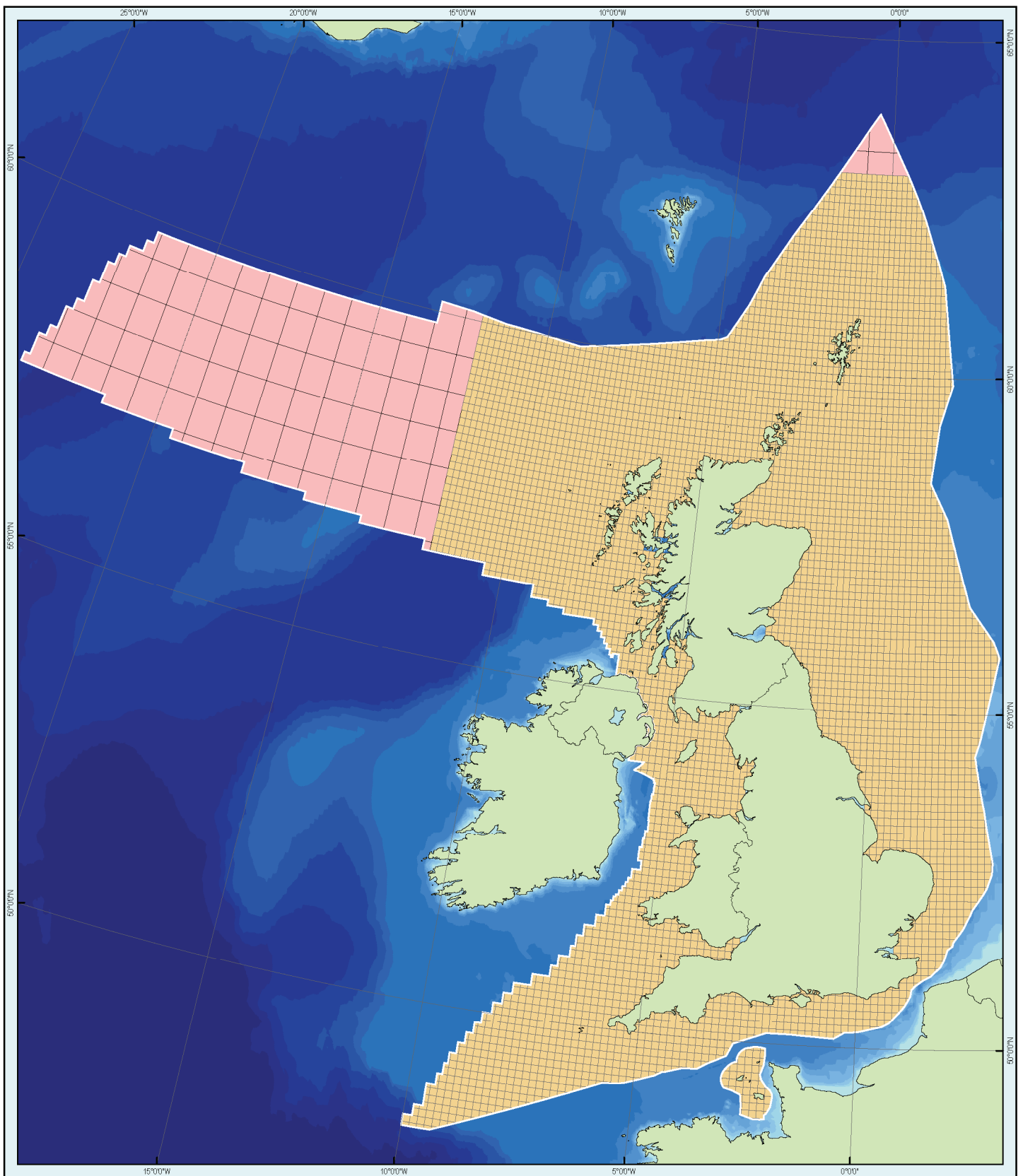


Figure 3 - Location of Wave Model Grids

Model

- Global (approximately 60km)
- UK (approximately 12km)
- Land
- UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data sourced from the Met Office UK Waters and Global Wave models.
3. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
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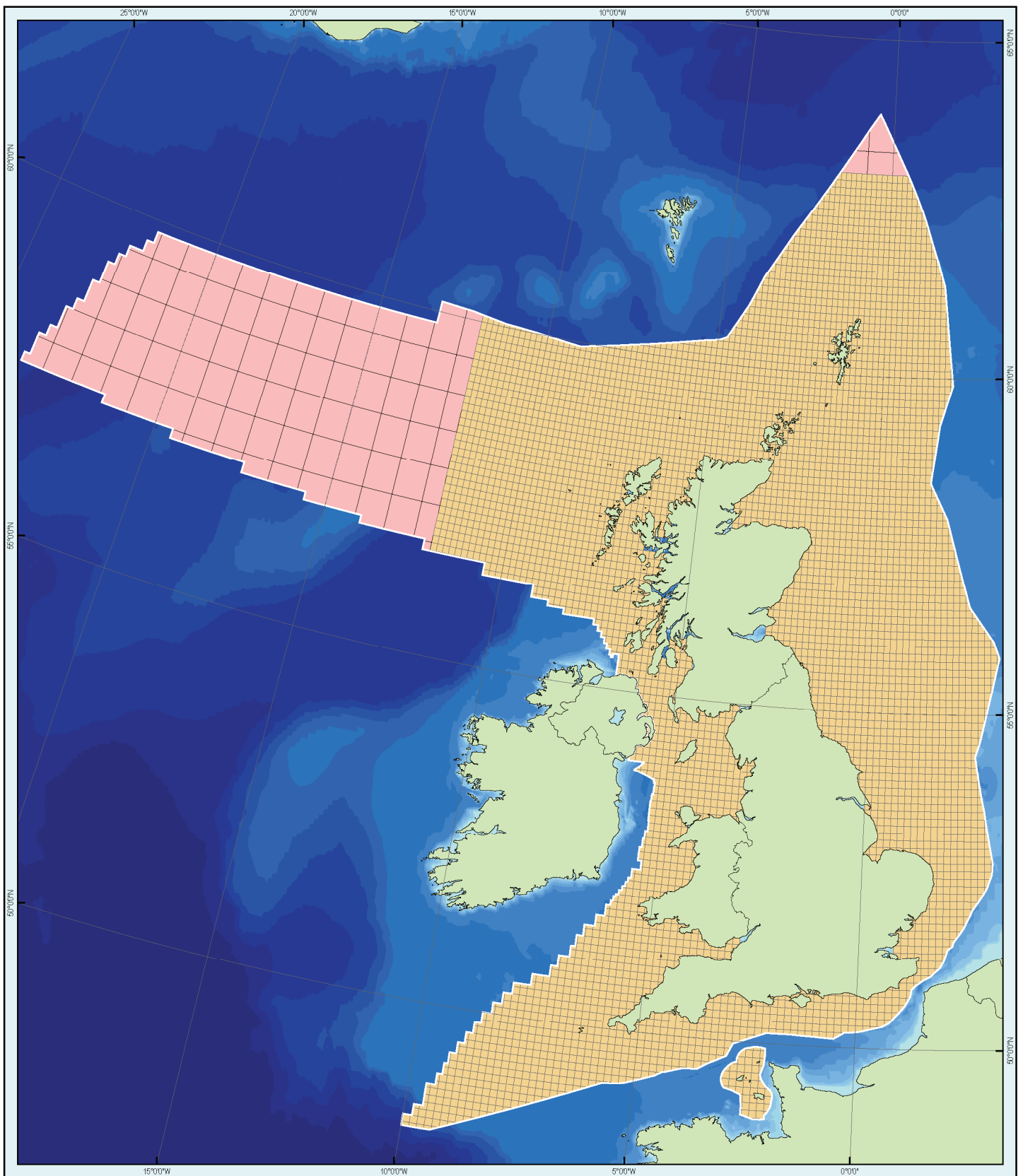


Figure 4 - Location of Wind Model Grids

Model

- Global (approximately 60km)
- UK (approximately 12km)
- Land
- UK Continental Shelf & Channel Islands
Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wind data generated by Met Office Mesoscale and Global Numerical Weather Prediction (NWP) models; sourced from the Met Office UK Waters and Global Wave models.
3. Modelled wind data will be less robust at land-sea boundary points.
4. March 2008, Version 2.0.
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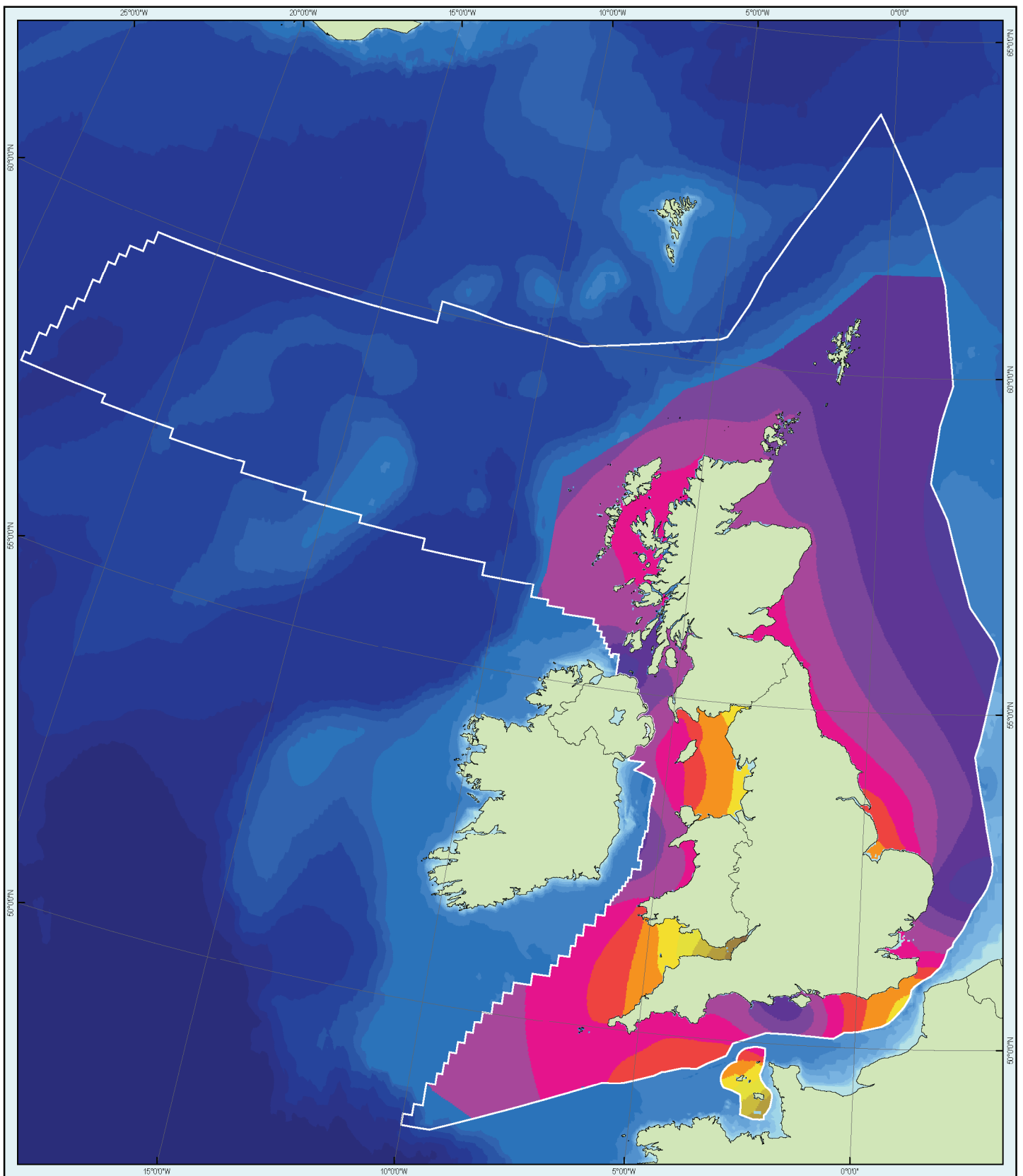


Figure 5 - Mean Spring Tidal Range

Tidal Range (m)



Land
 UK Continental Shelf & Channel Islands
 Territorial Sea Limits



Projection Transverse Mercator
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Scale 1:6,250,000
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- Notes
1. Model accuracy is less robust in areas closer than 1km to land.
 2. Tidal model based on data derived for an average tidal year.
 3. Tidal range is calculated in metres.
 4. March 2008, Version 2.0.
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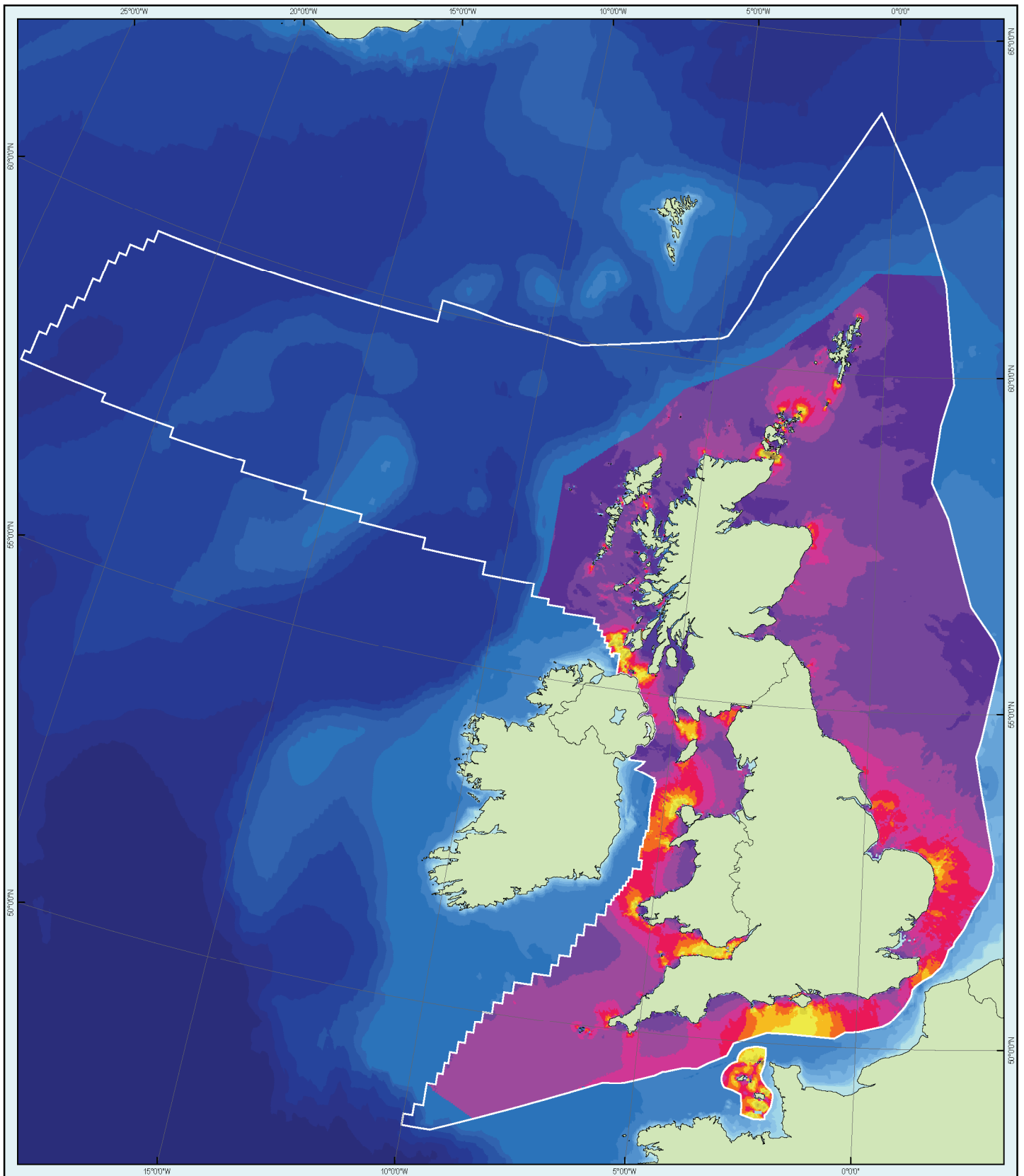
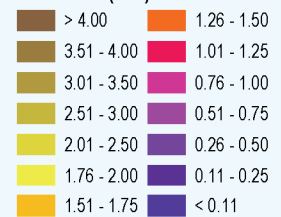


Figure 6 - Peak Flow for a Mean Spring Tide

Peak Flow (m/s)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
 WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
 when printed A3

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Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model based on data derived for an average tidal year.
3. Tidal flow is calculated in metres per second.
4. Tidal flow is calculated at mid depth in the water column.
5. March 2008, Version 2.0.
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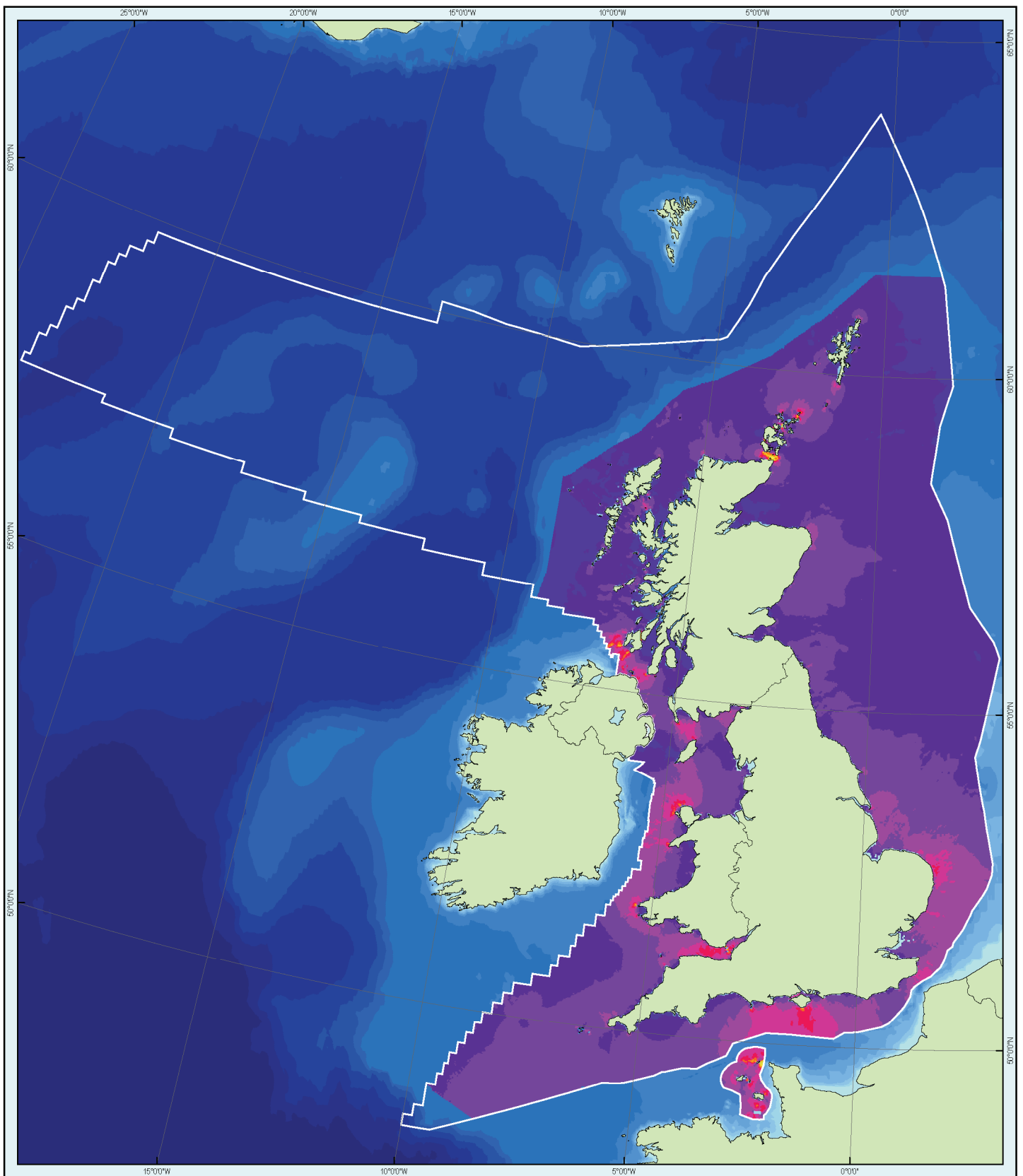
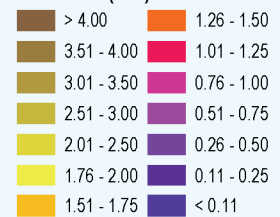


Figure 7 - Peak Flow for a Mean Neap Tide

Peak Flow (m/s)



Land

UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model based on data derived for an average tidal year.
3. Tidal flow is calculated in metres per second.
4. Tidal flow is calculated at mid depth in the water column.
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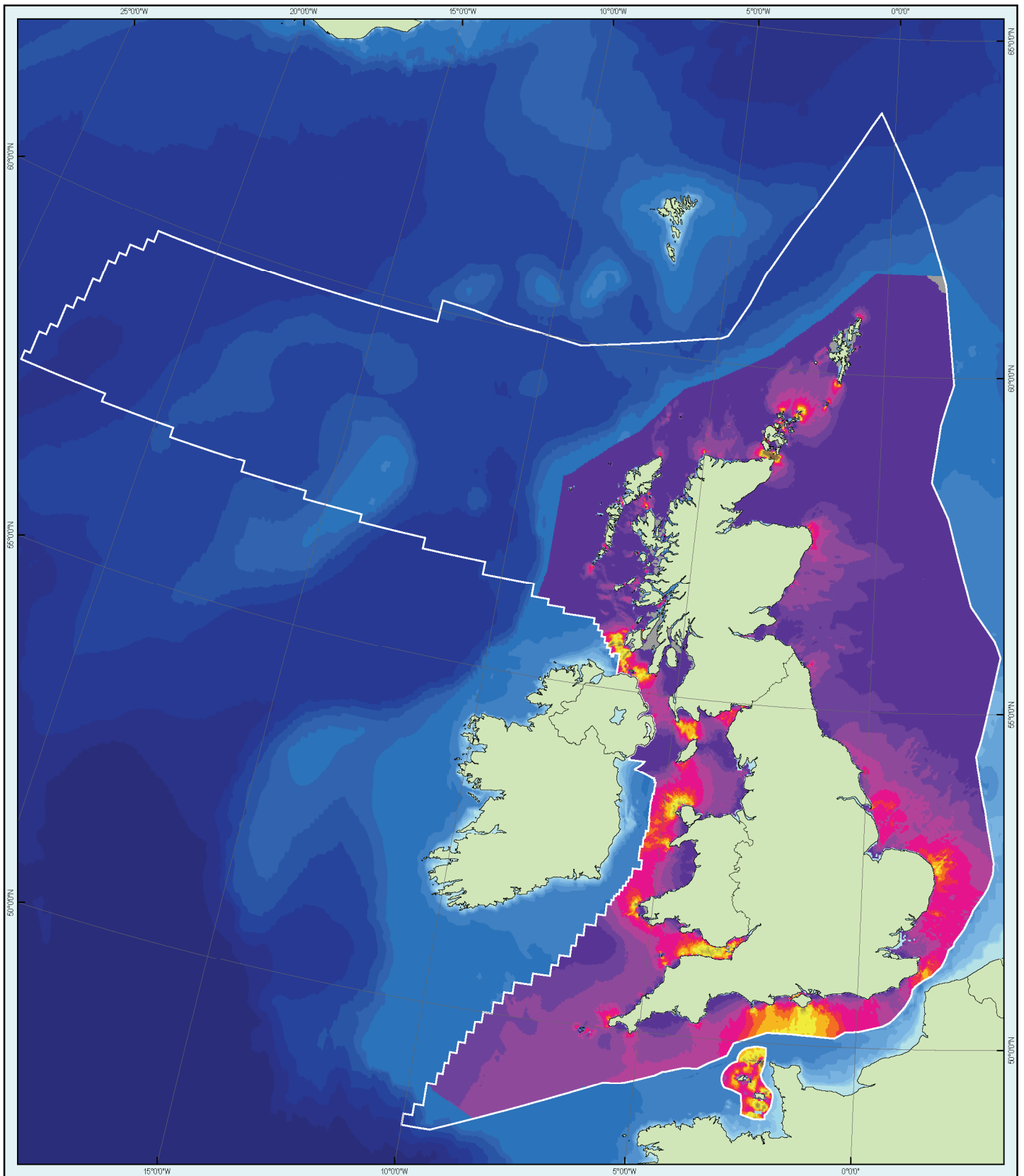
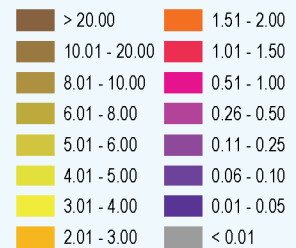


Figure 8 - Mean Spring Tidal Power

Tidal Power (kW / m²)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
 WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model based on data derived for an average tidal year.
3. Tidal power is calculated in kilowatts per square metres of vertical water column.
4. Tidal power is calculated at mid depth in the water column.
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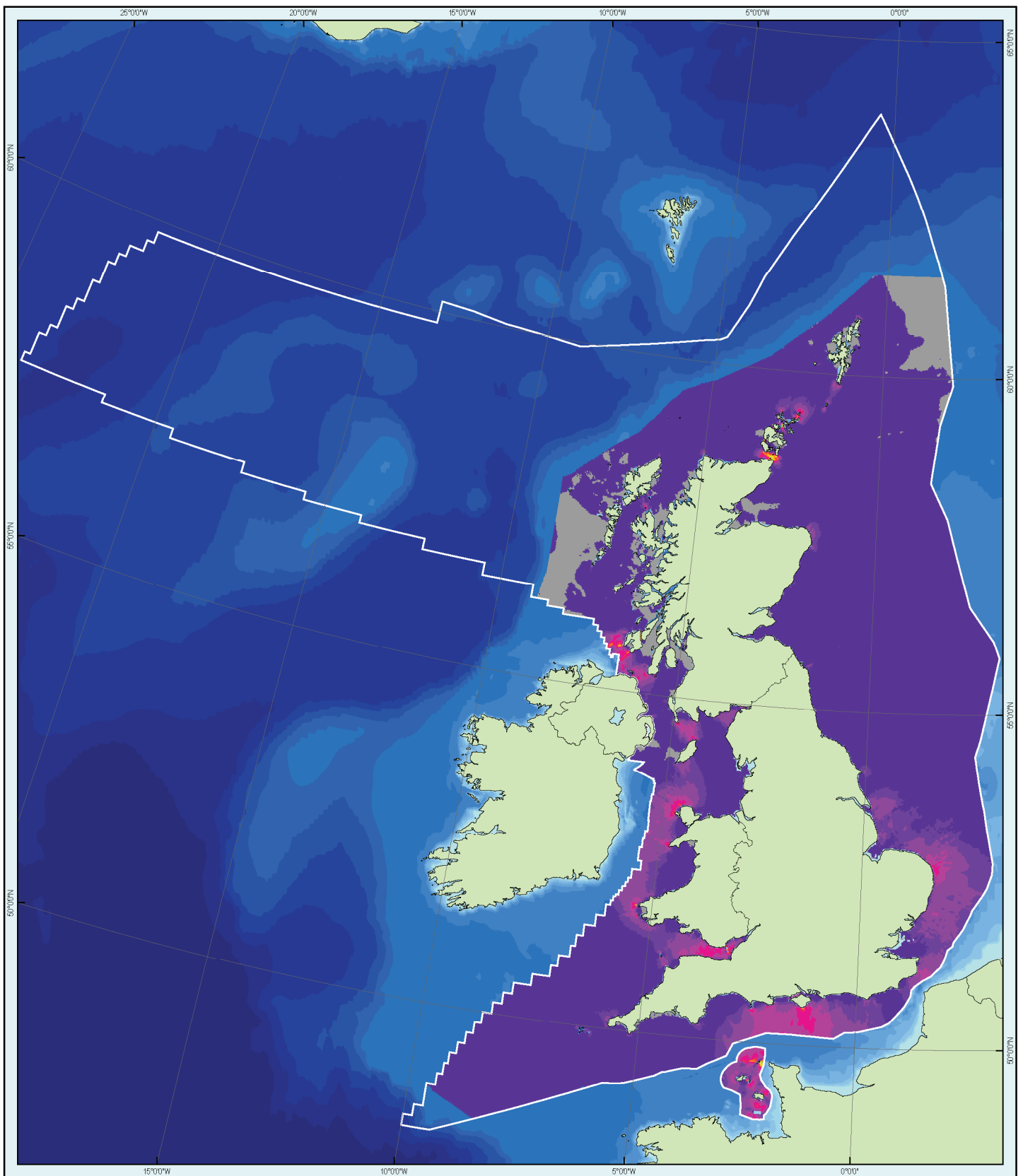
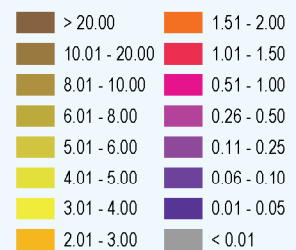


Figure 9 - Mean Neap Tidal Power

Tidal Power (kW / m²)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model based on data derived for an average tidal year.
3. Tidal power is calculated in kilowatts per square metre of vertical water column.
4. Tidal power is calculated at mid depth in the water column.
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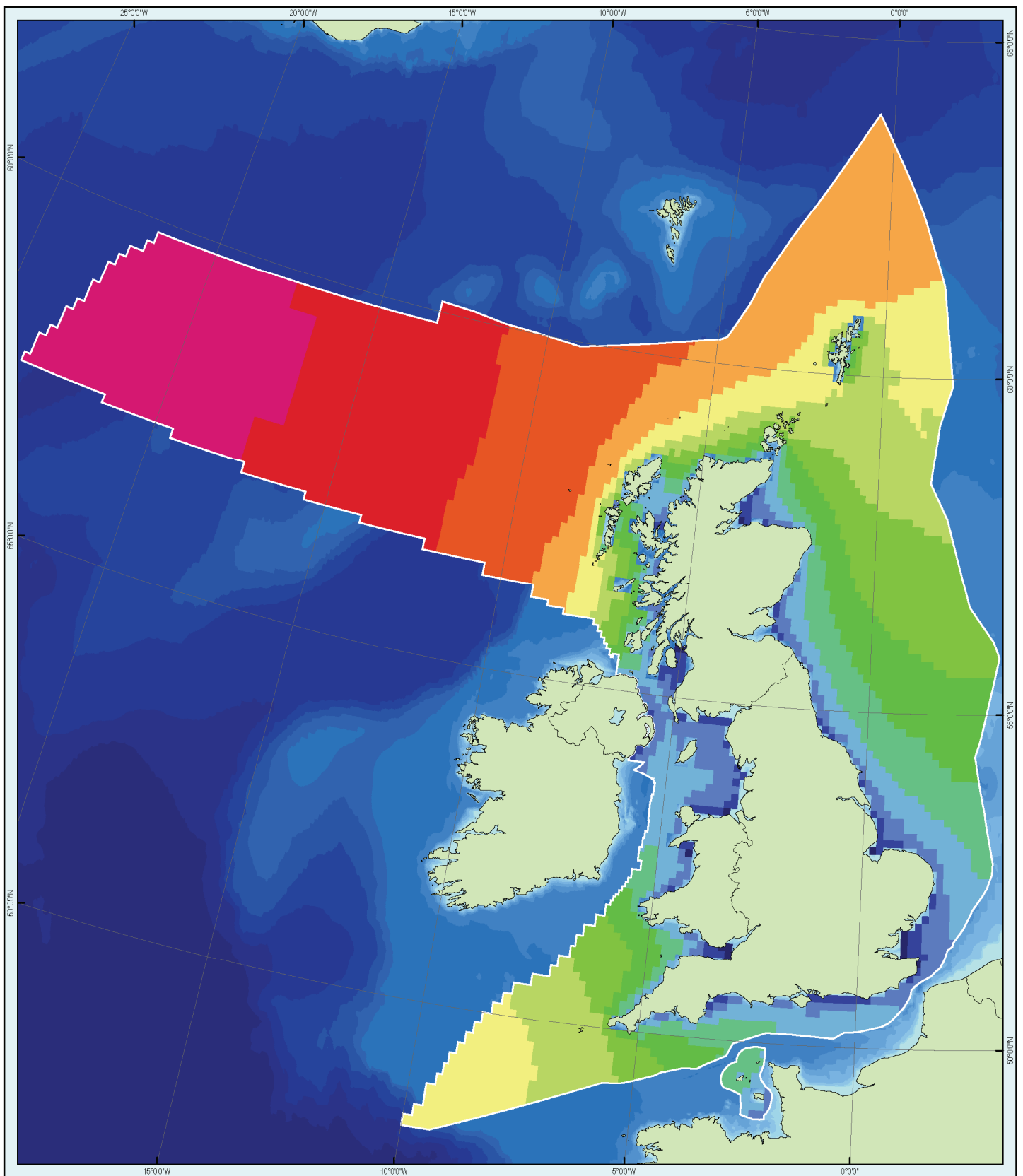
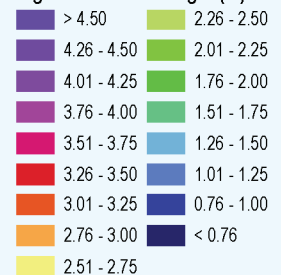


Figure 10 - Annual Mean Significant Wave Height

Significant Wave Height (m)



Land
 UK Continental Shelf & Channel Islands
 Territorial Sea Limits



Projection Transverse Mercator
 WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
 when printed A3

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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Wave height is measured in metres.
5. March 2008, Version 2.0.
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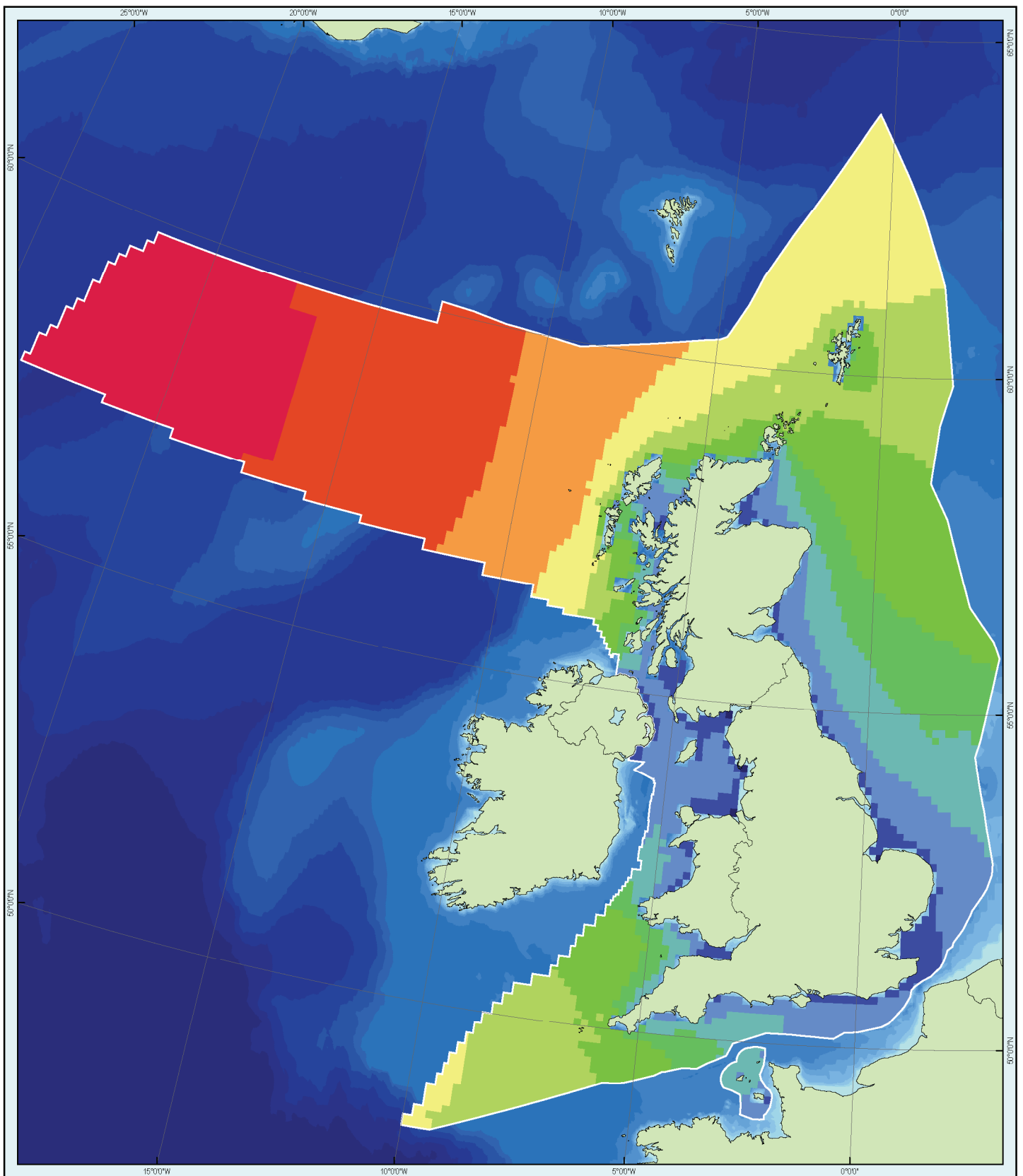
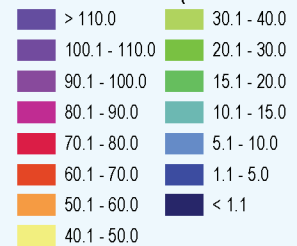


Figure 11 - Annual Mean Wave Power - Full Wave Field

Mean Wave Power (kW / m of wave crest)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Full Wave Field Power is calculated using the summation of wave power attributed to wind-wave and swell components.
5. Wave power is calculated for each horizontal metre of wave crest using the energy period calculation (T_e).
6. March 2008, Version 2.0.
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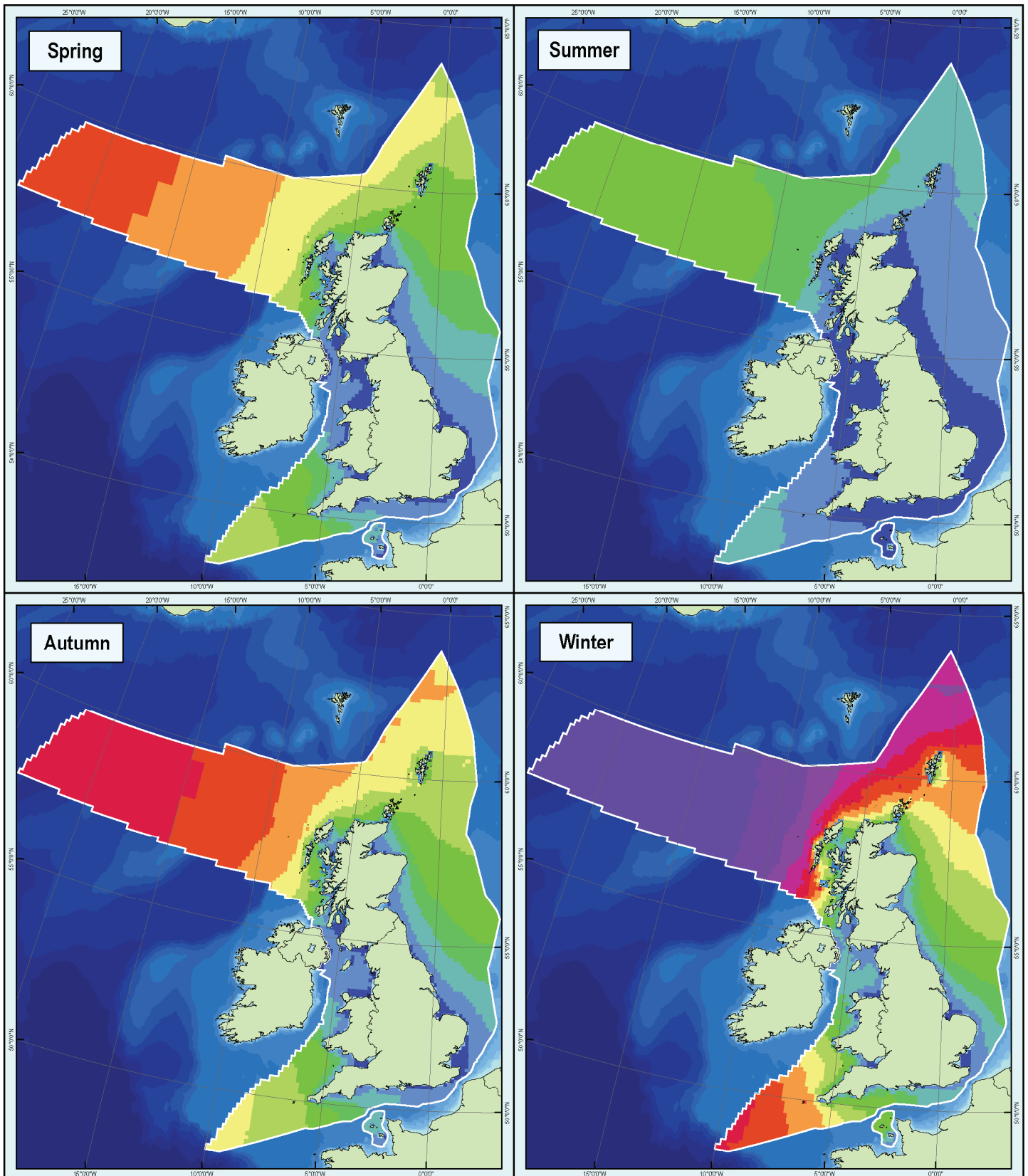
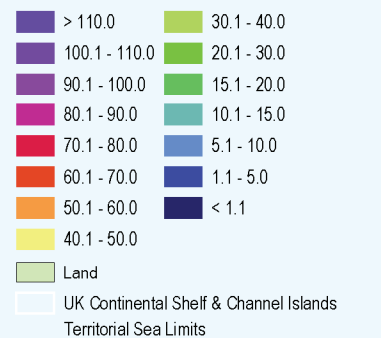


Figure 12 - Seasonal Mean Wave Power - Full Wave Field

Mean Wave Power (kW / m of wave crest)



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:12,800,000
when printed A3

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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
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5. Wave power is calculated for each horizontal metre of wave crest using the energy period calculation (T_e).
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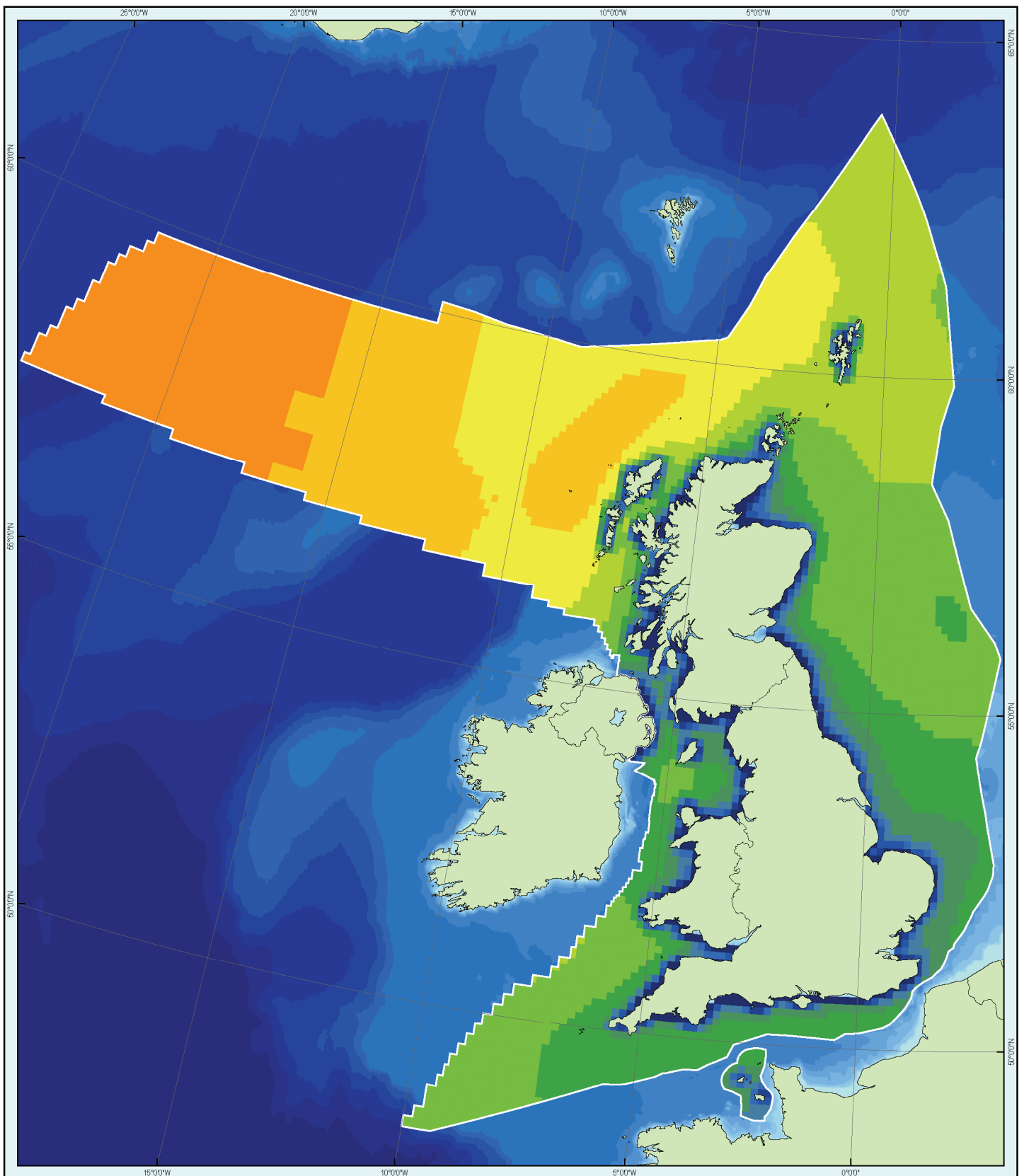
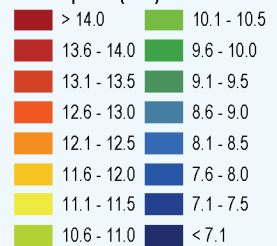


Figure 13 - Annual Mean Wind Speed at 100m

Wind Speed (m/s)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wind data will be less robust at land-sea boundary points.
3. Wind data are based on hourly model hindcast values over 7 years.
4. Wind speed at 100 metres above sea level.
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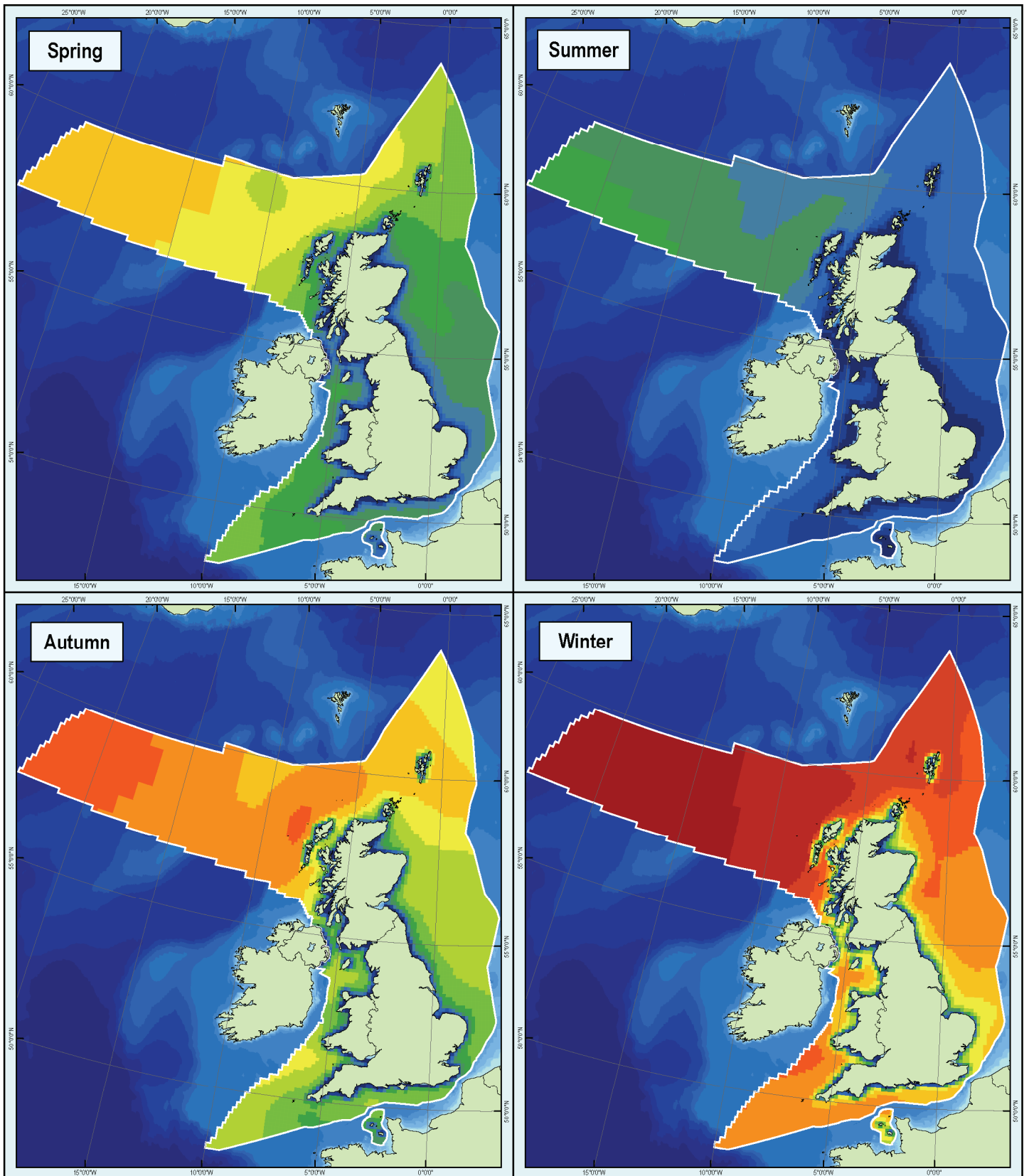
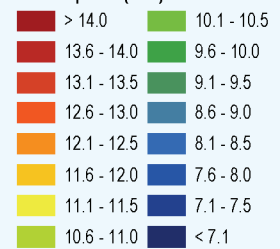


Figure 14 - Seasonal Mean Wind Speed at 100m

Wind Speed (m/s)



Land
 UK Continental Shelf & Channel Islands
 Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:12,800,000
when printed A3

Map Designed and Produced by ABPmer

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Enterprise & Regulatory Reform

Atlas of UK Marine Renewable Energy Resources

Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wind data will be less robust at land-sea boundary points.
3. Wind data are based on hourly model hindcast values over 7 years.
4. Wind speed at 100 metres above sea level.
5. March 2008, Version 2.0.
6. © Crown copyright, All rights reserved.

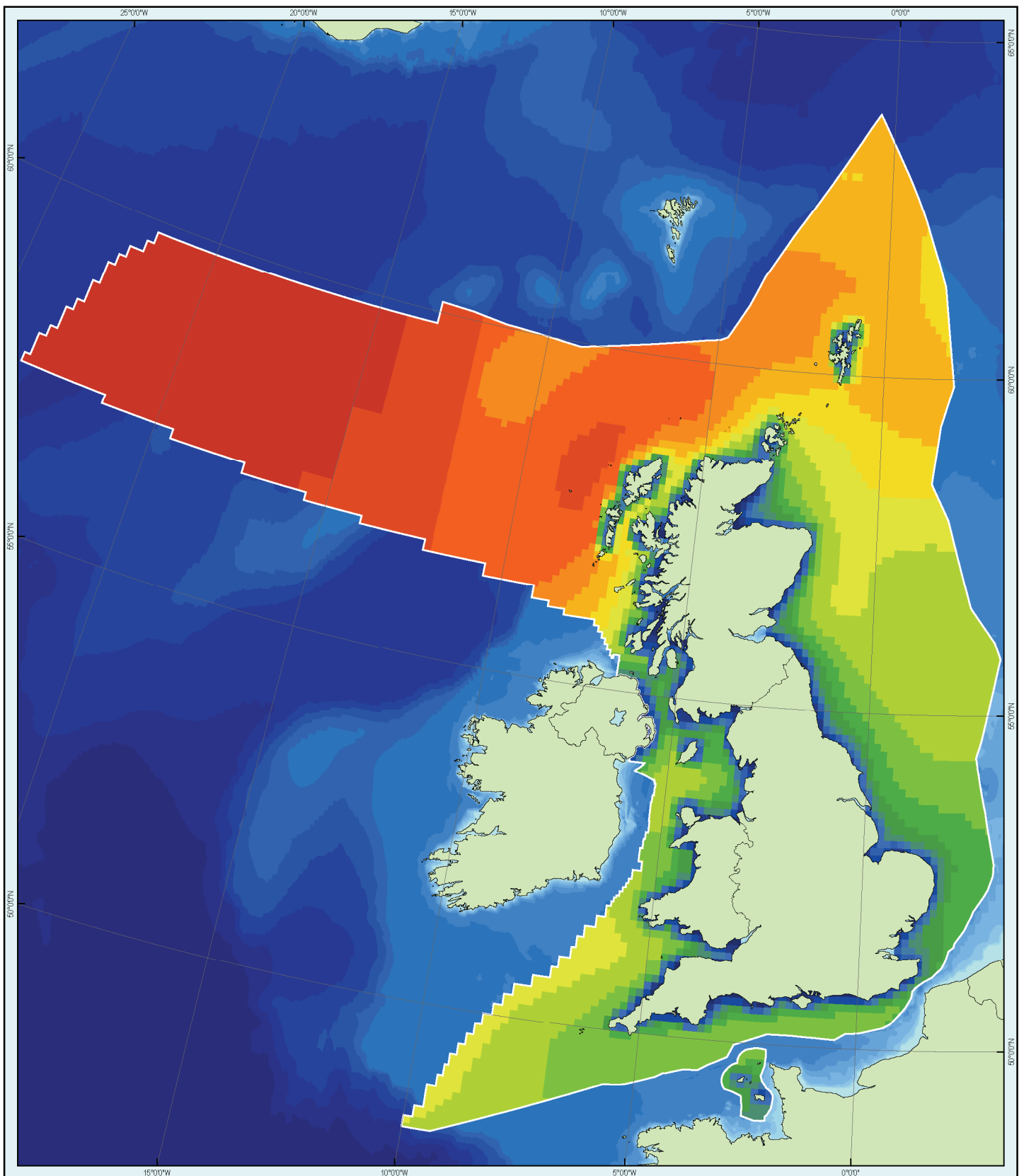
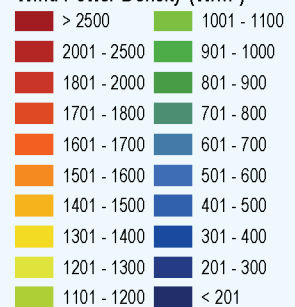


Figure 15 - Annual Mean Wind Power Density at 100m

Wind Power Density (W/m^2)



Land
 UK Continental Shelf & Channel Islands Territorial Sea Limits



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
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Atlas of UK Marine Renewable Energy Resources

Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wind data will be less robust at land-sea boundary points.
3. Wind data are based on hourly model hindcast values over 7 years.
4. Wind power density at 100 metres above sea level.
5. Wind power density per metre squared of rotor swept area.
6. March 2008, Version 2.0.
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Appendices

Appendix A

Atlas End-User Survey Summary

Appendix A. Atlas End-User Survey Summary

A1. Introduction

At the outset the of the Atlas project to update and refine the Atlas of UK Marine Renewable Energy Resources, ABPmer conducted an End-User survey with an aim to validate the planned refinements to the original Atlas and help finalise the Atlas project specifications. The range of end-users has included project funders, SEA Programme Managers and representatives of the marine renewable industry who are known to be presently working with the Atlas GIS database. The collective views expressed in these results have been reported below, however individual comments and responses have been offered in confidence.

A2. Methodology

In order to receive the results of the survey in a timely manner it was decided to conduct an online questionnaire. This approach is considered to have offered added benefits and enabled respondents to complete the survey very efficiently through a web site. Other advantages of utilising a web survey are as follows:

- **Response Rate:** Web-based surveys and forms are easier to fill out than to traditional postal surveys, as such preferable user response rates, are usually achieved;
- **Results Processing:** Results are automatically calculated as users respond, thus reducing proceeding time and enabling the results to be viewed immediately;
- **Accessibility:** Distribution via web access and email is easy. Web surveys and forms can be accessed from any computer with web access; and
- **Eliminate Disposal of Paper:** Good for the environment as well as reducing costs.

An extensive array of end-users were selected for the survey in order to obtain as broad a view as possible of any potential improvements that could enhance the current Atlas and for the basis for the specification for the Atlas. The survey participants ranged from government agencies, to members of the marine renewable industry who presently work with the Atlas GIS database, including technology developers and energy suppliers.

The range of questions contained in the survey were designed to validate planned refinements to the original Atlas, as such they designed were to develop response to each of the areas of planed refinement, wind data, wave data, tidal data and information dissemination. Nine Questions were asked in all, with two questions for each of the four refinement areas and one final question polling the participants for further suggestions of enhancement. The questions were designed as multiple-choice with three possible responses:

- **Agree:** Agreed with the proposed area of development;
- **Neutral:** No viewpoint to offer (e.g. a tidal developer responding to a wave resource issue); and
- **Disagree:** Disagreed with the proposed area of development.

An additional response area for further comments was also included for each question, see Figure A1 for an example of how this appeared on the web site.

Page 1 of 5


DTI Offshore Renewable Atlas Update

Welcome to the Atlas 2 end-user survey.

As part of the Atlas 2 project we are inviting your assistance in completing this questionnaire to help finalise the project specification. The collective views expressed in these results will be used and reported in the forthcoming project work, however individual comments and responses will remain confidential.

It is the objective for the Atlas 2 project to build on the success of the original study published in 2004 and draw on a longer archive of wind and wave data now available; doubling the current data archive from 3.5 to 7 years thus improving the reliability of synoptic mapping and providing a more robust basis for strategic planning.

Please indicate to what extent you support the statements below (all 8 multiple choice questions require an answer).



Tidal Resource

* 1 - An enhanced description of the tidal resource through the water column would benefit those working in the tidal energy sector.

Agree
 Neutral
 Disagree

Further comments

Figure A1. Survey example

A3. Survey Results

The End-User survey was conducted between June 12 and July 6 2007. Individuals from 33 companies were initially invited to participate in the survey, with advertisements being placed through the British Wind Energy Association (BWEA) and the Renewable Energy Association (REA) websites and newsletters. The overall response rate was reasonable with 54% of the participants included in the survey responding. The range of industry sectors represented in the responses is shown in Figure A2. The range of response shown in Figure A2 is a fair representation of the Renewable Energy sector, with Energy Providers and Technology Developers providing the main impetus within the industry with support from Government and Consultants. The survey results reflect this with the majority of responses coming from Technology Developers and Energy Providers with 41% and 35% respectively, and Consultants and Government Agencies providing 18% and 6% of the responses (Figure A2).

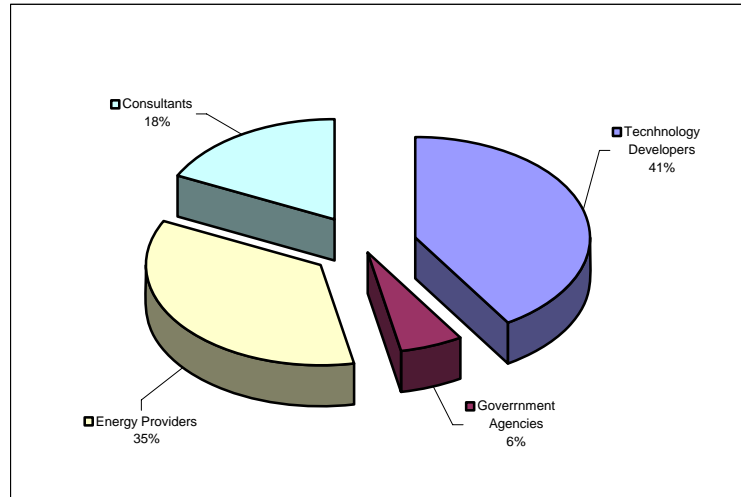


Figure A2. Participant sector

A3.1 Data Resolution

The results from the survey confirm that planned refinements, including increasing the temporal span of the data from 3.5 to 7 years and to include an enhanced spatial resolution for the tidal data, for the Atlas would be beneficial. For example, questions 3 and 5 examine the temporal resolution of the data and ask if an increased archive for wave and wind data would be useful to their activities. In both cases there is an overwhelming positive result, with 82% and 88% agreeing this would be useful, see Figures A3 and A4. Question 2 examines the spatial resolution of the tidal data and again there is a positive response with 82% agreeing, therefore justifying further investigation into higher resolution tidal data, see Figure A5.

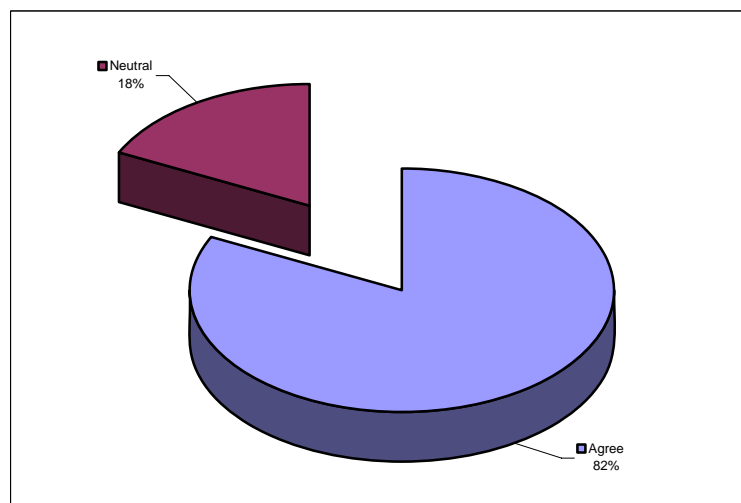


Figure A3. Question 3 - Wave statistics derived from a larger archive of recorded data would provide valuable information for the wave energy sector

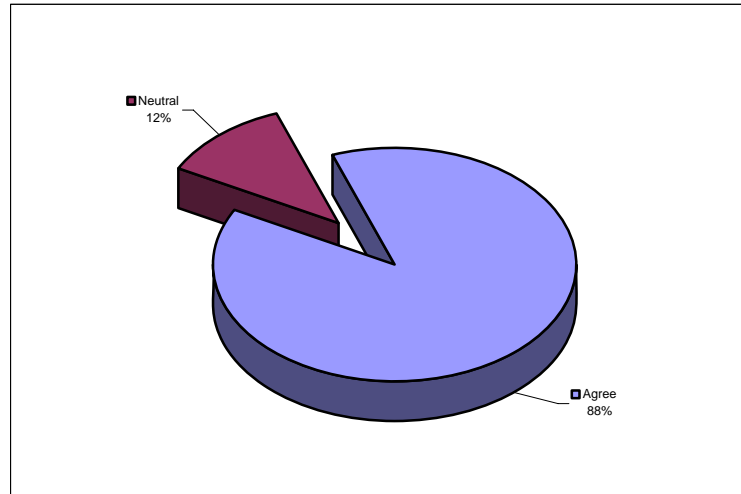


Figure A4. Question 5 - Statistics derived from a larger archive of wind data would provide benefits to those working in this sector

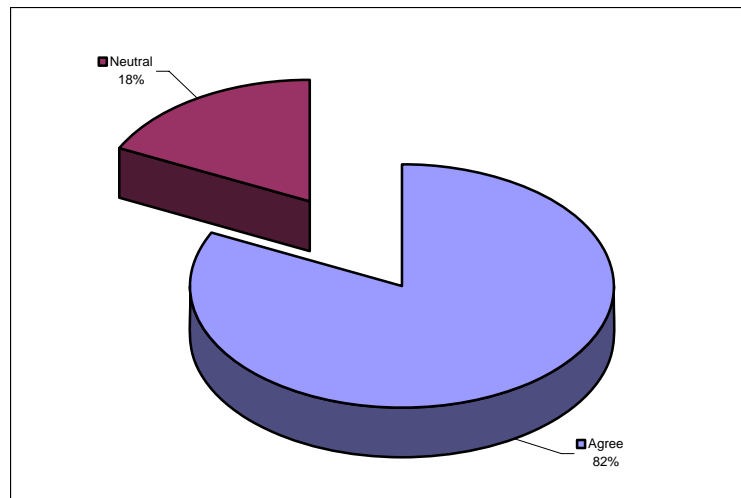


Figure A5. Question 2 - The tidal database would benefit from enhanced spatial resolution in areas of identified resource

A3.2 Data Content

The survey investigated the refinement of data content by adding a number of extra statistics including the following:

- Tidal - An enhanced description of the resource through the water column;
- Wind - Increased directional data and annual variations; and
- Wave - Inter-annual variations and a quantification of variability.

The results from the survey confirm that the above refinements would be beneficial to Atlas users. For example Question 1, which looks at enhanced tidal data, 70 % of respondents agreed this would be useful. However, 6% did disagree, stating that interpolations from current figure would be satisfactory, although they did indicate that validation from any increase in resolution would be useful, see Figure A6. Questions 4 and 6 investigated an increase in available wave and wind statistics and again the positive response was clear with 82% and 76% agreeing this would be of benefit, see Figures A7 and A8.

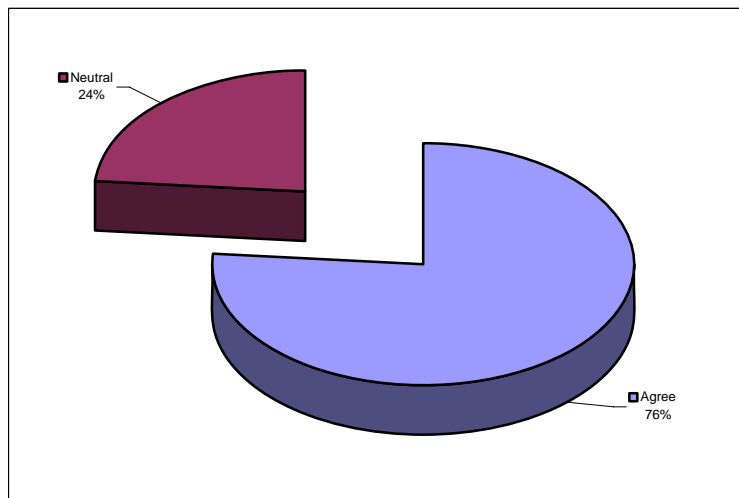


Figure A6. Question 1 - An enhanced description of the tidal resource through the water column would benefit those working in the tidal energy sector

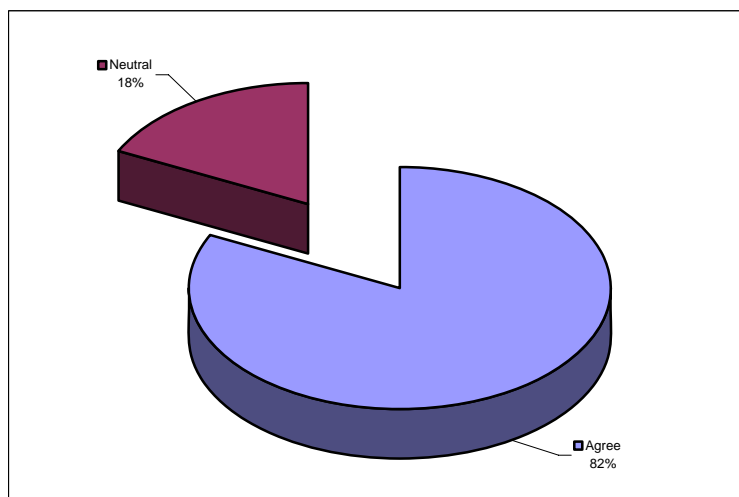


Figure A7. Question 4 - Additional wave statistics, including inter-annual variations and a quantification of variability within the dataset, would be useful to your activities

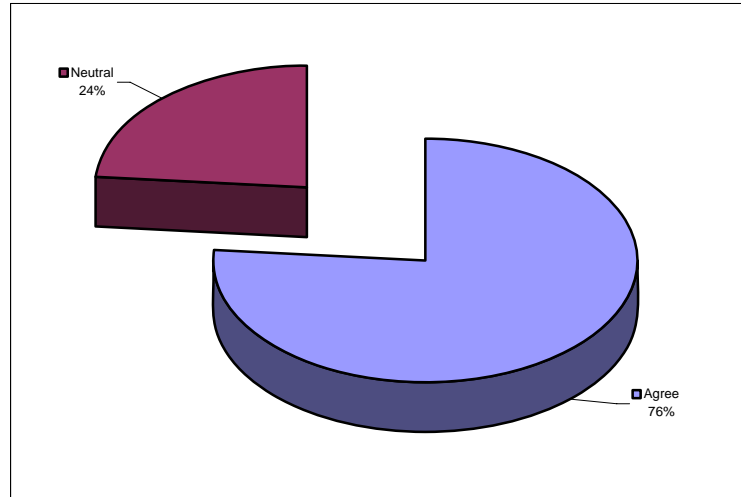


Figure A8. Question 6 - Additional wind rose information would benefit those working in the offshore wind energy sector

A3.3 Data Distribution

The issue of data dissemination has also been investigated in the survey, with plans to use a GIS based website to disseminate data and to provide pack contain presentation quality material, being explored. The concept of a webGIS to disseminate data was received extremely well, 76% of the respondents agreed this would be a valuable asset. Many of the positive responses were supported with further comments, which indicated that that a web-based system would be extremely beneficial, see Figure A9. The provision of an Atlas presentation pack was also well received with 82% of respondents indicating this would be useful, see Figure A10.

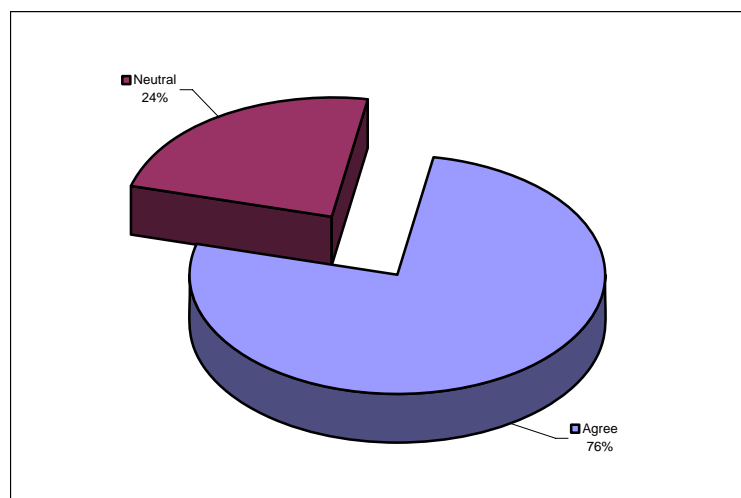


Figure A9. Question 8 - Online webGIS access to Atlas outputs and data layer downloads would provide a valuable dissemination tool

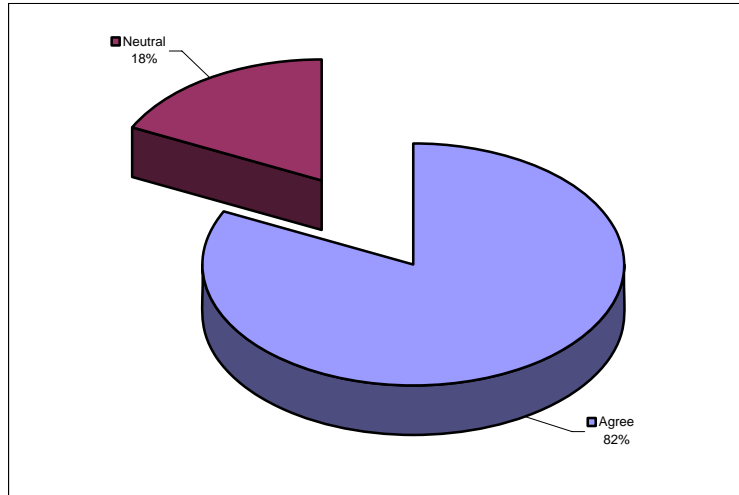


Figure A10. Question 7 - High quality graphical output from the Atlas 2 database for use in presentations would be useful

A3.4 Summary of Results

The overall response to the questions was positive with an average of 79% of the participants replying with a positive answer to the questions, only 1% disagreeing, and the rest remaining neutral, see Figure A11.

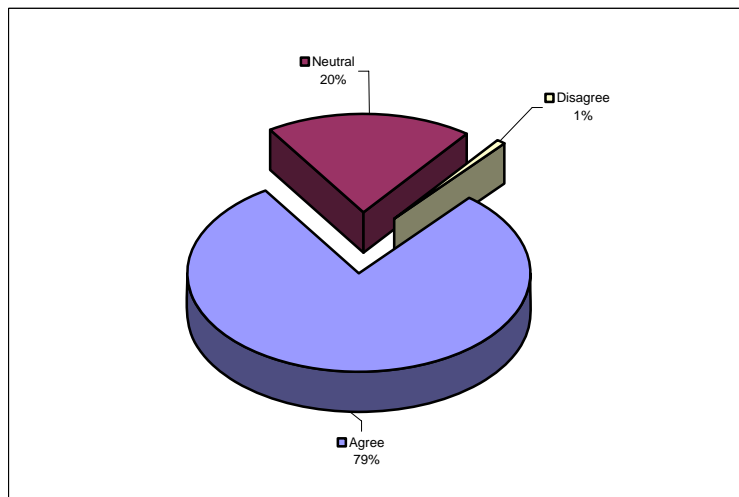


Figure A11. Average response to survey questions

The number of positive responses to the questions indicates that the underlying project specifications for the Atlas project are in line with the marine renewable energy sector’s current requirements for the identification of additional marine renewable energy sites. The results of the End-User survey provide a valuable industry-based validation of the planned refinements for the Atlas which include:

- Extra 3.5 years of data.
- Increased description of the tidal resource through depth;
- Additional wave statistics, including storm bias etc;
- Additional wind statistics, including storm bias, increased directional data, etc.
- A webGIS to disseminated the Atlas Data.

The survey as well as providing validation for existing specifications has also enabled the project team to develop the provision of additional components including, high-resolution materials for presentations which had favourable feed back in the survey. The survey also indicated that there would be significant interest in the provision of high-resolution tidal. The project team investigated this and decided that whilst some higher resolution datasets did exist they posed several issues regarding their utilisation. The main issue was that there was no consistent data available for the entire Atlas study area and the cost of creating a new one from scratch was prohibitively expensive and extremely data intensive. Data for specific priority areas was also investigated. However, it was found that the in accuracy provided by data in those areas would not justify the cost involved with utilising them within the Atlas. The available datasets were also Taking this into account it was decided that there would be no increase in the spatial resolution of the tidal data.

The results of the End-User survey have endorse the planed refinements to that Atlas whilst providing the opportunity to incorporate further enhancements which will allow the Marine Renewable Atlas to continue to perform a significant role in the identification and development of future renewable energy sites and benefit the industry as a whole.

Appendix B

Tide

Appendix B. Tide

B1. An Introduction to Tides and Tidal Numerical Modelling

B1.1 Tides and Tidal Harmonics

The tides are a regular and predictable phenomenon caused by the gravitational attraction of the moon and the sun acting on the oceans of the rotating earth. Most locations around the UK experience the familiar two high and two low waters each day (the average interval between successive high waters is approximately 12 hours 25 minutes), which leads to only 3 turning points on every 7-8th day (i.e. only 1 HW or LW and 2 of the other occurring on that day).

The relative motions of the Earth, Moon and Sun cause the tides to vary in numerous tidal cycles - the two most important ones being:

- The spring-neap cycle: A 14.77 day cycle resulting from the tidal influence of the sun and moon either reinforcing each other (called spring tides, although this has nothing to do with the season) or partially cancelling each other (neap tides).
- The equinoctial cycle: A half yearly cycle caused by the tilt of the earth, and its orbit around the Sun which leads to higher than average spring tides around the time of the equinoxes (March and September) and lower than average spring tides in June and December.

On average, the spring tidal currents are around twice as fast as the neap currents. However as power generated is proportional to the cube of the current speed, a spring tidal current can generate around 8 times the power of a neap tidal current.

Spring tides usually occur 1½ to 2½ days after full and new moon, with neap tides experienced just after the first and third quarter (when half the moon is visible). To aid in planning work, a table of moons phases for the next 4 years (2008 to 2011) has been included in the tables below. Moon phase data obtained from the Griffith Observatory, Los Angeles, USA. Times are Universal Time (GMT).

Table B1. Moons phases for next 4 years (2008 to 2011)

Year	New Moon	First Quarter	Full Moon	Third Quarter
2008	Jan 8 11:38	Jan 15 19:47	Jan 22 13:35	Jan 30 05:07
	Feb 7 03:45	Feb 14 03:36	Feb 21 03:31	Feb 29 02:21
	Mar 7 17:15	Mar 14 10:48	Mar 21 18:40	Mar 29 21:47
	Apr 6 03:56	Apr 12 18:34	Apr 20 10:26	Apr 28 14:10
	May 5 12:19	May 12 03:48	May 20 02:12	May 28 02:53
	Jun 3 19:24	Jun 10 15:03	Jun 18 17:31	Jun 26 12:07
	Jul 3 02:20	Jul 10 04:33	Jul 18 08:00	Jul 25 18:41
	Aug 1 10:14	Aug 8 20:18	Aug 16 21:18	Aug 23 23:52
	Aug 30 19:59	Sep 7 14:03	Sep 15 09:15	Sep 22 05:10
	Sep 29 08:13	Oct 7 09:04	Oct 14 20:04	Oct 21 12:02
	Oct 28 23:15	Nov 6 04:05	Nov 13 06:19	Nov 19 21:38
	Nov 27 16:56	Dec 5 21:29	Dec 12 16:39	Dec 19 10:34
	Dec 27 12:24			
2009		Jan 4 12:00	Jan 11 03:28	Jan 18 02:47
	Jan 26 07:56	Feb 2 23:17	Feb 9 14:50	Feb 16 21:36
	Feb 25 01:37	Mar 4 07:48	Mar 11 02:38	Mar 18 17:46
	Mar 26 16:08	Apr 2 14:34	Apr 9 14:56	Apr 17 13:34
	Apr 25 03:24	May 1 20:43	May 9 04:02	May 17 07:25
	May 24 12:12	May 31 03:19	Jun 7 18:12	Jun 15 22:15
	Jun 22 19:36	Jun 29 11:25	Jul 7 09:22	Jul 15 09:56
	Jul 22 02:35	Jul 28 21:57	Aug 6 00:56	Aug 13 18:59
	Aug 20 10:02	Aug 27 11:41	Sep 4 16:04	Sep 12 02:20
	Sep 18 18:45	Sep 26 04:51	Oct 4 06:12	Oct 11 09:60
	Oct 18 05:33	Oct 26 00:46	Nov 2 19:15	Nov 9 15:59
	Nov 16 19:14	Nov 24 21:44	Dec 2 07:32	Dec 9 00:15
	Dec 16 12:03	Dec 24 17:41	Dec 31 19:14	
2010				Jan 7 10:40
	Jan 15 7:13	Jan 23 10:57	Jan 30 6:19	Feb 5 23:48
	Feb 14 2:53	Feb 22 0:42	Feb 28 16:39	Mar 7 15:42
	Mar 15 21:03	Mar 23 10:57	Mar 30 2:26	Apr 6 09:37
	Apr 14 12:31	Apr 21 18:15	Apr 28 12:19	May 6 04:16
	May 14 1:06	May 20 23:38	May 27 23:08	Jun 4 22:16
	Jun 12 11:16	Jun 19 4:27	Jun 26 11:31	Jul 4 14:39
	Jul 11 19:41	Jul 18 10:12	Jul 26 1:38	Aug 3 05:03
	Aug 10 3:09	Aug 16 18:18	Aug 24 17:06	Sep 1 17:25
	Sep 8 10:30	Sep 15 5:55	Sep 23 9:19	Oct 1 3:54
	Oct 7 18:45	Oct 14 21:32	Oct 23 1:38	Oct 30 12:46
	Nov 6 4:52	Nov 13 16:42	Nov 21 17:29	Nov 28 20:37
	Dec 5 17:37	Dec 13 14:00	Dec 21 8:15	Dec 28 04:19
2011	Jan 4 9:05	Jan 12 11:31	Jan 19 21:23	Jan 26 12:59
	Feb 3 2:33	Feb 11 7:15	Feb 18 8:37	Feb 24 23:28
	Mar 4 20:48	Mar 12 23:40	Mar 19 18:11	Mar 26 12:09
	Apr 3 14:34	Apr 11 12: 1	Apr 18 2:44	Apr 25 02:47
	May 3 6:51	May 10 20:30	May 17 11:08	May 24 18:53
	Jun 1 21:03	Jun 9 2:11	Jun 15 20:13	Jun 23 11:49
	Jul 1 8:54	Jul 8 6:34	Jul 15 6:39	Jul 23 05:04
	Jul 30 18:40	Aug 6 11:15	Aug 13 18:58	Aug 21 21:57
	Aug 29 3:04	Sep 4 17:46	Sep 12 9:27	Sep 20 13:41
	Sep 27 11:09	Oct 4 3:20	Oct 12 2:07	Oct 20 03:32
	Oct 26 19:57	Nov 2 16:39	Nov 10 20:18	Nov 18 15:11
	Nov 25 6:11	Dec 2 9:50	Dec 10 14:38	Dec 18 00:49
	Dec 24 18:08			

B1.2 Tidal Harmonics

The tides that we can observe in our seas and oceans are a result of the gravitational forces that exist between the Earth, the Moon and the Sun. The complex movements within the earth-moon-sun system generate forces on the oceans that can vary over time. For example the distance between the moon and the earth varies over 27½ days thereby making the magnitude of the force vary over the same period.

While gravity provides the driving force, it is the Earth's rotation, the shape and size of the ocean basins and the local coastline that ultimately determines the magnitude and frequency of the tide at a particular place.

Using a process called harmonic analysis, the numerous different patterns in the tide can be broken down into a series of much simpler waves called tidal harmonics. Each harmonic (mathematically known as sine waves) has a very specific period relating to the movements of the Earth, Moon and Sun, however the amplitude (size) of each harmonic and its phase (time lag) is unique to each location. By combining these harmonics the tide can be computed for any point forwards or backwards in time provided the local conditions, such as the shape of the coastline, has not changed.

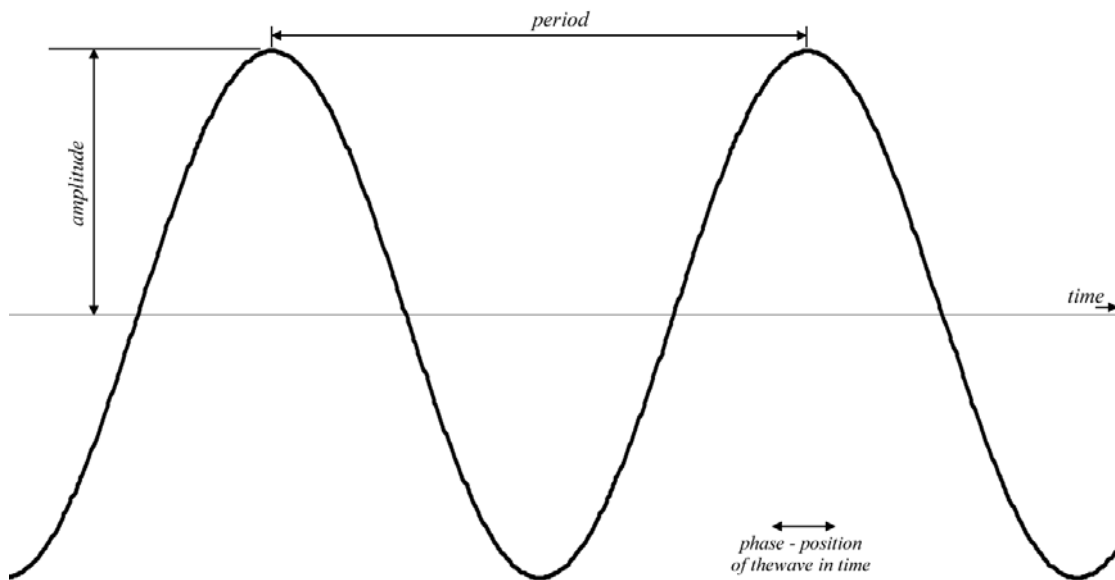


Figure B1. The shape of a tidal harmonic (a mathematical sine wave)

The principal tidal harmonics are listed below:

- M₂ The principal semi-diurnal lunar harmonic. For locations around the UK, this is inevitably the largest amplitude constituent and is what leads to the 2 tides per day. It has a period of around 12 hours 24 minutes.

- S_2 The principal semi-diurnal solar harmonic. This has a period of exactly 12 hours as Earth time is locked to its orbit around the sun. It is the combination of M_2 and S_2 that gives rise to the spring neap cycle as they move in and out of phase over a 14.8 day cycle.
- O_1, K_1 The two principal diurnal constituents - the combined effect of these is to express the effect of the moons declination on the tides. They account for the diurnal inequality in the tides (the difference in height between the two high or low waters of a tidal day).
- N_2, L_2 The two semi-diurnal lunar elliptic harmonics. These modulate the amplitude and frequency of M_2 for the effect of variation in the moons orbital speed due to its elliptical orbit.
- M_4, MS_4 These higher frequency harmonics are usually only about 5% the size of M_2 , however in locations where shallow water distorts the tide, they can show an amplitude of as much as 50% of M_2 .

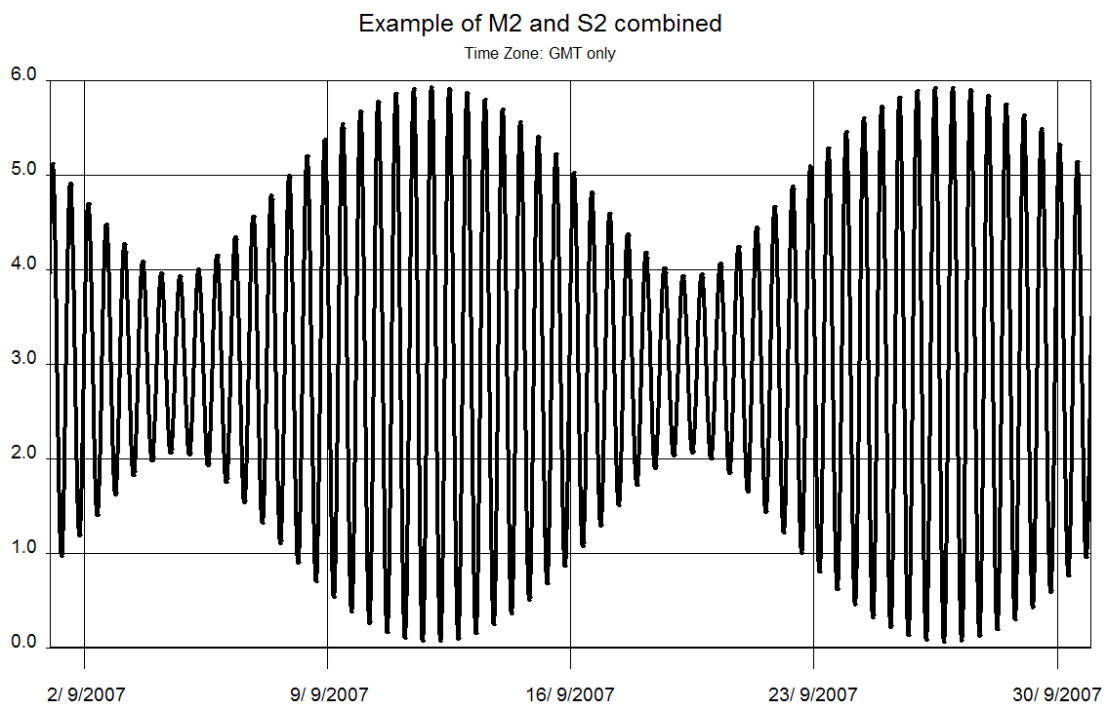


Figure B2. The basic spring neap cycle reproduced using just M_2 and S_2

For tidal levels, a single set of tidal harmonics for a location is required to compute the level at that location. For tidal currents, two sets of tidal harmonics are required to describe the horizontal flow in two perpendicular directions: usually one set for east-west flow and one set for north-south flow. These can be combined to compute the current magnitude and direction. The HRCS high resolution numerical model developed by POL for this Atlas uses 15 individual harmonics for each grid cell to recreate the tide.

B1.3 Introduction to Numerical Modelling

The word 'model' is used widely in the physical sciences and can take many different meanings. It can, for instance, refer to a physical replica such as a scale model of a harbour or a coastline; alternatively it can describe a set of complex interactions such as those between plankton, nutrients, oxygen and bacteria in an ecosystem.

Here are a few different definitions of 'numerical modelling':

- "Numerical modelling is the process of solving a set of equations to obtain a forecast of the future state of a system, given an initial system state and any external influences that are acting on the system. The equations effectively describe the evolution of one or more variables over time." - *Colin Bell*
- "A mathematical model is the use of mathematical language to describe the behaviour of a system. Mathematical models are used particularly in the sciences such as biology, electrical engineering and physics but also in other fields such as economics, sociology and political science." - *Wikipedia.org*
- "A representation of the essential aspects of an existing system (or a system to be constructed) which presents knowledge of that system in usable form" - *Eykhoff (1974)*

To run an ocean model to predict the state of the seas and oceans requires a lot of computing power. POL has a parallel computing cluster with 180 64-bit dual-core processors (360 cores) which is capable of nearly 2 trillion (2×10^{12}) calculations per second. Despite this, high resolution models can take hours or even days to run.

B1.4 Ocean Modelling

A numerical ocean model is - at its simplest - a set of equations that describe the evolution of a set of variables in a system over time. Those variables could be tidal currents, water temperature, salinity (salt content), sediment movement or indeed one of numerous chemical or biological properties.

One of the most common types of numerical model developed at POL is a tidal model. To set up such a model, the modelling software requires detailed bathymetry (water depth data) for the model domain, a definition of the initial sea state - usually just a still water level, and some data to force the model. For a tidal model the forcing data will usually be the known tides around the edge of the model - a surge model would also include wind data and atmospheric pressure data. The modelling software will then use the equations governing fluid flow to compute the tidal level and currents for the required period of time - often 6 or 12 months.

The initial sea state (at time zero) is usually just the still model water level, and the external forcing usually comes from the open boundary of the model (see later).

At the initial time $t=0$, the equations are used to compute a new sea state a very small time interval later, typically just a few seconds. This process is repeated until you have the required period of data.

This data will then be analysed to derive a set of harmonic constants for every cell in the model.

B1.5 Model Grids

As with all large problems, it is correct to divide the problem up into a number of smaller ones. In numerical modelling, the sea region to be modelled (the domain) is broken up into a number of equal sized boxes, or cells. This process is called gridding. The governing equations are solved for each model cell, or grid-box. This makes the task of solving the equations computationally feasible. Each cell is identified uniquely by its position within the grid, which is usually given by a pair of indices i , (the east-west position) and j (the south-north position).

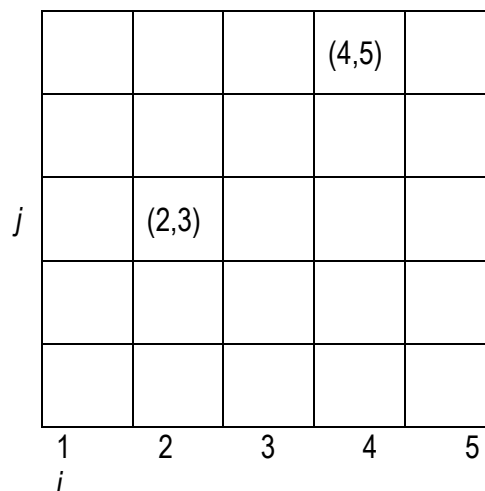


Figure B3. A two-dimensional model grid

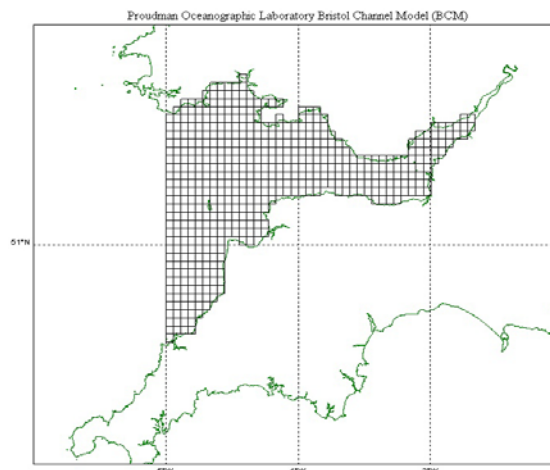


Figure B4. The Bristol Channel Model

In a two-dimensional model it is assumed that the horizontal velocities represent their depth-averaged values. In three-dimensional models, a similar division occurs in the vertical, slicing the water column up into a series of levels.

Figure B5 shows a 3D model divided up into a number of vertical slices. These slices can be defined at fixed levels (for example every 2 metres), although a more useful method is to define the level at specific fractions of the depth for that grid cell called sigma-coordinates. In a sigma-coordinate system, the number of vertical levels in the water column is the same everywhere in the domain irrespective of the depth of the water column. The sigma coordinate model also enables the bottom (benthic) boundary layer to be better resolved across the whole domain.

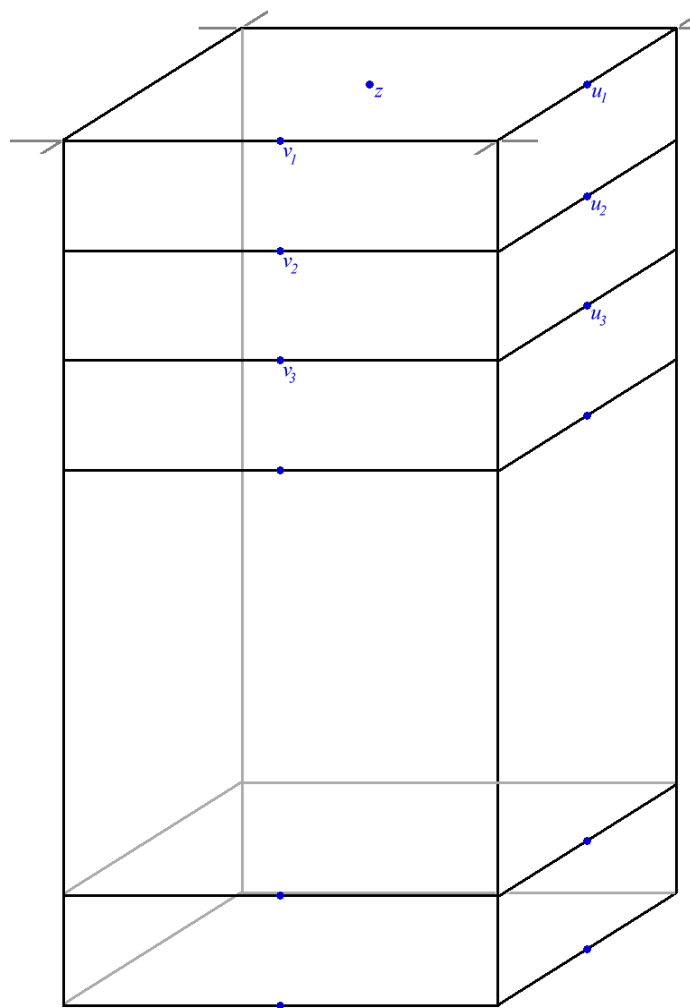


Figure B5. Vertical levels in a three-dimensional model grid

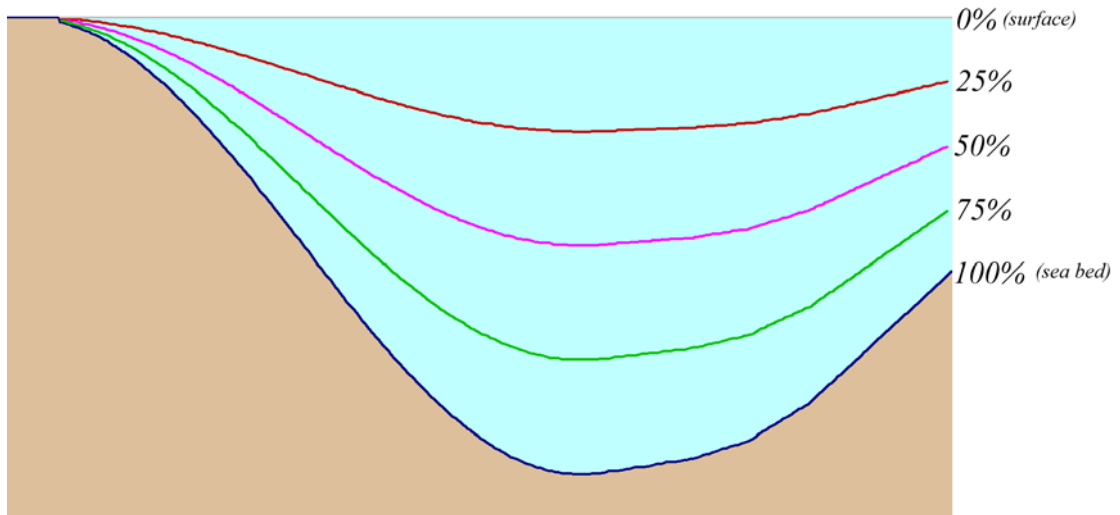


Figure B6. Vertical discretisation in ocean models using sigma coordinates

Each model cell contains one value for every variable of interest.

B1.6 Tidal Models

For a tidal model, the variables of interest are the tidal current U (east-west component) and V (north-south component) and the surface elevation Z .

It is convenient to stagger the variables on the model grid (i.e. the position of the current components and the elevation is different). This provides a way of computing the derivative functions that appear in the equations and is a technique called finite differences. Most of POL's tidal models are *finite difference models*.

The staggering of variables also ensures numerical stability (i.e. ensures small errors in the computation are not amplified).

In reality, physical variables like currents and elevations are continuous (they have some value everywhere in physical space). By dividing the model area up into a grid, and calculating the variables at only one place in each cell, we have distorted this reality. The process of converting a real flow field onto the gridded one is called *discretisation*. The most popular choice of grid for stability and second-order spatial accuracy in finite difference models is the Arakawa C-grid (Arakawa and Lamb, 1977) which is shown in Figure B7 below.

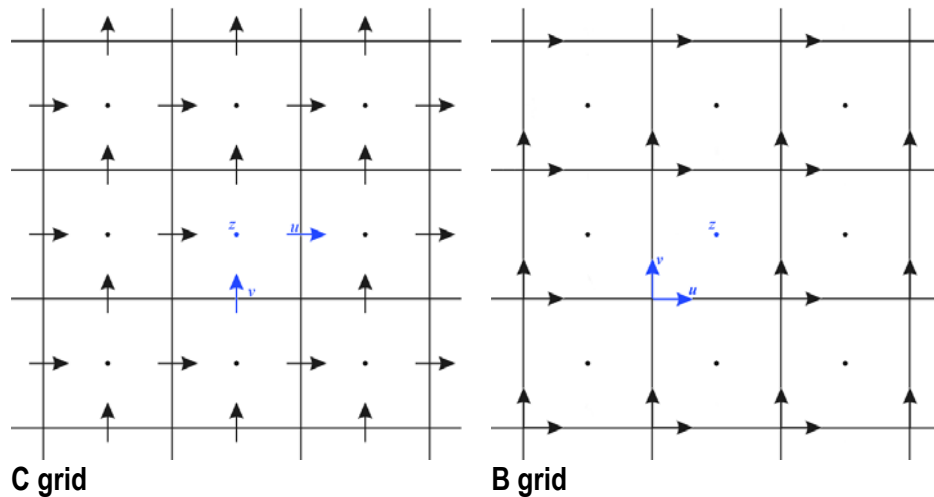


Figure B7. Examples of popular numerical grids

The C-Grid can be applied to rectangular coordinates as in POL's CS3 model or curvilinear coordinates as in the Princeton Ocean Model, POM (Blumberg and Mellor, 1987). The alternative B-grid is useful if one wishes to avoid averaging four velocity points in subsequent calculations (POL's HRCS model was developed on a B-Grid).

B1.7 Model Boundary

For the finite difference model to work, every elevation point needs to be flanked by current points and vice versa for the equations to be evaluated. In Figure B8, you will see that at the edges of the model domain this does not happen. Point Z_1 has no current flow to the left.

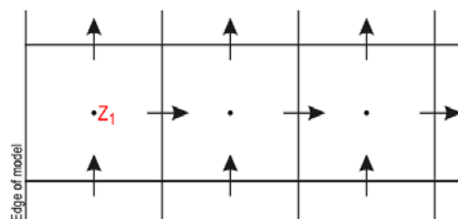


Figure B8. C grid model boundary

These are called boundary conditions and the missing variable must be defined at every time step. If the boundary is due to land, then it is reasonable to set this value to zero since there can be no flow through a solid boundary. However when the boundary is not land, known as an open boundary, the variable must be prescribed for every point in time. For example with a UK continental shelf model the tides at the boundary are in the North Atlantic Ocean and are derived from a larger scale model of the entire ocean. With smaller models such as harbours and small estuaries, it might be possible to provide open boundary input directly from observations of the tide.

Additional boundary conditions for a more complex model might include wind stress at the sea surface, solar heating and freshwater influence from rivers.

B1.8 Model Accuracy, Resolution and Numerical Considerations

As only one value for each variable of interest is available for each grid cell, each value computed for each grid cell can at best represent the average value for that cell. Therefore, the smaller the grid cell, the more accurately the model will be able to represent reality. This is particularly important when modelling parameters which can vary greatly over fairly small distances. The only expense in having more grid cells is increased computer memory and computational time. A close analogy would be the resolution of the sensor in a digital camera - an 8 MegaPixel camera will capture more detail in the image than a 2 MegaPixel camera (it has a higher resolution) but the image files are a lot bigger and take longer to download and process.

The model resolution determines the types of motion that the model is capable of simulating. A model with a 10km resolution can distinguish between the height of the tide at Portland and Plymouth, but not Portland and Weymouth because the two places fall inside the same cell. To compute tides for Portland and Weymouth separately, a higher resolution model would be needed.

Model accuracy will depend on a number of factors - in particular the type of model. A tidal model with an accuracy of $\pm 5\%$ might be considered reasonable whereas a suspended sediment transport model will be doing very well to get an accuracy of $\pm 25\%$, as this may be equivalent to the tolerance in the actual field measurement.

Accuracy of a model can be increased by any of the following:

- Improved horizontal resolution (smaller grid);
- Improved vertical resolution (more layers);
- Improved resolution in the bathymetry;
- More accurate boundary conditions; and
- Better temporal resolution of the boundary conditions.

B1.9 Model Validation

Numerical models require good observations that can be used to test and improve them. The process of testing a model against observations is called validation.

A good example of validation for a tidal model is to compare the predicted height of the tide with that observed at several locations. Accurate records of tidal elevations are made at standard ports around the UK. Predicted tidal elevation amplitude from a model can be compared with measured amplitudes wherever data is available. One way of visualising the comparison is to plot model vs. actual tide height on a simple scatter diagram. A regression

line slope close to unity is a useful metric for gauging the predictive skill of the model. See also Section B4.

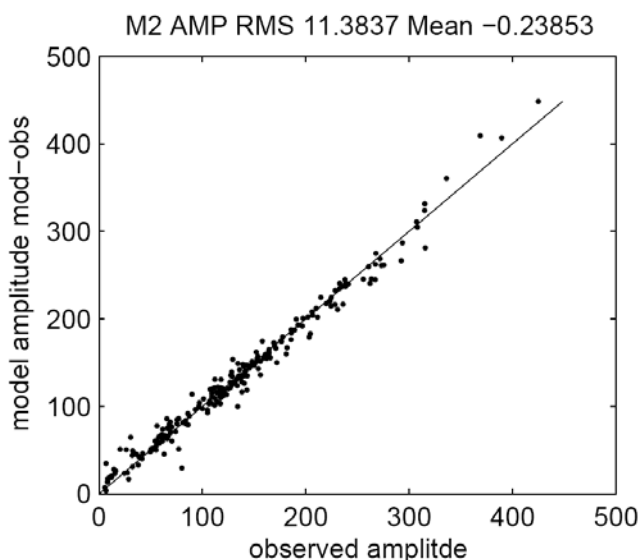


Figure B9. Comparison of modelled elevations against tidal observations

B1.10 Models and Computer Architecture

Running a high resolution model of the ocean requires very large amounts of computing power. Although a modern PC is capable of 44 GFLOPS (Intel Core 2 Extreme X6850 processor; 1 GFLOP = 1 billion floating-point operations per second), this is insufficient to run a large area high resolution model in a reasonable length of time.

Ocean models lend themselves to parallel computer architectures - the models are run on clusters of many processors linked by high speed communications. Efficient communications between the processors allows the scaling up of problems onto as many processors as are available. This allows models to become more complex and/or run at higher resolution with relative ease as more computer power becomes available.

POL's Coastal Ocean Modelling System (POLCOMS) is formulated to run on parallel computers - a sophisticated pre-processor allows total scalability to suit any machine, from a single processor workstation through to massive clusters. POL has it's own 180-processor LINUX cluster (each with 2 cores) although POLCOMS can also run efficiently on the 2560 processor IBM machine at Daresbury Laboratory.

Scaling for multi-processors is done by splitting up the model domain into smaller regions, a process called domain decomposition. Each processor works on a specific part of the model, communicating with surrounding processors for necessary data.

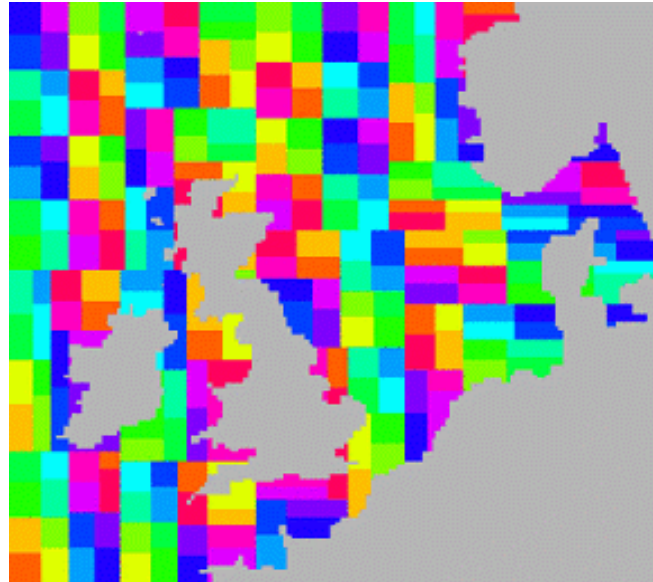


Figure B10. Domain decomposition for 256 processors

B2. Tidal Resource Parameters

B2.1 Introduction

The POL High Resolution Continental Shelf Model (also known as HRCS) has been used to derive the tidal parameters for the Atlas. This model has a resolution of $1/60^\circ$ latitude by $1/40^\circ$ longitude - a horizontal resolution of approximately 1 nautical mile (1.8km).

The domain of the model covers 12°W to 13°E ; 48°N to 63°N within the 200m depth contour. The model is a 3D model with tidal data available at 32 evenly spaced sigma levels.

For the purposes of this project, the domain has been limited to UK's Exclusive Economic Zone. The tidal current parameters have been computed independently for the 5 sigma levels closest to the depths of 50%, 60%, 70%, 80%, 90% from the surface. There is less tidal variation in the top 50% of the water column than in the bottom 50%, and currents near the surface are usually of less interest to the tidal renewable energy sector.

B2.2 Changes to the HRCS Model Since Version 1 of the Atlas

Higher resolution in the vertical - Version 1 used just depth-averaged currents along with independent surface and bottom layers. The revised model has been run with 32 sigma levels of which 5 independent levels have been used to create the data for the Atlas.

- This run used an improved vertical mixing scheme - the general ocean turbulence model (Umlauf, L., Burchard, H. and Bolding, K., 2005. GOTM - Scientific Documentation Version 3.2. No. 63 of Marine Science Reports, Baltic Sea Research Institute, Warnemünde, Germany). This gives more accurate tidal currents, although it tends to have higher friction, hence slower currents in many regions. Vertical profiles are determined by how the bottom friction is transmitted through the water column by turbulent mixing (hence the importance of the turbulence model);
- Some of the grid cells in the HRCS model used in Version 1 of the Atlas are not part of the latest HRCS model runs. These are in wetting and drying areas and have been deliberately removed so as to improve the accuracy of the nearby model grid cells which are outside of the wetting and drying zone.

The governing equations that are represented within a hydrodynamic model are the equations of momentum (effectively Newton's 2nd law), and continuity of mass (or volume). Both are based on hard physical principles and are central planks of fluid dynamics. Wetting-drying algorithms one might employ to allow for a moving coastal boundary have a less physical basis. A plethora of approaches exists, and all are eminently sensible and based on good logic (e.g. if this cell is full, but its neighbours are empty then allow the cell to empty according to some modified friction law) but none have the same solid foundation as the governing equations. Consequently, wetting-drying can - in some circumstances - produce unrealistic behaviours in models in very shallow areas (e.g. see-saw oscillations) and impact on the accuracy of surrounding grid cells. It was for this reason that some very shallow areas were removed from the HRCS model in this run.

B2.3 Details of Parameters

The parameters included in the Atlas have been selected to give a good overview of the tidal conditions that are most relevant to someone working in the field of offshore renewable energy. They have also been selected to provide average conditions so that meaningful comparisons can be made between different sites. It should be understood, however, that being an average means that there will be variations across the tidal cycles, and from one tidal cycle to the next. For example mean spring peak current will give an average that the current speed will peak at during an average spring tide, however there can be $\pm 20\%$ variation on this value across the course of a year.

Some of the parameters are derived from 2 or 4 tidal harmonics and it is often asked why more harmonics are not used. The additional harmonics create a more temporally specific description of the tide which moves the parameters away from the average that we are trying to capture in the Atlas. For example M_2 and S_2 can give an accurate average of the spring and neap tidal range. Inclusion of further harmonics will not make the average tidal range any more accurate - however, it would show up differences between one spring range and the next. This would lead to the problem of how this could be included in an Atlas that is attempting to capture the average conditions.

The Proudman Oceanographic Laboratory can of course use a complete set of harmonics to compute a detailed tidal profile of any given location for any specific point in time, however, to do this for the complete UK waters would lead to vast quantities of data.

B2.4 Depth

Indicates the average depth (in metres rounded to the nearest metre) for that model grid cell.

B2.5 Data Depth

Indicates the height above the seabed at which the parameters have been computed. This is a function of the sigma levels selected and the depth of that model grid cell.

B2.6 Mean Spring Range (MSR) and Mean Neap Range (MNR)

These two parameters are computed directly from the two principle semi-diurnal harmonic components M_2 and S_2 . These are the two components that govern the timing of the spring neap cycle and their amplitudes can be used to compute the average tidal range at springs and neaps. At spring tides, the lunar and solar tides reinforce each other and therefore the mean spring range can be computed using the formula:

$$\text{MSR} = 2(H_{M_2} + H_{S_2})$$

H_{M_2} is the amplitude of the M_2 harmonic constituent
 H_{S_2} is the amplitude of the S_2 harmonic constituent

At neap tides, the solar tide partially cancels out the lunar tide and therefore the mean neap range can be computed using the formula:

$$\text{MNR} = 2(H_{M_2} - H_{S_2})$$

Typically the amplitude of S_2 is about 35% the size of the amplitude of M_2 , thereby making the neap tidal range typically around half the size of the spring tidal range.

B2.7 Age of the Tide

The average time delay (in hours) from the full and new moon to the point of spring tides (usually between 36 hours and 60 hours). This is a theoretical figure computed from the phase and speed of the two principle semi-diurnal constituents.

It is often useful to know the date and time of spring tides. The easiest way of knowing when spring tides occur is to compute the phase of the moon (there are numerous public domain algorithms for doing this accurately) and add on the value for the age of the tide.

B2.8 Type of Tide

This value gives an indication of the type of tidal regime experienced at the location. Using the amplitudes of the 2 principle semi-diurnal harmonic constituents (M_2 and S_2) and the two principle diurnal constituents (O_1 and K_1), the formula returns a value which indicates the type of tides one might expect.

Value	Description of Tidal Regime
< 0.25	Semi-diurnal tides
0.25 - 1.5	Mixed tides (mainly semi-diurnal)
1.5 - 3.0	Mixed tides (mainly diurnal)
> 3.0	Diurnal tides

The value for the Age of the Tide becomes less reliable when the value for the Type of Tide exceeds 0.5.

B2.9 Tidal Ellipse Parameters

The tidal data in the Atlas are computed using tidal harmonic constituents - the four principal ones being M_2 , S_2 , O_1 and K_1 . For each location in the model, two sets of harmonics exist - one for the east-west flow of the current and one for the north-south flow. To visualise the actual current speed and direction more easily, these are combined into current ellipse parameters for each harmonic which shows the size of the semi-major and semi-minor axes, the orientation and phase of the ellipse, and the currents direction of rotation.

If the tidal current at a particular location is plotted as a vector for a single tidal harmonic, the ellipse is the shape that is formed by the tips of the current vectors.

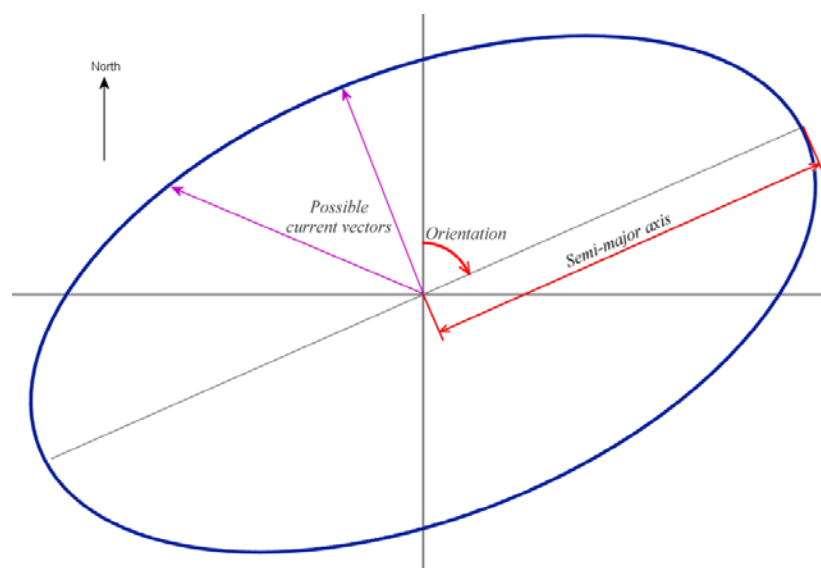


Figure B11. A tidal harmonic ellipse

The size of the semi-major axis gives an indication of the maximum current speed that the tidal harmonic will contribute. Taking (M_2+S_2) gives an approximation of the average spring current speed while (M_2-S_2) gives an estimate of the average neap current.

The orientation of the M_2 ellipse will give the average direction of the maximum current flow. For most UK locations, the orientation of M_2 and S_2 will be very close. Sometimes they will be around 180° apart, although as there are two semi-major axes which are 180° apart this means the orientation is the same.

The difference in the size of the semi-major axis and the semi-minor axis gives an indication of the type of current flow. If the semi-minor axis is very small compared to the semi-major axis (i.e. the ellipse is very flat), then the flow is said to be **rectilinear** with two periods of low or slack current each tidal cycle. In the open ocean, the semi-minor axis can be almost as large as the semi-major axis (the ellipse is almost circular). In this case, the current speed remains more constant throughout the tidal cycle and the direction shows a progressive rotation and is called **rotary flow**. The direction of the flow is given by the rotation parameter.

B2.10 Mean Spring/Neap Peak Current

These parameters give the average value for the peak flow of the current (this is the current equivalent of the Mean Spring/Neap Range for levels given earlier). It is computed using the semi-major axes from the M_2 and S_2 ellipses. It is important to remember this is the average of the peaks (shown in red in Figure B12) - when working out power potential, you would need to consider the whole tidal cycle.

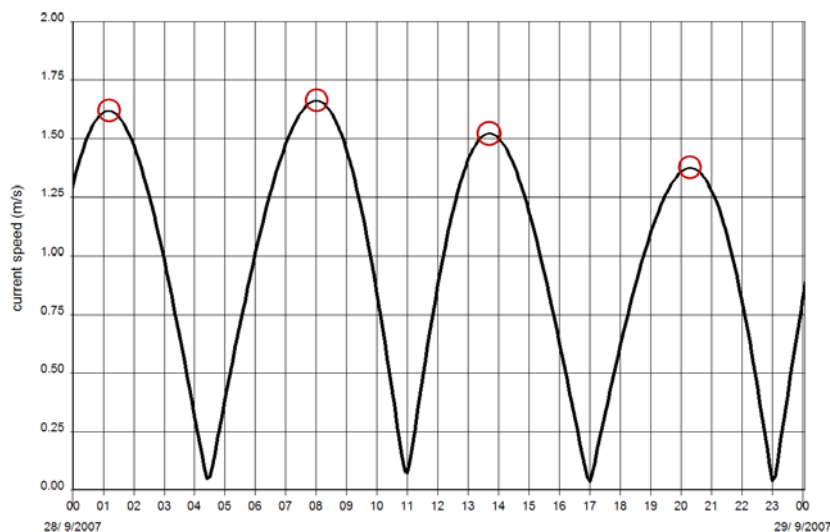


Figure B12. The peaks of a 24 hour current curve - averaged to give the mean spring/neap peak current parameters

B2.11 Persistence Data

This data forms a traditional histogram giving the percentage time the current speed is within a specific range. There are 41 values per current layer and the upper limit for each interval (units: m/s) are:

0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
2.9	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	∞	

The distribution is determined from hourly data of the tidal currents for one year. The year 2001 was selected to represent a 'typical' year as the tidal conditions are fairly average. This is preferred over picking a year that exhibits above average current speeds and which may lead to false expectations. Sampling at a higher frequency than hourly had an insignificant impact on the results.

Note that only the current speed is represented within this histogram and no account is taken of the current direction. However, if you know the shape of the current ellipse, you can use the data in Table B2 to get an idea of how much time the flow is within $\pm x^\circ$ of the principal flow axis. The shape (or fatness) of the ellipse (S) is derived by dividing the semi-major axis by the semi-minor axis.

$$S = \frac{M_{2_{\text{semi-major axis}}}}{M_{2_{\text{semi-minor axis}}}}$$

The percentage values are for flow in one direction - double the value for bi-directional flow.

Table B2. Current flow

S	Angle Relative to Major Axis				
	$\pm 5^\circ$	$\pm 10^\circ$	$\pm 20^\circ$	$\pm 30^\circ$	$\pm 45^\circ$
1	2.78	5.56	11.11	16.67	25.00
2	5.51	10.79	20.03	27.28	35.24
3	8.17	15.49	26.40	33.33	39.76
4	10.72	19.55	30.84	36.99	42.20
5	13.13	23.00	34.01	39.39	43.72
6	15.39	25.90	36.33	41.05	44.74
8	19.44	30.37	39.47	43.21	46.04
10	22.88	33.58	41.47	44.54	46.83
12	25.77	35.95	42.84	45.44	47.35
15	29.27	38.49	44.23	46.34	47.88
20	33.47	41.20	45.65	47.25	48.41
25	36.35	42.90	46.52	47.80	48.73
30	38.41	44.05	47.09	48.16	48.94
40	41.14	45.52	47.82	48.62	49.20
50	42.85	46.40	48.25	48.90	49.36

Example: Suppose for a location that the ellipse parameters for M_2 are:

Semi-major axis = 1.74;
Semi-minor axis = 0.21;
Orientation = 37° .

$S=1.74/0.21 = 8.29$ (nearest value of S in table is 8).

From the table the percentage for $\pm 5^\circ$ is 19.44%. This means that for nearly 20% of the time the current flow is $37^\circ \pm 5^\circ$ (i.e. between 32° and 42° from North). For 30.37% of the time it is within 27° and 47° (the $\pm 10\%$ figure).

B2.12 Annual Tidal Energy Yield

The general equation for power available from tidal currents is given by:

$$P_{\text{cross-section}} = \frac{1}{2} \rho A_{\text{cross-section}} U^3$$

where:

ρ is the density of water (kg/m^3);
 $A_{\text{cross-section}}$ is the cross sectional area (m^2); and
 U is the instantaneous current velocity (m/s).

The average value throughout the year gives the mean power potential at the site. The figures in the Atlas are given for a one square metre cross sectional area, therefore the formula is:

$$P = \frac{1}{2} \rho \langle U^3 \rangle \quad \rho = 1027 \text{ kg/m}^3 \text{ and } \langle \rangle \text{ indicates the averaging period}$$

The reality is that no device will ever be 100% efficient and so power extracted will be less than the theoretical maximum given by these equations.

The power figures are also based on current speed only, and therefore for a fixed axis device, the type of flow and the devices efficiency for off-axis currents will have an impact on the power available across the tidal cycle.

Three values are given for the tidal energy yield - all based on average power per square metre of vertical cross section.

- Average power obtainable over a complete year taking into account the complete tidal curve (i.e. not just the peak current values);
- Average neap power - taking into account the peak only of the neap tidal curve; and
- Average spring power - taking into account the peak only of the spring tidal curve.

B3. Tidal Model Configuration

The model (HRCS) has been set up over the domain of the NW European continental shelf shown in Figure B13. Horizontal grid resolution is $1/60^\circ$ latitude by $1/40^\circ$ longitude (approximately 1.8 km) and there are 32 levels in the vertical.

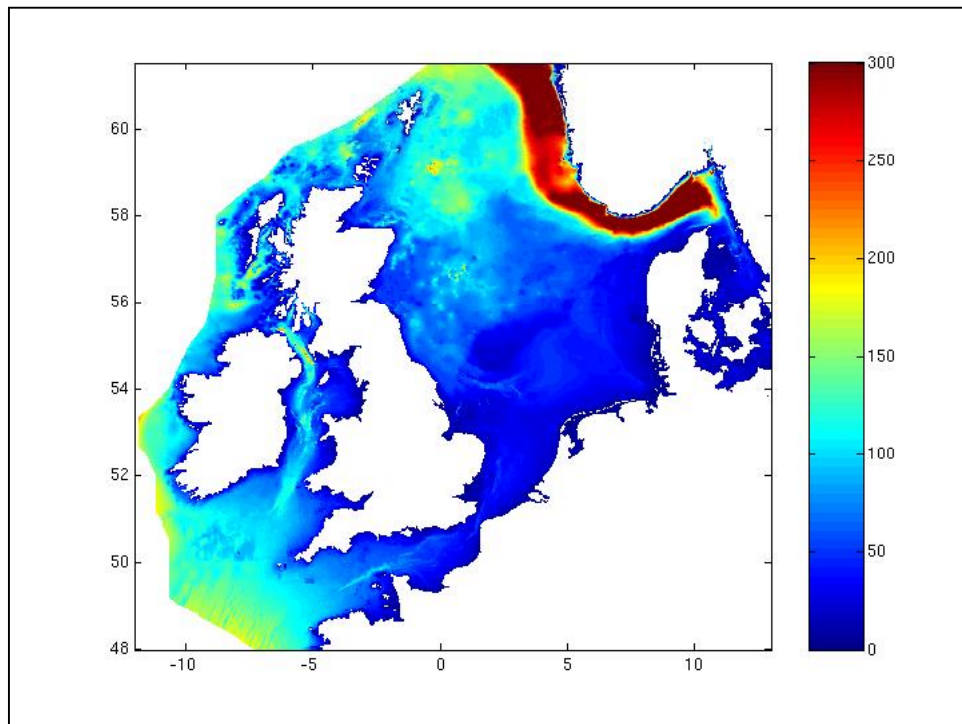


Figure B13. Domain of HRCS (high resolution continental shelf) model and depths (m)

Bathymetry for this model domain has been constructed from a variety of sources. The underlying bathymetry originates from the GEBCO (General Bathymetric Chart of the Oceans) 1 minute digitised bathymetry. This data has been interpolated onto the $1/40^\circ$ longitude by $1/60^\circ$ latitude grid of HRCS and the model coastline guided (but not defined) by the World Vector Shoreline. Where possible, the bathymetry has been improved by the replacement of the GEBCO depths with bathymetry from higher resolution datasets available to POL. This has provided significant improvements over GEBCO bathymetry in near-shore inter-tidal regions.

The model, an adaptation of Proctor & James (1996), solves the 3-dimensional incompressible, Boussinesq, hydrostatic equations in spherical polar coordinates with a transformed vertical coordinate, σ . The equations used are:

$$\begin{aligned} \frac{\partial u}{\partial t} = & -L(u) + \left(f + \frac{u \tan \varphi}{R} \right) v - \frac{1}{R \cos \varphi} \left(\frac{\partial \Phi}{\partial \chi} - \left[\frac{\partial \zeta}{\partial \chi} + \sigma \frac{\partial D}{\partial \chi} \right] b \right) \\ & - \frac{1}{\rho_o R \cos \varphi} \frac{\partial P_a}{\partial \chi} + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(A \frac{\partial u}{\partial \sigma} \right) \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\partial v}{\partial t} = & -L(v) - \left(f + \frac{u \tan \varphi}{R} \right) u - \frac{1}{R} \left(\frac{\partial \Phi}{\partial \varphi} - \left[\frac{\partial \zeta}{\partial \varphi} + \sigma \frac{\partial D}{\partial \varphi} \right] b \right) \\ & - \frac{1}{\rho_o R} \frac{\partial P_a}{\partial \varphi} + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(A \frac{\partial v}{\partial \sigma} \right) \end{aligned} \quad (2)$$

$$\frac{\partial b}{\partial t} = -L(b) + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(K \frac{\partial b}{\partial \sigma} \right) \quad (3)$$

where :

- u, v & Ω = the positive velocity components in east (χ), north (φ) and vertical (σ) directions respectively;
- D = total depth ($= H + \zeta$);
- ζ = surface elevation above mean sea level;
- f = the Coriolis parameter;
- P_a = the atmospheric pressure;
- Φ = (total pressure $P - P_a$)/ $\rho_o + gz$;
- b = buoyancy = $g(\rho_o - \rho) / \rho_o$;
- A = the coefficient of vertical viscosity; and
- K = the coefficient of vertical diffusivity.

The non-linear terms, $L(a)$, are given by:

$$L(a) = \frac{u}{R \cos \varphi} \frac{\partial a}{\partial \chi} + \frac{v}{R} \frac{\partial a}{\partial \varphi} + \Omega \frac{\partial a}{\partial \sigma} \quad (4)$$

where:

Ω is the velocity component in the vertical (σ) direction given by:

$$\Omega = -\frac{\sigma}{D} \frac{\partial \zeta}{\partial t} - \frac{1}{DR \cos \varphi} \left[\frac{\partial}{\partial \chi} \left(D \int_0^\sigma u d\sigma \right) + \frac{\partial}{\partial \varphi} \left(D \cos \varphi \int_0^\sigma v d\sigma \right) \right] \quad (5)$$

also:

$$b = \frac{1}{D} \frac{\partial \Phi}{\partial \sigma} \quad (6)$$

so:

$$\Phi = D \int_0^\sigma b d\sigma + g\zeta. \quad (7)$$

The vertical coordinate is $\sigma = (z - \zeta) / (H + \zeta)$, and the interior water column is divided into N-2 (where N=34) σ levels. To maintain resolution near the surface in deep water the σ spacing is allowed to vary in the horizontal according to the transformation

$$\begin{aligned} \sigma_{k-0.5} &= S_k + \frac{h_{i,j} - h_c}{h_{i,j}} [C(S_k) - S_k] & h_{i,j} > h_c \\ &= S_k & h_{i,j} \leq h_c \end{aligned} \quad (8)$$

where:

S_k are N-1 evenly spaced levels between $\sigma = -1$; and $\sigma = 0$ and $C(S_k)$ is defined as

$$C(S_k) = (1 - B) \frac{\sinh(\theta S_k)}{\sinh \theta} + B \frac{\tanh(\theta[S_k + 0.5]) - \tanh(0.5\theta)}{2 \tanh(0.5\theta)}. \quad (9)$$

This follows from the s coordinate transformation of Song & Haidvogel (1994) except we retain the definition of σ i.e. the levels in σ space do not vary with time. Parameters h_c , θ and B can be tuned to give increased resolution at the surface and/or at the sea bed. In depths shallower than h_c the standard σ levels are used, for depths greater than h_c the transformation is invoked. It should be noted that in this application, where water depths on the continental shelf are mostly less than 150m, only the σ coordinate is used.

For numerical efficiency the equations are split into their depth-mean components and 3-dimensional deviations, the depth-mean equations are:

$$\frac{\partial \bar{u}}{\partial t} = f\bar{v} - \frac{g}{R \cos \varphi} \frac{\partial \zeta}{\partial \chi} - \frac{1}{\rho_o R \cos \varphi} \frac{\partial P_a}{\partial \chi} - \frac{1}{D} F_B + NLB_\chi \quad (10)$$

$$\frac{\partial \bar{v}}{\partial t} = -f\bar{u} - \frac{g}{R} \frac{\partial \zeta}{\partial \varphi} - \frac{1}{\rho_o R} \frac{\partial P_a}{\partial \varphi} - \frac{1}{D} G_B + NLB_\varphi \quad (11)$$

where :

F_B, G_B = components of bottom stress given by

$$(F_B, G_B) = C_{DB} (u_b, v_b) \sqrt{(u_b^2 + v_b^2)}. \quad (12)$$

where :

u_b, v_b = components of bottom current;

C_{DB} = bottom stress coefficient (set to $\left[\kappa^{-1} \log \left(\frac{\delta}{z_0} \right) \right]^{-2}$, $C_{DB} > 0.005$,

where:

δ is depth of u_b, v_b above the seabed,

$z_0 = 0.003$ and κ is von Karman's constant (= 0.41); and

NLB_χ and NLB_ϕ are depth-means of the non-linear and buoyancy terms held constant through the depth mean solution:

$$NLB_\chi = \int_{-1}^0 \left[-L(u) + \frac{uv \tan \phi}{R} - \frac{1}{R \cos \phi} \left(\frac{\partial}{\partial \chi} \left[D \int_0^\sigma b d\sigma \right] - \left[\frac{\partial \zeta}{\partial \chi} + \sigma \frac{\partial D}{\partial \chi} \right] b \right) \right] d\sigma \quad (13)$$

$$NLB_\phi = \int_{-1}^0 \left[-L(v) + \frac{u^2 \tan \phi}{R} - \frac{1}{R} \left(\frac{\partial}{\partial \phi} \left[D \int_0^\sigma b d\sigma \right] - \left[\frac{\partial \zeta}{\partial \phi} + \sigma \frac{\partial D}{\partial \phi} \right] b \right) \right] d\sigma \quad (14)$$

The continuity equation is:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left[\frac{\partial}{\partial \chi} (D\bar{u}) + \frac{\partial}{\partial \phi} (D \cos \phi \bar{v}) \right] = 0 \quad (15)$$

For velocity deviations from the depth mean, $u_r = u - \bar{u}$, $v_r = v - \bar{v}$:

$$\begin{aligned} \frac{\partial u_r}{\partial t} = & -L(u) + f v_r + \frac{uv \tan \phi}{R} - \frac{1}{R \cos \phi} \left(\frac{\partial}{\partial \chi} \left[D \int_0^\sigma b d\sigma \right] \right. \\ & \left. - \left[\frac{\partial \zeta}{\partial \chi} + \sigma \frac{\partial D}{\partial \chi} \right] b \right) + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(A \frac{\partial u}{\partial \sigma} \right) + \frac{1}{D} F_B - NLB_\chi \end{aligned} \quad (16)$$

$$\begin{aligned} \frac{\partial v_r}{\partial t} = & -L(v) - f u_r - \frac{u^2 \tan \phi}{R} - \frac{1}{R} \left(\frac{\partial}{\partial \phi} \left[D \int_0^\sigma b d\sigma \right] \right. \\ & \left. - \left[\frac{\partial \zeta}{\partial \phi} + \sigma \frac{\partial D}{\partial \phi} \right] b \right) + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(A \frac{\partial v}{\partial \sigma} \right) + \frac{1}{D} G_B - NLB_\phi \end{aligned} \quad (17)$$

The equation for salinity S is:

$$\frac{\partial S}{\partial t} = -L(S) + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(K \frac{\partial S}{\partial \sigma} \right) \quad (18)$$

and a similar equation for temperature T :

$$\frac{\partial T}{\partial t} = -L(T) + \frac{1}{D^2} \frac{\partial}{\partial \sigma} \left(K \frac{\partial T}{\partial \sigma} \right) \quad (19)$$

S and T are linked to give buoyancy b by an equation of state $b = b(T, S)$ (Gill 1982).

It should be noted that in these tide-only simulations, buoyancy terms are omitted, S and T are held constant and there is no advection of S or T . The water column is assumed to be temporally and spatially homogeneous.

A turbulence closure scheme is used, based on the Mellor-Yamada "level 2.5" turbulent energy model (Mellor & Yamada, 1974), with algebraic mixing lengths as described by Galperin *et al.* (1988). This scheme includes turbulent kinetic energy as a prognostic variable. The scheme gives better results than the previously used Richardson number scheme, particularly in the depth and sharpness of the seasonal thermocline. The flux of turbulence from surface wave breaking is included through the Craig & Banner (1994) formulation. A small value of background viscosity is chosen to be $10^{-5} \text{ m}^2\text{s}^{-1}$ to allow for diapycnal mixing. Horizontal viscosity and diffusion is included, based on the Smagorinsky shear-dependent formulation described by Oey (1998).

An important component of the numerical solution is the advection scheme. In shallow seas with strong tidal advection, numerical diffusion can be excessive and erode the density structure (James 1986). For long time integrations such as those envisaged with this model (>1 year) a feature-preserving scheme is vital to the model's success. We adopt the PPM (piecewise parabolic method) scheme (Colella & Woodward 1984). This method ensures conservation and positivity, has excellent feature preserving properties (James 1996) and is not limited by a vertical CFL condition (James 2000).

On the open sea boundaries the model uses a "radiation" condition to prescribe the forcing. This takes the form:

$$q - (q_T + q_M + q_D) = (c/H)(\zeta - (\zeta_T + \zeta_M + \zeta_D)) \quad (20)$$

where :

$$c = \sqrt{gH}$$

This allows depth-averaged tidal current and surface elevation (q_T, ζ_T), meteorological driven motion (q_M, ζ_M) and density driven motion (q_D, ζ_D) to be input, whilst allowing internally generated gravity waves to propagate out of the model domain. Such a radiation scheme has been used highly successfully in tide and storm surge models (Flather *et al.* 1991). On closed boundaries there is no normal flow. It should be noted that meteorological terms (M) and density driven terms (D) are not included in these simulations. Tidal forcing is derived from a set of tidal constituents (15) specified around the open boundaries of the domain (shown in Figure B13) from the NS3 model, i.e.

$$\zeta_T(s, t) = \sum_i f_i H_i(s) \cos(\omega_i t - G_i(s) + U_i + V_i) \quad (21)$$

where :

- t = time,
- H_i = amplitude of the tidal elevation constituent i at position $s(\chi, \varphi)$ on the open boundary
- G_i = phase of the tidal elevation constituent i at position $s(\chi, \varphi)$ on the open boundary,
- ω_i = the phase speed of tidal constituent i ;
- V_i = phase at time t_0 relative the Greenwich, and
- f_i & U_i = nodal corrections for the 18.6 year nodal variation.

The depth-averaged q_T is given in a similar manner. Values of H and G for both ζ_T and q_T are obtained from a larger area Atlantic Margin Model (AMM). The AMM is run operationally at the Met Office and :

- Covers the north-west European continental shelf and much of the shelf break to the west of the British Isles;
- Has a resolution of $1/9^\circ$ latitude and $1/6^\circ$ longitude;
- Is fully baroclinic with prognostic temperature and salinity, representing dynamical processes both on the shelf and in deeper water;
- Has a state-of-the-art piecewise parabolic advection scheme to preserve strong gradients and minimise diffusion, even with advection over many tidal cycles;
- Is driven by hourly winds and pressures, and three-hourly heat fluxes from the Met Office mesoscale model;
- Uses sigma (terrain-following) vertical co-ordinates with 14 model levels;
- Includes tidal forcing (15 harmonic constituents) at Atlantic boundaries; and
- Takes freshwater inputs from 47 sources (rivers and the Baltic).

The data from the AMM are interpolated on to the HRCS open boundary points. Tide generating forces (the 'equilibrium tide') are not directly included in HRCS simulations because the waters on the shelf are only affected by these forces to a second order. The forces are included, however, in the AMM which produces the open boundary forcing for HRCS.

At the sea surface heat and salt (precipitation-evaporation) fluxes may be prescribed via bulk formulae or obtained directly from an atmospheric model but, in these barotropic simulations, are not input. At the sea bed there is zero heat and salt flux. Likewise, rivers may be represented as a freshwater inflow having a given volume flux at a given salinity extending over a given depth but these are not included in the tidal simulations.

The equations are solved in finite difference form on an Arakawa B grid. James (1986) has shown that the B grid (Figure B14) has superior properties for the preservation of sharp fronts, because there is less numerical diffusion introduced at the velocity points than with the more usually adopted C grid. An explicit, forward-time, centred-space scheme is used to solve the momentum and scalar equations, with an implicit (Crank-Nicholson) solver for vertical diffusion. A full description of the hydrodynamic model can be found in Holt & James (2001).

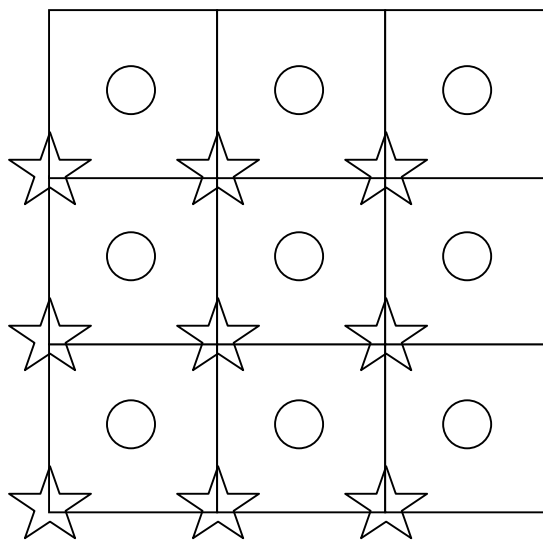


Figure B14. B-grid schematisation: locations of depth and surface elevation points (o), east (u) and north (v) velocity points (star)

The model code has been parallelised (using Message Passing Interface (MPI-1) processes) to run efficiently on a range of machines such as the Cray T3E, SG Origin 3800, the SGI Altix 3700, the IBM pSeries 690 *Regatta* (HPCx), and the POL Cluster Computer (where the model runs were carried out). The hydrodynamics provide the framework for POLCOMS (the Proudman Oceanographic Laboratory Coastal Ocean Modelling System, www.pol.ac.uk/home/research/polcoms), a multi-disciplinary modelling system including hydrodynamics, sediment dynamics, ecosystem dynamics and lagrangian particle tracking. Aspects of the system's performance can be found in Ashworth *et al.* (2002) and studies of physics, ecosystem and sediment dynamics are described in {Holt *et al.*, (2001), Holt and Proctor (2003)}, {Allen *et al.* (2001), Holt *et al.* (2004)} and Proctor *et al.* (2001) respectively.

B3.1 References

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B4. Tidal Model Validation

B4.1 Tidal Elevations

Six tidal components, representing the more important tidal components, have been selected for assessment here, these are the diurnal constituents O_1 and K_1 , semi-diurnal constituents N_2 , M_2 , S_2 and quarter-diurnal constituent M_4 . These are compared against data contained within the BODC which consists of 257 coastal and offshore tide gauges and 278 current meter instruments.

Figure B15 shows the comparison between the amplitudes of the BODC and model datasets for these six components. The scatter plots show model and observed values together with a line of perfect agreement and show that the model is generally in good agreement with the observed tidal constituents. This is further supported by the mean and root mean square (RMS) differences (shown above each plot and provided in Table B3). The greatest discrepancy is in the Bristol Channel where the observed high tidal range is overestimated by the model, most noticeably in the M_2 . More scatter is noticeable in the higher harmonic M_4 indicating, probably, the highly local nature of the generation mechanism of this constituent.

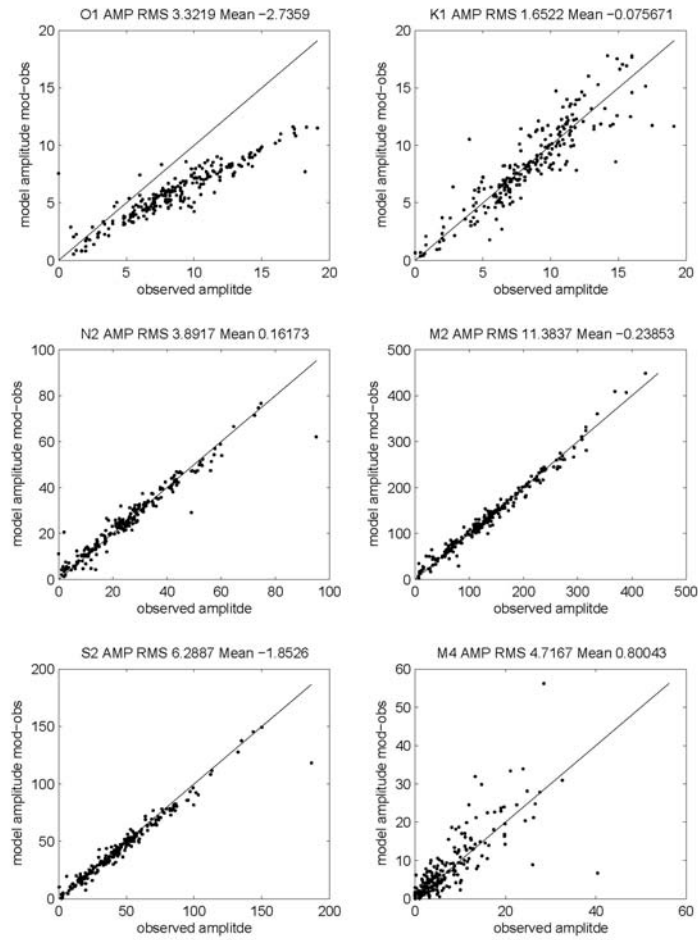


Figure B15. Scatter plots of model vs. observed tidal amplitudes (cm)

Table B3. Error statistics for the tidal elevations

Constituent	Amplitude (Run 005) (cm)		Amplitude (Run 011) (cm)		Phase (Run 005) (degrees)		Phase (Run 011) (degrees)	
	RMS	Mean	RMS	Mean	RMS	Mean	RMS	Mean
O ₁	2.1	-1.5	3.3	-2.7	19.3	-3.2	19.4	3.5
K ₁	2.0	0.8	1.7	-0.1	30.6	-9.3	31.8	-10.7
N ₂	4.2	0.8	3.9	0.2	27.7	-3.7	29.1	-4.3
M ₂	15.1	4.8	11.4	-0.2	25.1	5.7	15.9	-1.0
S ₂	6.7	2.4	6.3	-1.9	22.9	-3.0	22.2	-4.0
M ₄	5.4	1.8	4.7	0.8	71.8	22.2	67.4	16.8

Figure B16 shows similar scatter plots for the phase of the tidal constituents and the error statistics are also given in Table B3. These indicate small phase errors.

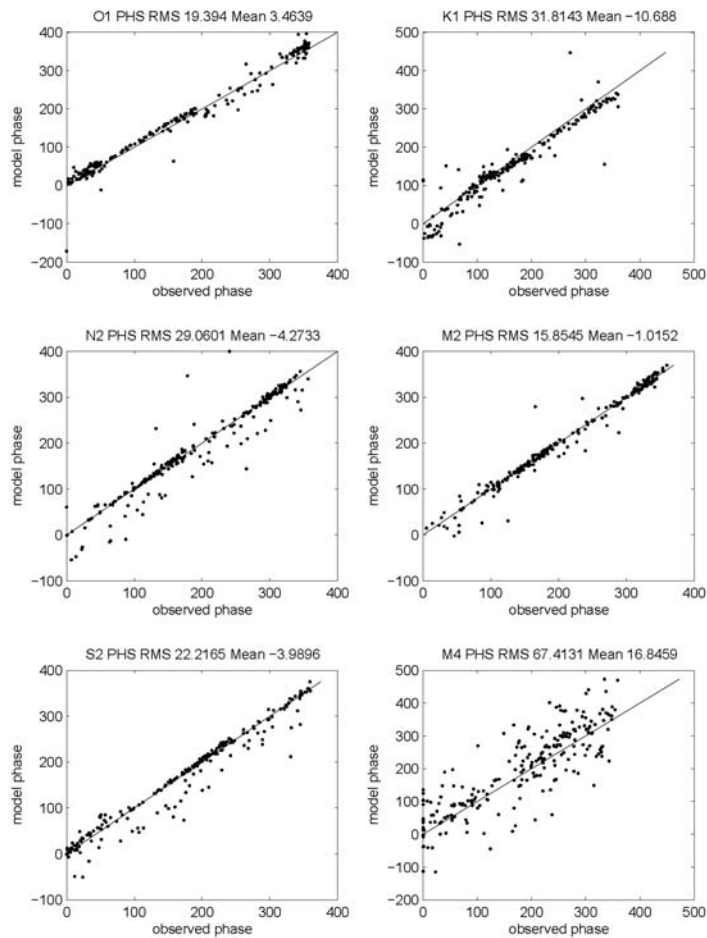


Figure B16. Scatter plots of model vs. observed tidal phases (degrees)

To indicate the spatial error variability, Figure B17 shows the error between the model and observed in M_2 amplitude and phase for all the available data points. This figure clearly indicates the overall good agreement between observed and computed tidal elevations over the UKCS.

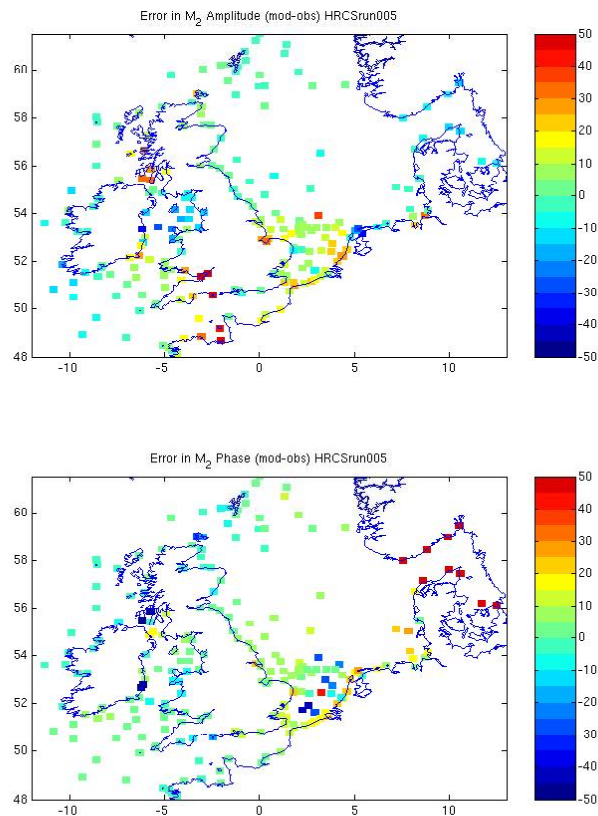


Figure B17. Spatial distribution in differences (model - observed) for M_2 amplitude (cm, upper) and phase (degrees, lower)

B4.2 Tidal Currents

For the tidal currents, all 278 available BODC current meter data were extracted and compared with modelled currents. A subset of these comparisons is provided here.

Figure B18 shows the model and observed differences in speed and direction for the semi-major component of the M_2 tidal ellipse. This was calculated for the uppermost (i.e. the highest above the sea bed) current meters. Where a current meter mooring consisted of one instrument this was used whilst if there was more than one instrument on a mooring, the upper most was used. Therefore, it is the errors in the strongest tidal currents that are shown, as in general tidal currents become weaker closer to the sea bed. It is shown that the model has, in general, small errors in both speed and direction, when compared to the BODC observations.

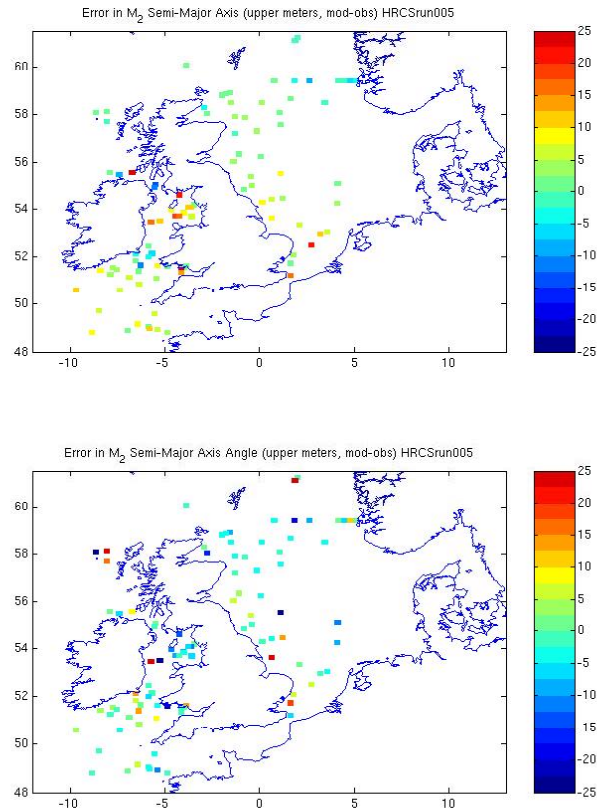


Figure B18. Spatial distribution in differences (model - observed) for speed (cm/s, upper) and direction (degrees, lower) of M₂ semi-major axis of tidal ellipse

A statistical analysis has also been carried out. Table B4 shows the mean and RMS differences between the model and observed semi-major axis of the tidal ellipse for the same six constituents presented in the tidal elevation comparison.

Table B4. Error statistics for tidal current speed (cm/s)

Constituent	Speed (cm/s) – Run 005		Speed (cm/s) – Run 011	
	RMS	Mean	RMS	Mean
O ₁	0.71	-0.36	1.09	-0.75
K ₁	1.07	0.09	1.23	-0.18
N ₂	2.00	0.25	1.89	0.19
M ₂	6.85	2.18	5.74	1.16
S ₂	2.83	1.02	2.10	-0.02
M ₄	1.25	0.13	1.11	-0.06

Figure B19 shows the model vs. observed scatter plots for this parameter. This plot differs slightly in construction to the scatter plots of tidal elevation.

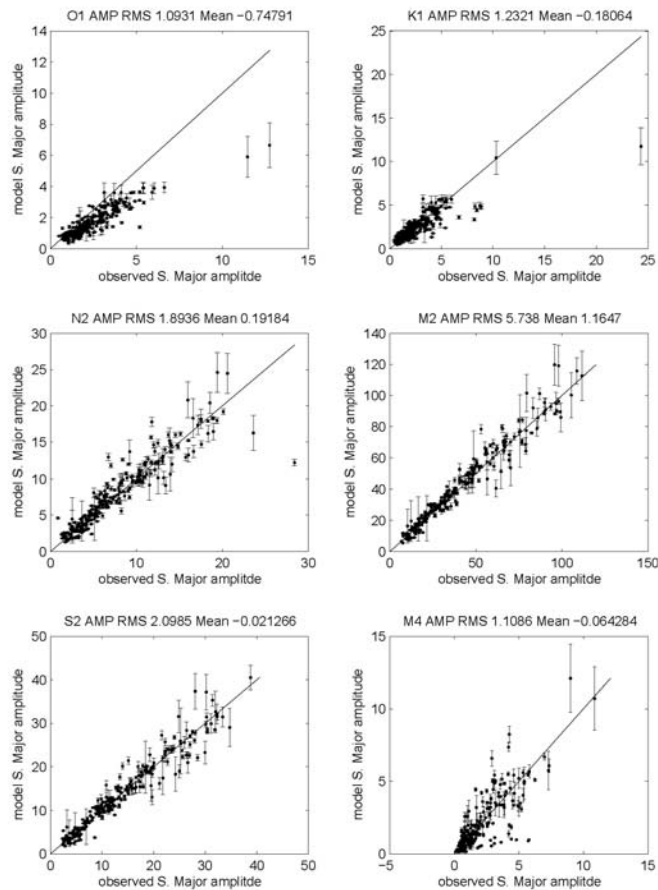


Figure B19. Plots of model vs. observed semi-major axis tidal current speeds (cm/s)

Here, to give some indication of the tidal current variability (which are expected to be greater than for the tidal elevations due to the larger influence of topography/bathymetry on the current structure) a mean model semi-major axis current speed and a model standard deviation for a 12 km x 12km area surrounding the current meter location has been calculated, for each observation point (k):

$$\text{mean } s\text{-}m \text{ axis}_k = \frac{1}{M} \sum_{i=-3}^3 \sum_{j=-3}^3 s\text{-}m \text{ axis}_{k-(i,j)} \quad (22)$$

where

i = east-west element;
 j = south-north element.

In open water, $M = 7 \times 7 = 49$. Elements within the search area that are on land are omitted and M is reduced accordingly.

$$\text{standard deviation} = \sqrt{\frac{1}{M-1} \sum_{i=-3}^3 \sum_{j=-3}^3 (s - m \text{ axis}_{k-(i,j)} - \text{mean } s - m \text{ axis}_k)^2} \quad (23)$$

Therefore, for each point in the scatter plot there is a model mean value and a standard deviation error bar which indicates the range of the modelled current within the 12km square box. It is clear that for most tidal components the model is, in general, in good agreement with the observations. The spread, which in general increases with current speed, shows the variability due to bathymetry which might be expected within a 12km square box, indicating the care which should be exercised when comparing observed data with model data.

Appendix C

Wind

Appendix C. Wind

C1. Description of Met Office NWP Model

Wind data provided to the project are generated from the Met Office's Numerical Weather Prediction (NWP) system, at the heart of which is the Unified Model. An understanding of the source of this data is important so that both its strengths and weaknesses can be properly understood.

This model forms the basis of all forecasts issued by the Met Office. It should though be noted that in the majority of operational forecasts this raw model output is further refined. This is achieved by the application of a more site-specific model or by a forecaster with their knowledge of the particular location and how the model is likely to perform in the present atmospheric conditions. For example, when forecasting for wind farms, a forecaster would be used to modify upwards the wind-speeds to allow for the exposed nature of that location compared to the average provided by the raw model output.

The atmospheric component of the Unified Model is grid-point based and uses a regular latitude-longitude grid in the horizontal. Data used in the Atlas analysis originate from two of the Met Office's operational configurations of its Unified Model (Figure C1.1), which are resolved spatially at a Global Model scale and as a Mesoscale Regional Model. Prior to December 2005, the Global Model had a horizontal resolution of 0.8333° longitude and 0.5555° latitude giving an approximate resolution of 60km in mid-latitudes. There were 30 vertical levels with humidity calculated on the lowest 27 levels (Table C1.1). Post December 2005 Global Model horizontal resolution changed to 0.5625° longitude and 0.375° latitude (approximate resolution of 40km in mid-latitudes), and vertical resolution increased to 50 levels. The Global Model is used to provide boundary conditions to a Mesoscale Atmospheric Model, which is a regional model. Prior to November 2006 the model region was centred on the United Kingdom, and post November 2006 was expanded to a North Atlantic European domain. This model has a resolution of 0.11° latitude by 0.16° longitude, which equates to approximately 12km. This model has 38 levels in the vertical with additional levels in the boundary layer to provide extra detail for forecasting over the land. The higher-resolution Mesoscale Model covers the majority of the Atlas domain.

Table C1. Details of the numerical schemes

Model	Horizontal Resolution	Horizontal Grid EW x NS	Vertical Levels
Global (pre Dec 2005)	$0.8333^\circ \times 0.5555^\circ$ (approx. 60km)	432 x 325	30
Global (post Dec 2005)	$0.5625^\circ \times 0.375^\circ$ (approx. 40km)	961 x 640	50
UK Mesoscale (pre Nov 2006)	$0.111^\circ \times 0.166^\circ$ (approx. 11 km)	146 x 182	38
NAE Mesoscale (pre Nov 2006)	$0.111^\circ \times 0.166^\circ$ (approx. 11 km)	432 x 320	38

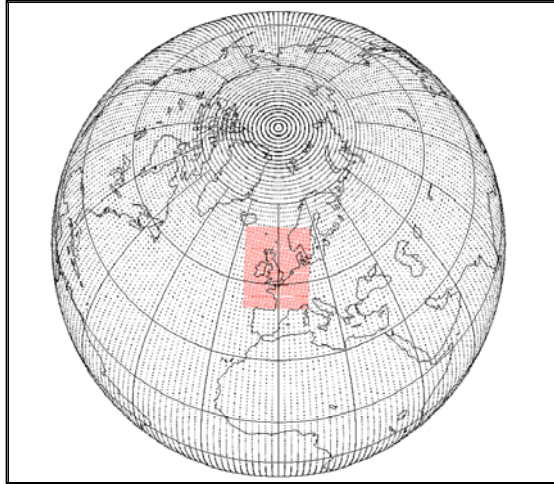


Figure C1. The grids used by the Global (grey) and UK (red) forecast systems

The vertical levels within the numerical models are arranged in a hybrid system. The lower levels are based upon sigma levels, i.e. the ratio of pressure to surface pressure such that they closely follow the ground terrain. The upper levels are pressure levels (Figure C2).

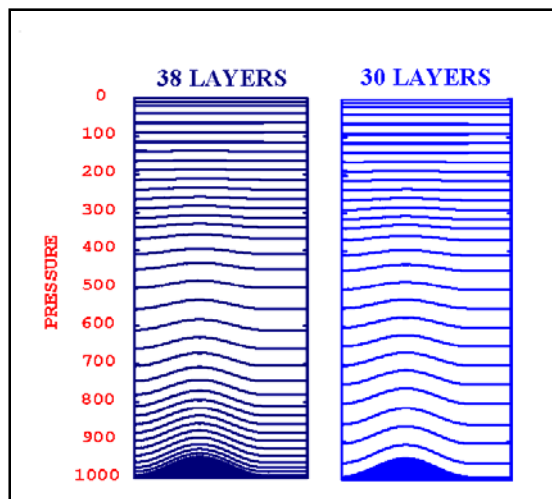
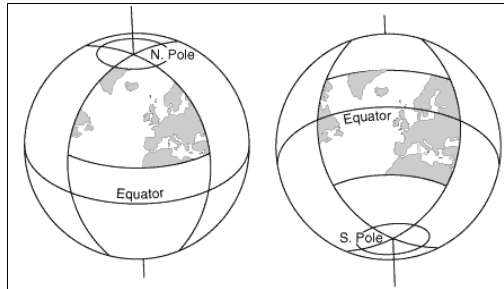


Figure C2. The distribution of levels used in the pre December 2005 Global (right) and UK Mesoscale (left) configurations

In the Mesoscale Model the grid's North Pole is not located at the geographical North Pole but is rotated to 37.5°N 177.5°E (Figure C3). This therefore places the UK near the equator allowing a fairly uniform horizontal resolution to be obtained over the area of interest, i.e. the UK.



- Left: An example of a limited area grid with boundaries defined by lines of actual latitude and longitude, with grid-points converging polewards.
- Right: The limited area grid rotated to place the area of interest near the equator. Thus the grid boxes are a more uniform dimensions.

Figure C3. Illustration of the location of the North Pole in the UK Waters Model

The boundary conditions for Mesoscale Model are provided by Global Model fields interpolated onto the Mesoscale Model co-ordinates. These are applied to the outermost points around the Mesoscale Model grid.

The primary physical parameters of potential temperature (q), surface pressure (p^*) and specific humidity (q) are calculated on grid points, and the two horizontal wind components (u,v) are calculated in the centre of the grid boxes. This arrangement of variables is known as the Arakawa 'B' grid (see Figure C4). Collectively these variables are called 'tracers' as they are calculated at every stage of a model run.

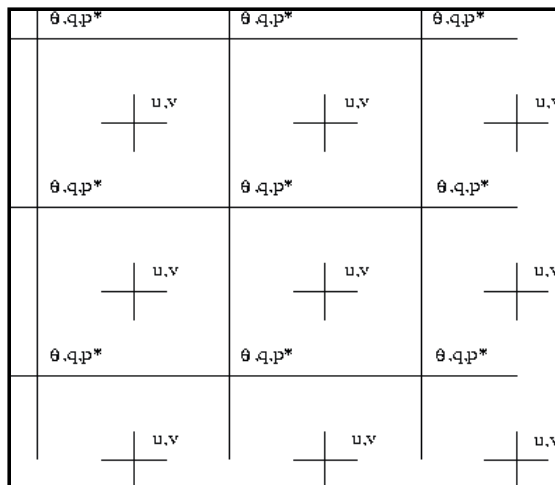


Figure C4. The Arakawa B grid

Potential Temperature (θ), surface pressures (p) and specific humidity (q) are calculated at a grid point and the horizontal wind components (u,v) are calculated at the centre of the grid boxes.

The atmospheric prediction uses a set of equations that describe the time-evolution of the atmosphere. The equations are solved for the motion of a fluid on a rotating, almost-spherical planet. The main variables are the zonal (latitudinal) and meridional (longitudinal) components of the horizontal wind, potential temperature and specific humidity. To solve the system of equations, a number of approximations or assumptions have to be made.

In common with most other atmospheric models, the Unified Model's atmospheric prediction scheme is based on the hydrostatic primitive equations. This means that the model atmosphere is always in hydrostatic balance such that there are no vertical accelerations. Other atmospheric models make the shallow-atmosphere approximation which derives its name from the fact that the depth of the atmosphere is much smaller than the radius of the Earth. The Unified Model does not make this assumption. This makes the equations a little more complicated to solve by adding in extra terms which can be important when planetary-scale motions are considered.

The physical processes represented in the Unified Model include:

- Atmospheric radiation which allows for the effects of clouds, water vapour, ozone, carbon dioxide and a number of trace gases;
- Land surface processes including a multi-layer soil temperature and moisture prediction scheme;
- A treatment of the form drag due to the sub-grid scale variations in orography;
- Vertical turbulent transport within the boundary layer;
- Large-scale precipitation determined from the water or ice content of a cloud;
- The effects of convection through a scheme based on the initial buoyancy flux of a parcel of air. It includes entrainment, detrainment and the evaporation of falling precipitation. An explicit treatment of downdraughts is included; and
- The effects of the drag caused by vertically propagating gravity waves is modelled using sub-grid scale orographic variance and known absorption properties of gravity waves.

The representation of these processes within the code determine the evolution of the model-atmosphere as it runs forward in time to produce forecast data. The model requires initialisation and this is termed the 'analysis field'. It is derived from observations (from radar, satellites, ground-based observing sites etc) which are assimilated onto the regular model grid and blended with previous model output to ensure the evolving model atmosphere is not subjected to step-changes as these can introduce instabilities.

The Mesoscale Model is run in this way four times each day (at 0,6,12 and 18hours GMT) and out to 48 hours from the start time. Wind fields from this model are then incorporated into and used to force the UK Waters Wave Model. This step requires a further interpolation of the wind field from the rotated Mesoscale Model grid onto the standard latitude-longitude grid employed by the UK Waters Wave Model. The UK Waters Wind fields form the underlying datasets for analysed performed for this Atlas.

This brief description of the model indicates the large number of i) parameters necessary to model the evolution of the atmosphere during the forecast period (many of which are available as output); and ii) geographical points for which data is available.

C2. Wind Resource Parameters

C2.1 Speed Conversion and Power Calculations

Native wind speed values from the NWP model are provided at 10m above mean sea level. In order to gauge resource in terms consistent with the requirements of wind farm developers, these data were transformed to equivalent hub heights of 80m and 100m.

The transformation was made following guidance in ISO document 19901/1 'Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating conditions', and assuming conditions of neutral atmospheric stability.

In this case, and making the assumption that wind values used in the Atlas represent a 1-hour sustained wind speed, the transformation from the 10m reference wind speed follows the equation:

$$U(z) = U(10) \left[1 + C \ln \left(\frac{z}{10} \right) \right],$$

where:

$U(z)$ is the wind speed at level z metres above mean sea level, and
 C is described by the equation:
 $C = 0.0573 [1.0 + 0.15U(10)]^{1/2}$.

The transformation is wind speed dependent but, as an example, for a 10 m/s wind speed will yield an approximately 18% increase between the 10m and 80m reference levels and a 21% increase for the 100m level.

Offshore wind power density was calculated using previous methods detailed in the European Wind Atlas, (Troen and Petersen, 1989). It represents the average for the time series at each point and as such gives a value of wind power density of the rotor swept area. This parameter is calculated using:

$$P_{\text{wind}} = 1/2\rho V^3$$

where:

P_{wind} = offshore wind power density (kW per metre square of rotor swept area)
 ρ = air density (1.225 kg/m³);
 V = mean wind speed (m/s)

(N.B. this expression is entirely comparable to the equation used to estimate the tidal stream power density. The fundamental change is the density of the respective fluid from water to air).

C2.2 Statistical Analysis of Wind Resource Parameters

To enable a more detailed description of the wind regime a number of standard statistical expressions are provided for wind speed and power density. Statistical values are contained in the Atlas database for further examination.

The analyses were divided into three components:

- Non-directional wind parameters;
- Wind speed distribution statistics
- Directional wave analyses
- Monthly mean time-series

Each set of statistics was defined not only in terms of annual value (using the 7 year period from June 2000 to May 2003) but also at seasonal and monthly timescales (using appropriate data from the data base) in order to express important variations in wave climate occurring during an annual cycle. Specifically these can be described as:

- Non-directional wind speed and power statistics; e.g. mean, median and inter-annual variability of wind speed and power (Table C2). These statistics allow a simple inter-comparison of the bulk differences in wind and wind power climate between sites over the UKCS when visualized in map form. For power, two additional statistics are provided that aim to assess the practicality of exploiting the resource on a year round basis. These are a seasonal variability index that shows the ratio between summer and winter power yields; and a performance index that compares the power estimate for a device that exploits energy for 100% of the time, versus a device that shuts down and yields no power during the lowest 2.5% of events and the highest 2.5% of events.

Table C2. Non-directional wind parameters

Parameter	Mean	Median	Seasonal Variability	Inter-annual Variability	Performance Index
10m wind speed (m/s)	Available	Available	N/A	Available	N/A
10m wind power density (W/m ² of rotor swept area)	Available	Available	Available	Available	Available
80m wind speed (m/s)	Available	Available	N/A	Available	N/A
80m wind power density (W/m ² of rotor swept area)	Available	Available	Available	Available	Available
100m wind speed (m/s)	Available	Available	N/A	Available	N/A
100m wind power density (W/m ² of rotor swept area)	Available	Available	Available	Available	Available

- Wind Speed Distribution statistics. Normalized frequency statistics that show the proportion of time for which a given wind speed class is expected over a prescribed period (Table C3). These values are useful in assessing the amount of time for which wave conditions fall within a given operating range, and may also be useful for comparison of many sites when visualized in map form. It should be noted however, that these data have not been analysed with the intention of providing any form of design statistic and as such are not recommended for this purpose.

Table C3. Wind speed distribution intervals

Wind Speed (m/s)	
<1.0	<14.0
<2.0	<15.0
<3.0	<16.0
<4.0	<17.0
<5.0	<18.0
<6.0	<19.0
<7.0	<20.0
<8.0	<21.0
<9.0	<22.0
<10.0	<23.0
<11.0	<24.0
<12.0	<25.0
<13.0	>25.0

- Directional wind speed and power statistics (Table C4). Unless able to be driven from all directions, wind power devices will be dependent upon waves propagating from a prevailing direction. The statistics in these tables aim to allow assessment of the degree of 'directionality' in the wind climate at given sites. Two statistics are available: the first provides frequency and mean parameter (wind speed and power) information through 12 directional sectors (Table C5); the second is a wind 'rose' showing a distribution of wind speed through 12 directional sectors.

Table C4. Directional wind analyses (using 12 direction sectors)

Parameter	Normalised Frequency	Mean
10m wind speed (m/s)	Available	Available
10m wind power density (W/m ² of rotor swept area)	Available	Available
80m wind speed (m/s)	Available	Available
80m wind power density (W/m ² of rotor swept area)	Available	Available
100m wind speed (m/s)	Available	Available
100m wind power density (W/m ² of rotor swept area)	Available	Available

Table C5. Wind speed rose (using 12 direction sectors)

Parameter	Normalised Frequency			
10m Wind Speed (m/s)	< 5m/s	< 10m/s	< 15m/s	> 15m/s

C3. Validation of the Wind Data

Validation of both wind and wave data aims to assess the following issues:

- Over the defined climate period, does the distribution of wave model data represent a measured spread of wind and sea-state conditions well?;
- Does the sourced data broadly represent long-term variations in wave climate?; and
- Is the performance of the sourced model data better or worse for specific regions of the UKCS?

The validation exercise was undertaken in two parts. To test validity against a measured source and geographic variation in performance, the UK Waters Model and observation time-series data from in-situ wave and meteorological measurement platforms were compared. To determine how the sourced data compare to longer term assessments in the climate over the UKCS the archive of Met Office European Wave Model data was utilised. This data source extends over 15 years, and comparisons were made between the whole 15 year period and the Atlas' specific 7 year analysis period.

C3.1 Comparison Between Met Office UK Waters Model and Observations

A comparison between the UK Waters Wave Model dataset and long term observations from a network of offshore observing platforms has been used to indicate the level of confidence that might be placed in the Atlas at various locations around the UK.

Observation time-series data were selected from sites comprising the Met Office Marine Automatic Weather Station (MAWS) Network (Figure C23) in order to undertake the validation exercise.

These sites provide observations of both marine wind and wave parameters, specifically wind speed (at 10m above sea-level) and wind direction. Locations were chosen to provide a spread of data around the UKCS, and are summarized in Table C6. Where possible the time-series used for comparison have provided a match between model and observed data over the entire 7 years of the Atlas dataset. However, some of the buoys were decommissioned during this period, in which case the analysis period in years is noted in Table C6.

Table C6. Met Office Marine Automatic Weather Station (MAWS) sites used in validation study

Station Name	WMO Number	Station Position		Station Type	Water Depth (Model* m)
		Latitude	Longitude		
K5	64045	59° 04' N	11° 25' W	Buoy	> 200.0
RARH (3 years)	62106	57° 00' N	09° 54' W	Buoy	> 200.0
Aberporth	62301	52° 17' N	04° 30' W	Buoy	31.0
Turbot Bank	62303	51° 37' N	05° 09' W	Buoy	40.0
Seven Stones	62107	50° 04' N	06° 04' W	Lightship	73.0
Lyme Bay (2.5 years)	62101	50° 37' N	02° 44' W	Buoy	33.0
Greenwich	62305	50° 25' N	00° 00' E	Lightship	54.0
K17 (3.5 years)	62026	55° 25' N	01° 10' E	Buoy	69.0
K16 (3.5 years)	62109	57° 00' N	00° 00' E	Buoy	84.0

Five measures for comparison are used:

- Annual mean wind speed;
- Mean in year variability (standard deviation) of wind speed;
- RMS Error for monthly wind speed average;
- Wind speed (V_{10}) and direction (W_d) distributions; and
- Monthly mean wind speed.

The comparison focuses on the 10m wind speed, since this is the base value from which all the wind parameters in the Atlas are derived and the common level at which model and observations are available.

Distributions are presented in Figures C5 to C13. Comparison statistics are provided in Table C7.

Table C7. Annual wind statistics for validation sites

Station Name	V_{10} Mean (m/s)			V_{10} Std. Dev. (m/s)			V_{10} RMS Error (m/s)
	Model	MAWS	% Error ^e	Model	MAWS	% Error ^e	
K5	9.33	7.99	17	4.38	4.22	4	2.95
RARH	9.29	8.07	15	4.51	4.16	8	2.86
Aberporth	7.24	5.60	29	3.91	3.33	17	3.00
Turbot Bank	7.05	6.47	9	3.52	3.51	0	1.96
Seven Stones	8.19	8.61	-5	3.91	4.40	-11	2.02
Lyme Bay	5.02	5.34	-6	2.58	2.79	-8	1.53
Greenwich	7.98	8.43	-5	3.93	4.47	-12	1.93
K17	8.13	7.14	14	3.88	3.50	11	2.43
K16	8.29	6.94	19	4.00	3.56	12	2.01

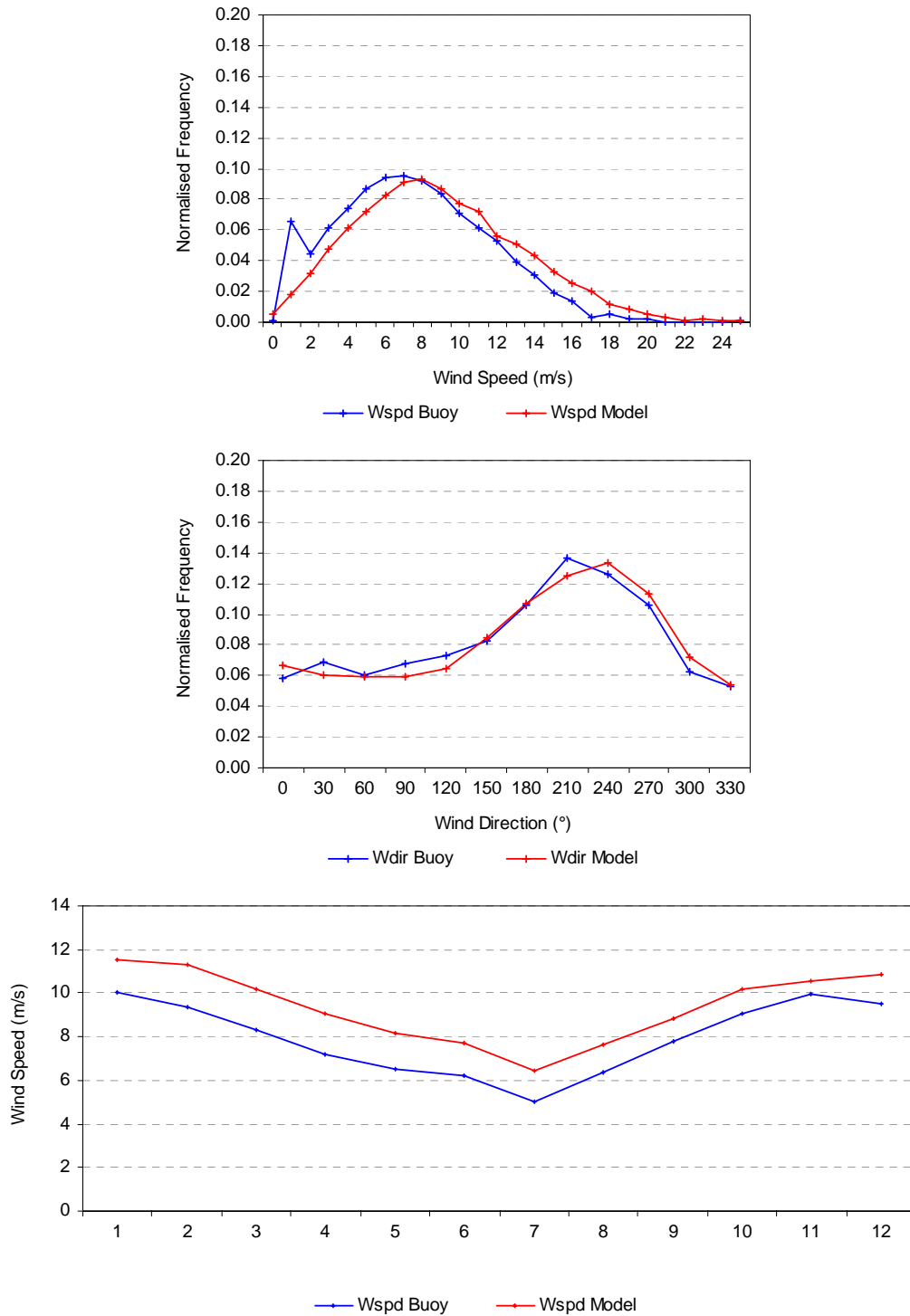


Figure C5. K5 MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

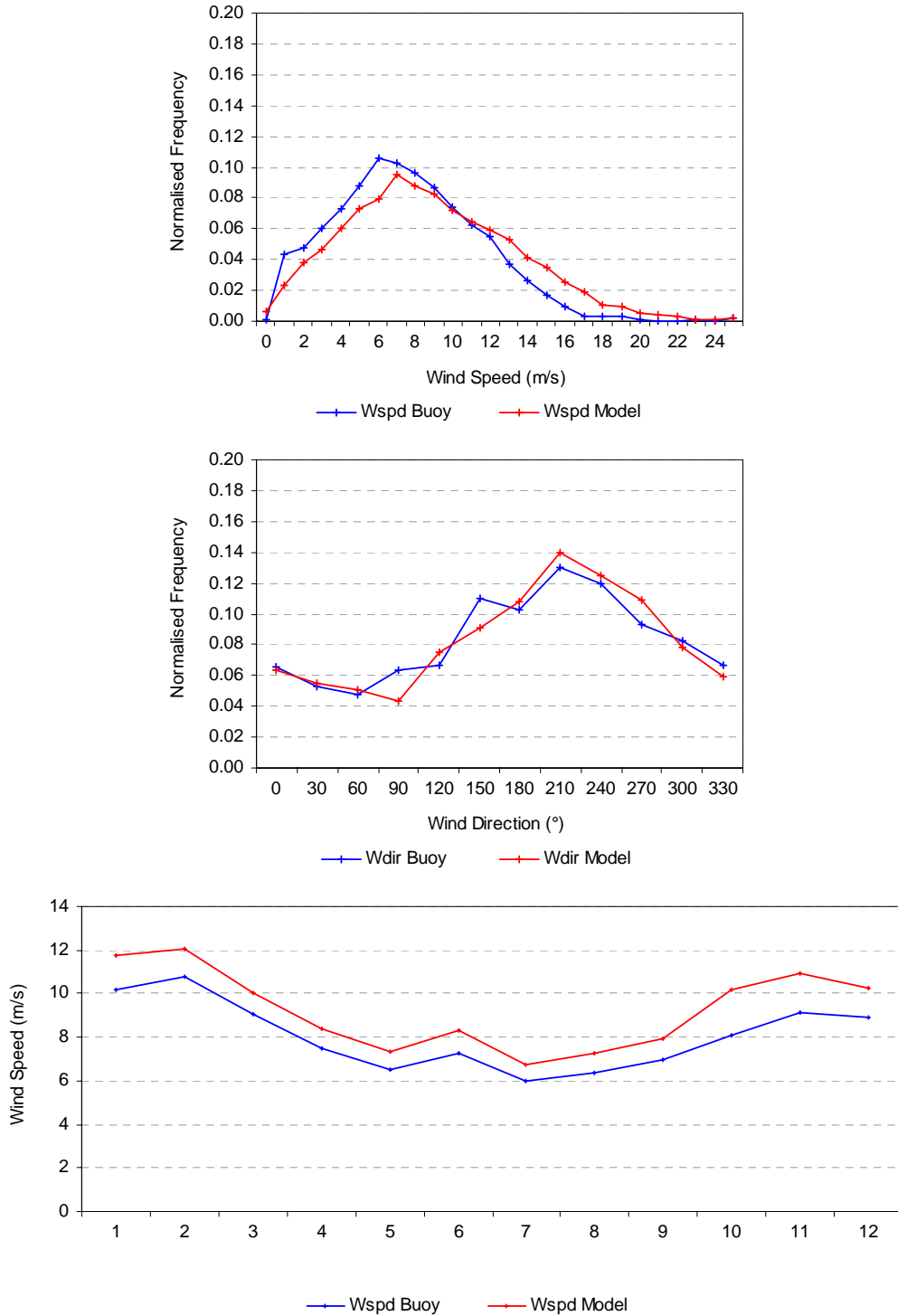


Figure C6. RARH MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

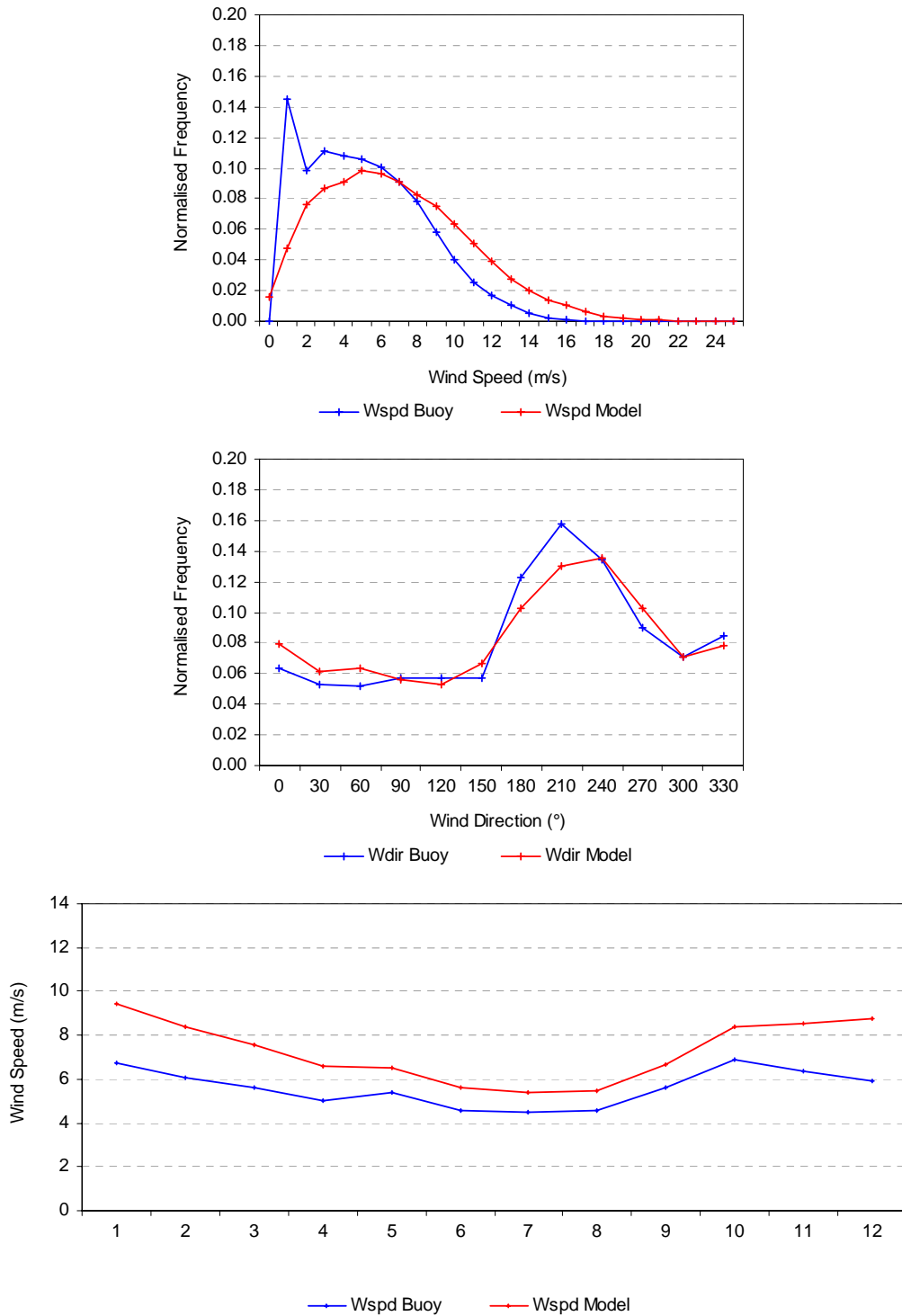


Figure C7. Aberporth MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

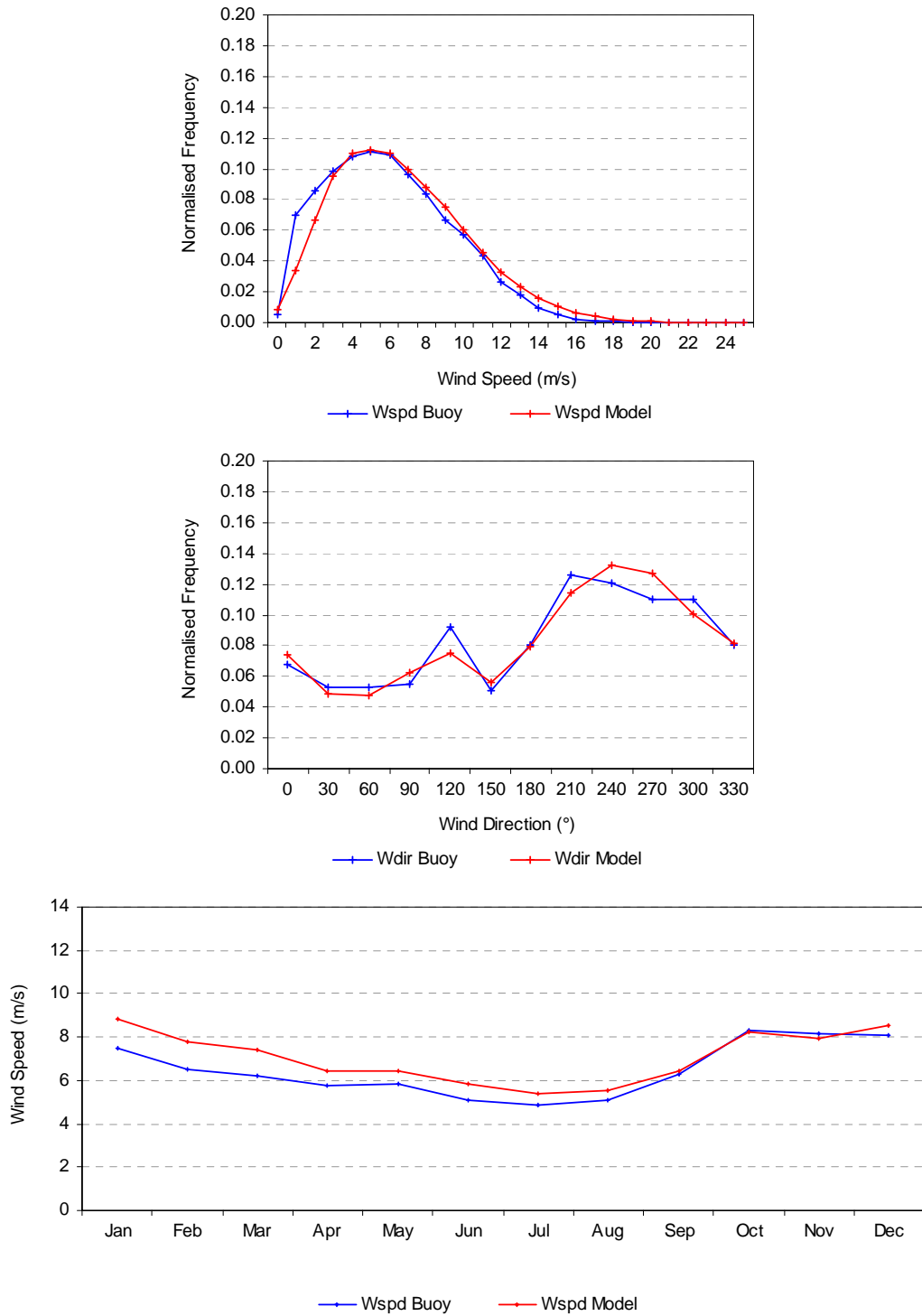


Figure C8. Turbot Bank MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

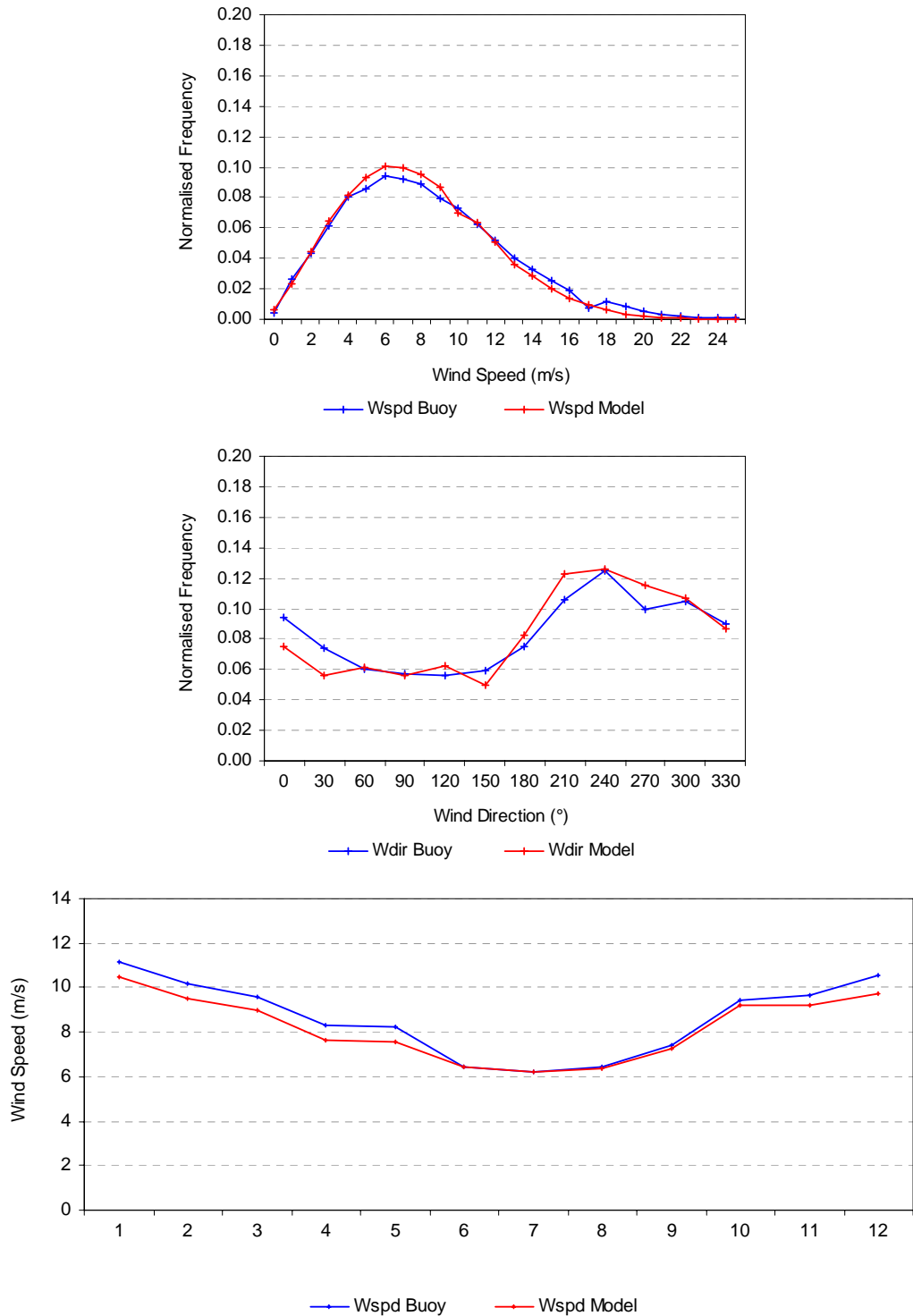


Figure C9. Seven Stones MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

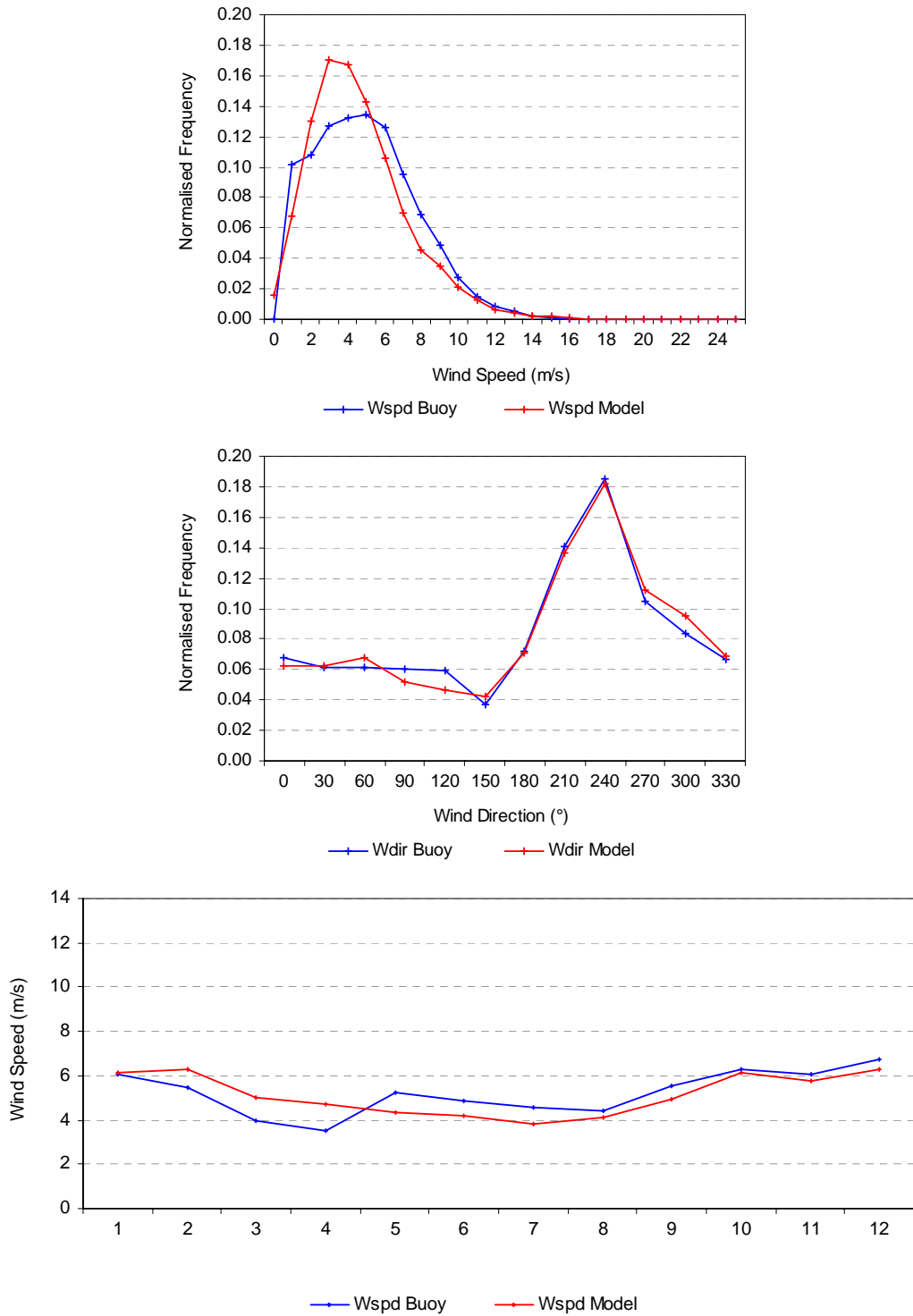


Figure C10. Lyme Bay MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

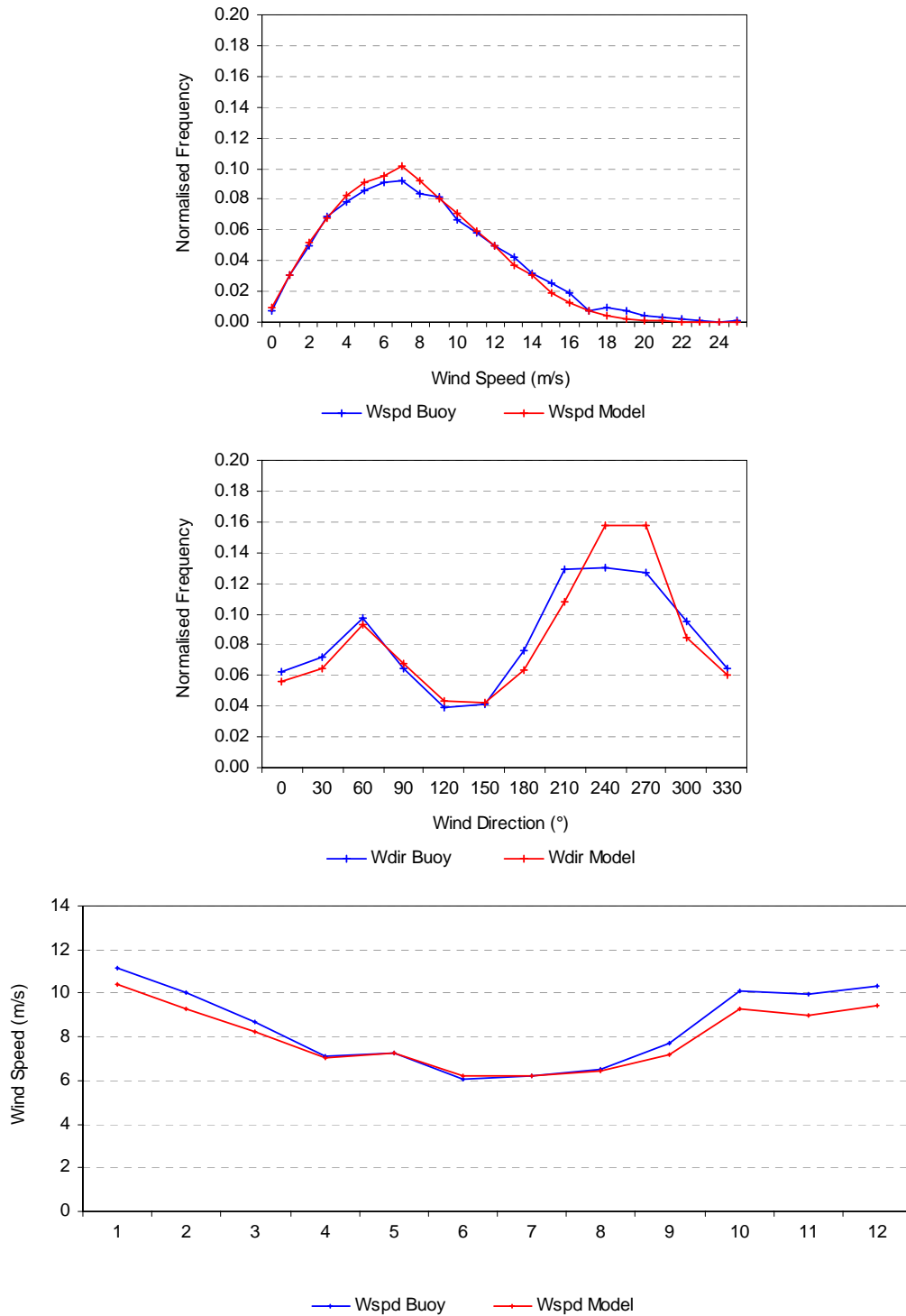


Figure C11. Greenwich MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

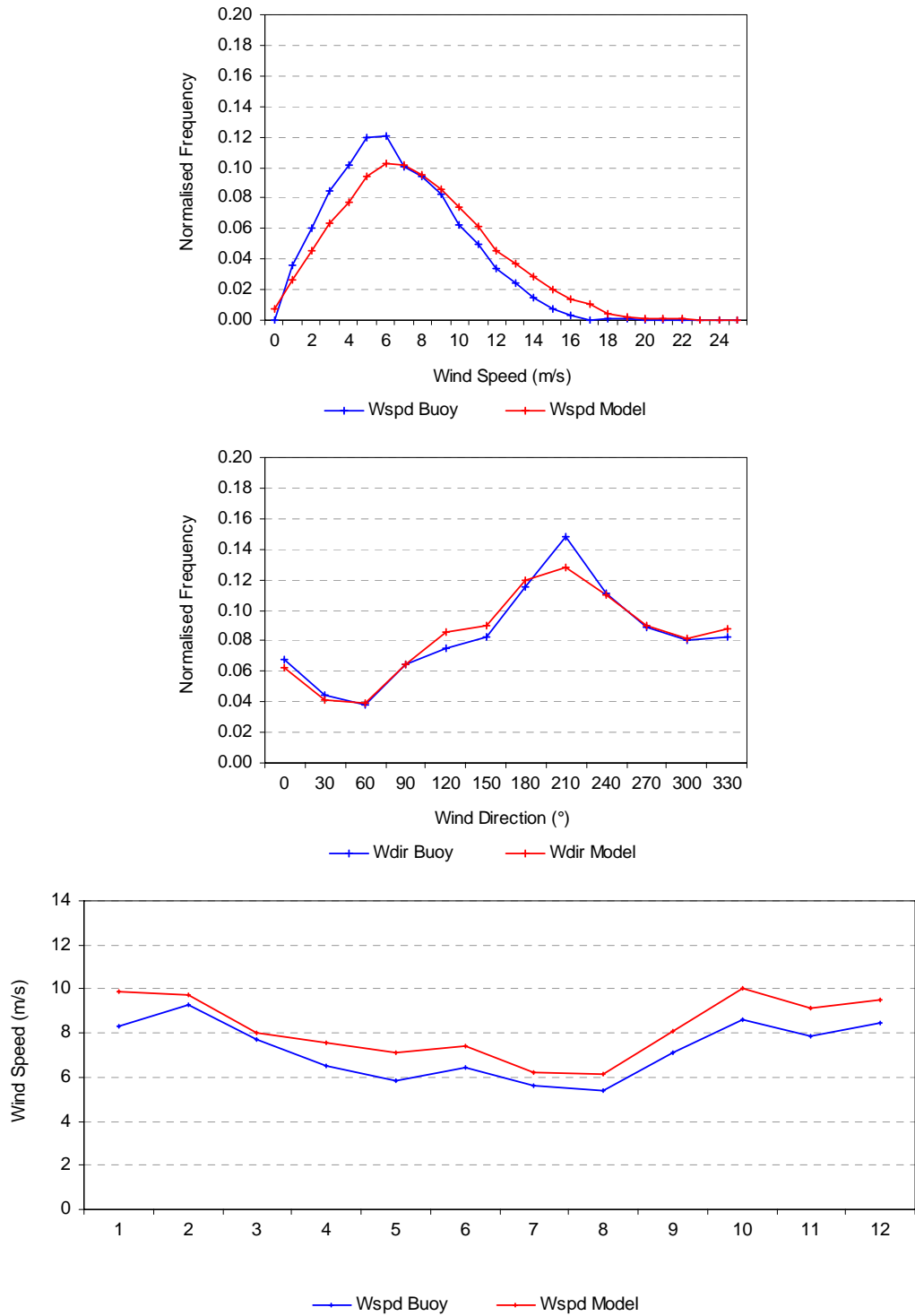


Figure C12. K17 MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

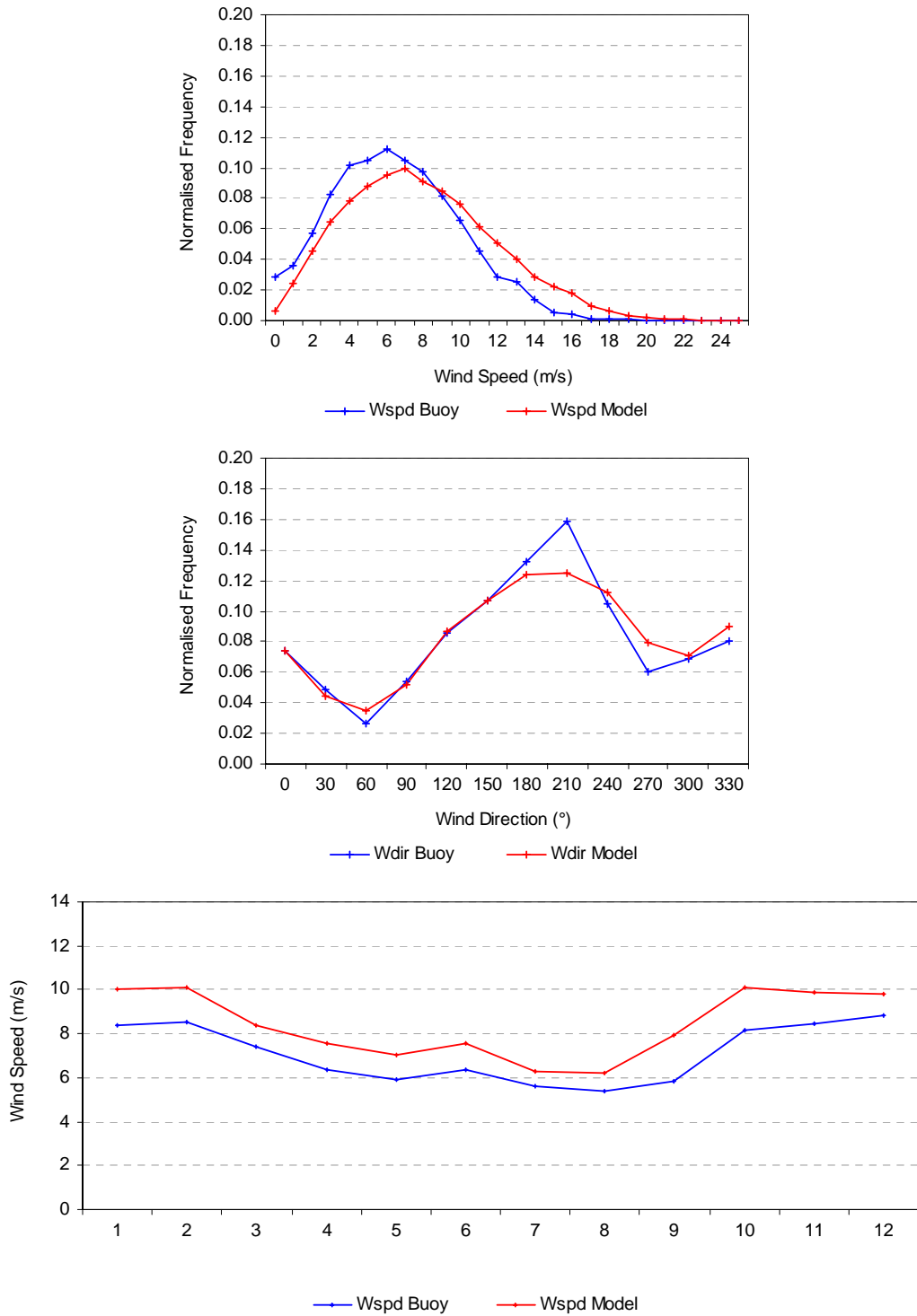


Figure C13. K16 MAWS station modelled and observed: windspeed (V_{10}) and wind direction (W_d) distributions; monthly average wind speed values

Mean wind speeds calculated from the model and the observed data generally show a differential of less than 20% (Table C3). This should be considered relative to measurement errors which could plausibly be of the order 5-10%. Geographically mean errors show a trend where wind speed values are:

- Underestimated for MAWS stations south of 52°N (Seven Stones, Lyme Bay and Greenwich); and
- Overestimated for those stations north of 52°N.

In examining the distributions of wind speed (Figures C5 to C13) the reason for these differences becomes clearer. Model distributions for the northern sites show a higher frequency of wind speeds above approximately 10m/s and a lower frequency of wind speeds below 10m/s when compared to the observations. This suggests a certain systematic overestimate of wind speed at these sites. At Turbot Bank, Seven Stones and Greenwich the match between model and observed wind speed distributions is very close. At Lyme Bay, the wind model is biased toward a high frequency of wind speeds below 10m/s relative to the observations.

Modelled mean in-year variability (the standard deviation of monthly average wind speeds per year) is generally within 15% of the observed value, and shows a similar geographic split. Both model and buoy indicate that the variation within a given year in the sample is high relative to the mean. The differentials between winter and summer month wind speed averages can be seen clearly in the monthly wind speed average plots (Figures C5 to C13) for all the sites. In these plots a systematic overestimate is clear at K5, RARH, Aberporth, K16 and K17.

The RMS error statistic directly compares modelled and observed averages of wind speed over each month in the data sample. RMS errors increase in line with both average wind speed and the geographic tendency for stations north of 52°N to be associated with an overprediction. This suggests that differentials between model and observation are not simply a systematic overestimate at the northern sites, but also contain more random variation than for the southern sites.

The results for Aberporth and Lyme Bay show different behaviours, but are both liable to result from the near coastal locations of these sites. In the case of Aberporth (Figure C7) a systematic overestimate of wind speed is found. At Lyme Bay (Figure C10) wind speeds tend to be underestimated. In both cases, a significant prevailing wind direction is exhibited in the wind direction distributions; for Aberporth this sees the wind blowing from seaward, but with the expectation that some form of protection will be afforded by high relief topography to the south of Cardigan Bay (extending down to St David's Head); for Lyme Bay the prevailing wind direction is from landward. It is likely that the effects of the land in both these coastal zones is not modelled perfectly, leading to too little sheltering in the Aberporth case and too much in the Lyme Bay case.

Concluding from these results:

- In general, the mean offshore wind resource in terms of speed and power should be well enough represented for the purposes of the Atlas, since an agreement in mean wind speed values within 20% was found for all sites except for one near-coastal location.
- The model has shown a tendency to overestimate observed wind speeds at sites in northern areas of the UKCS.
- Differences between model and observed wind speed distributions for stations at Lyme Bay, and Aberporth highlight the difficulties in making an accurate model estimate of wind conditions at this resolution close to land-sea boundaries. As a result it is suggested that in the near coastal zone local effects of topography (which are likely to be well known within region, e.g. by local weather centres/coastguard) be given due consideration and the Atlas data treated appropriately.

C3.2 Short Versus Long Term European Model Comparisons

This analysis compared the Atlas analysis period (7 years, June 2000 to May 2007) with a longer analysis period (15 years June 1992 to May 2007) in order to assess the impact of using a longer time-series. In order to eliminate possible inconsistencies resulting from comparing different model formulations, both the data samples were obtained using data from the Met Office 35km resolution European Wave Model. However, to afford some cross-referencing of this study with the validation of mode performance versus observations, this analysis is tested at the MAWS locations described previously (Figure C23, Table C8).

Table C8. Location of MAWS sites for the European Model

Site Name	Closest European Model Point (deg WGS84)	
K5	59.00'N	11.26'W
RARH	57.00'N	10.06'W
Seven Stones	50.00'N	06.06'W
Turbot Bank	51.50'N	05.26'W
Lyme Bay	50.50'N	02.86'W
Greenwich	50.50'N	00.06'W
Aberporth	52.25'N	04.46'W
K17	55.50'N	01.14'E
K16	57.00'N	00.06'W

The statistics used for comparison comprise:

- Annual mean wind speed;
- Mean in year variability (standard deviation) of wind speed; and
- Wind speed (V_{10}) and direction (W_d) distributions.

Results are presented in Table C9 and Figures C14 to C22.

Table C9. European model archive 15 years versus 7 year 10m wind speed statistics for validation sites

Station Name	V_{10} Mean (m/s)			V_{10} Std. Dev. (m/s)		
	15 year	7 year	% Error ^e	15 year	7 year	% Error ^e
K5	9.06	8.77	3	4.58	4.24	8
RARH	9.42	9.49	-1	4.51	4.38	3
Aberporth	7.59	7.69	-1	3.92	3.91	0
Turbot Bank	8.57	8.76	-2	4.26	4.22	1
Seven Stones	8.26	8.30	0	4.04	3.94	2
Lyme Bay	6.73	6.56	3	3.46	3.29	5
Greenwich	7.37	7.28	1	3.84	3.70	4
K17	8.73	8.75	0	4.35	4.21	3
K16	8.80	8.76	0	4.39	4.21	4

The analysis shows little discernable differences between the 7 and 15 year datasets. All 7 year mean wind speed values fall within 5% of the 15 year value. Wind speed distributions are near identical, although the directional distributions do show small amounts of variation in the prevailing direction at K5, K17 and K16.

To conclude from this section of the analysis, the 7 year time period described by the Atlas for wind resource is unlikely to have led to significantly different results to an analysis based upon a data period of the order 10-20 years. This justifies the trade off between length of time-series and improved accuracy resulting from higher spatial resolution chosen when creating the Atlas.

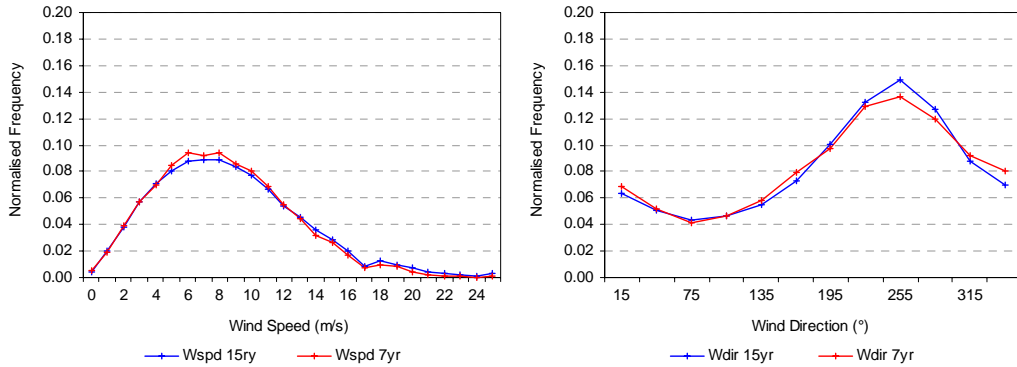


Figure C14. K5 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

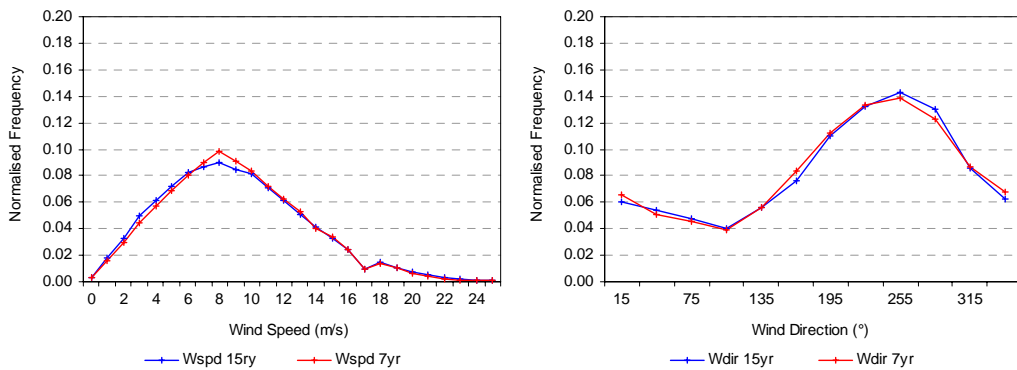


Figure C15. RARH 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

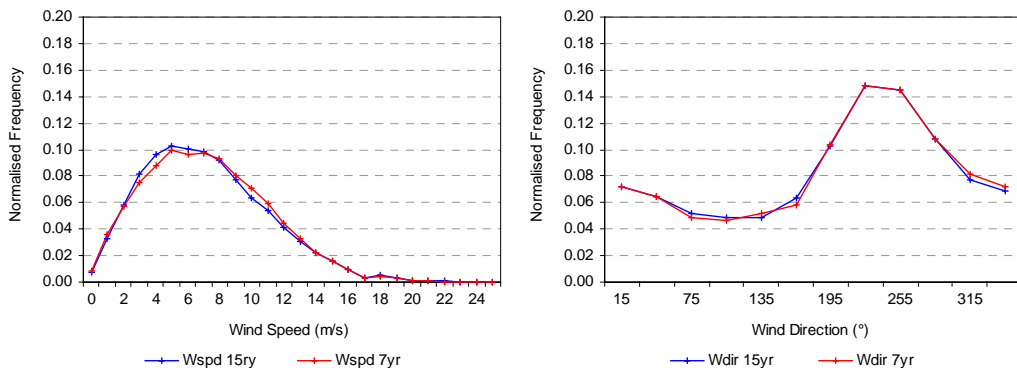


Figure C16. Aberporth 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

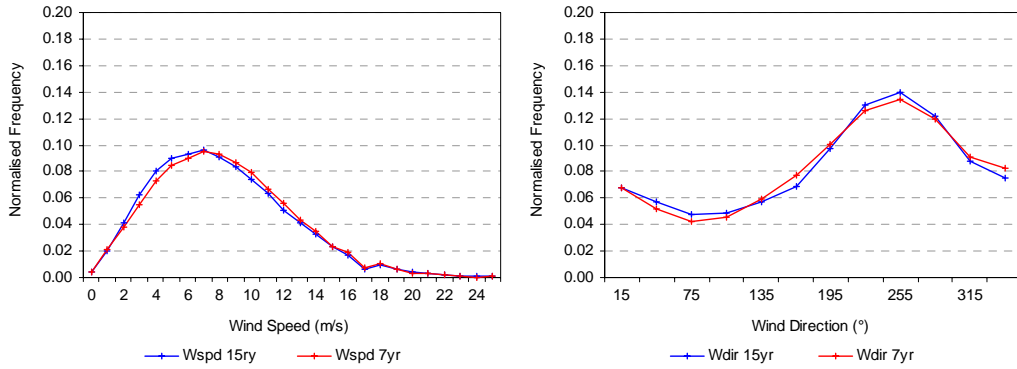


Figure C17. Turbot Bank 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

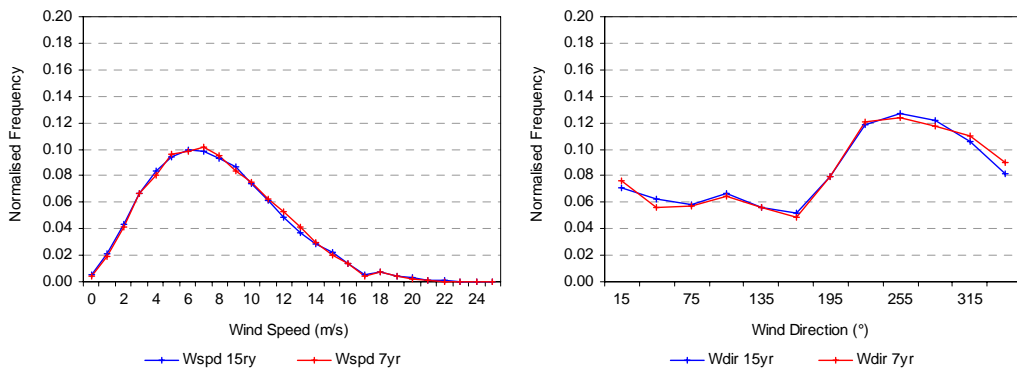


Figure C18. Seven Stones 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

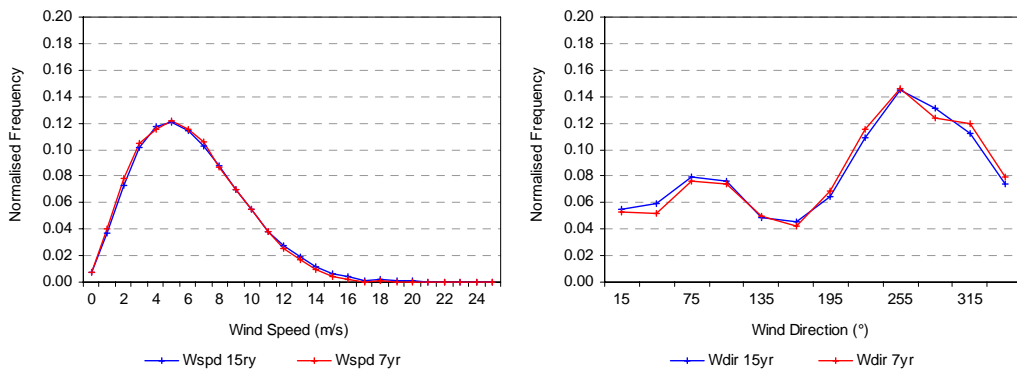


Figure C19. Lyme Bay 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

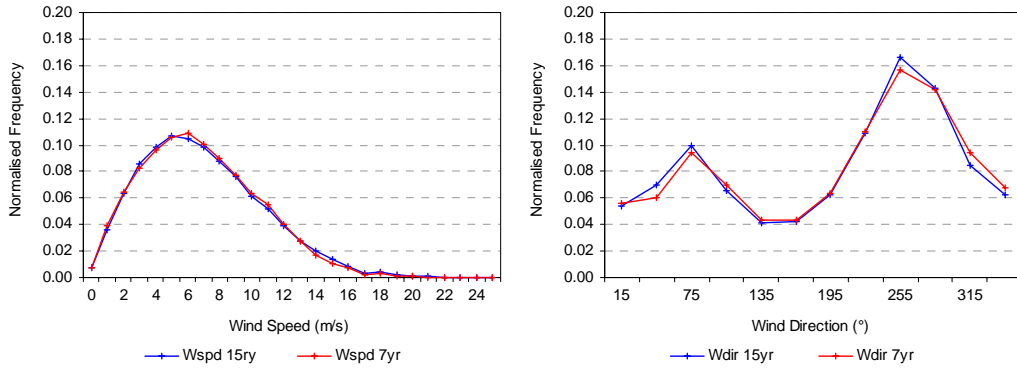


Figure C20. Greenwich 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

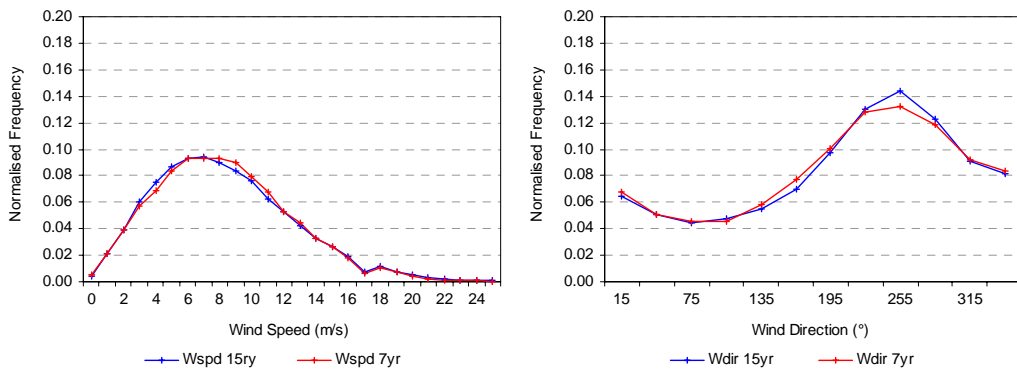


Figure C21. K17 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

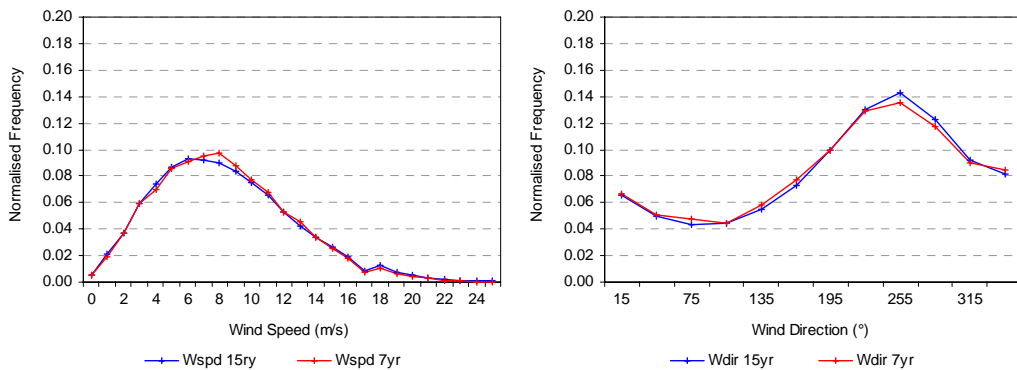


Figure C22. K16 15 year and 7 year European model windspeed (V_{10}) and wind direction (W_d) distributions

C4. Discussion of the Atlas Wind Resource

C4.1 NWP Model Performance

Met Office numerical weather prediction (NWP) models are subject to constant review and development in order to produce a robust and generally highly reliable source of atmospheric data. The models include a highly developed data assimilation scheme; as a result the data used for the Atlas are constrained as much as possible by sound meteorological observations. The UK Waters model archive, from which the Atlas database is sourced, is the highest resolution dataset available as a long term archive.

An important part of the modelling process is day-to-day validation of the model focusing on predictive capacity. For purposes of the Atlas database, this validation study has attempted to provide some insight into the behaviour of a UKCS wide model dataset as an indicator of climatology through some simple data comparisons carried out over a small selection of sites where reliable observed marine data is available. A more complete examination of the model data may well be possible through comparison with existing larger geographical datasets (e.g. from satellite observations) but in terms of time and cost falls outside of the remit of this project. Nevertheless results from this study, allow a valid discussion of the integrity of the Atlas wind resource.

Results of the wind resource validation indicate that in general modelled mean statistics are within 5-20% of the observations. This is a favourable comparison when compared with the likely measurement accuracies. However, the Atlas is subject to some geographical variations in it's reliability; for example, the model data performs best at 'open sea' sites (i.e. away from the near coastal zone), and is subject to greater variability versus observations in the most energetic regions to the north of the domain.

That the model performed best in open seas is not entirely surprising since closer to the coastline effects of the land-sea boundary (for example coastal steering of wind, effects of complex topography not resolved by the model grid) will compromise model performance. The recommendation is to treat the near coastal zone carefully, making full use of available local observations where possible in any decision making. Tools such as WAsP exist, which have been created specifically to assess downscaling effects for wind turbines sited on complex terrains.

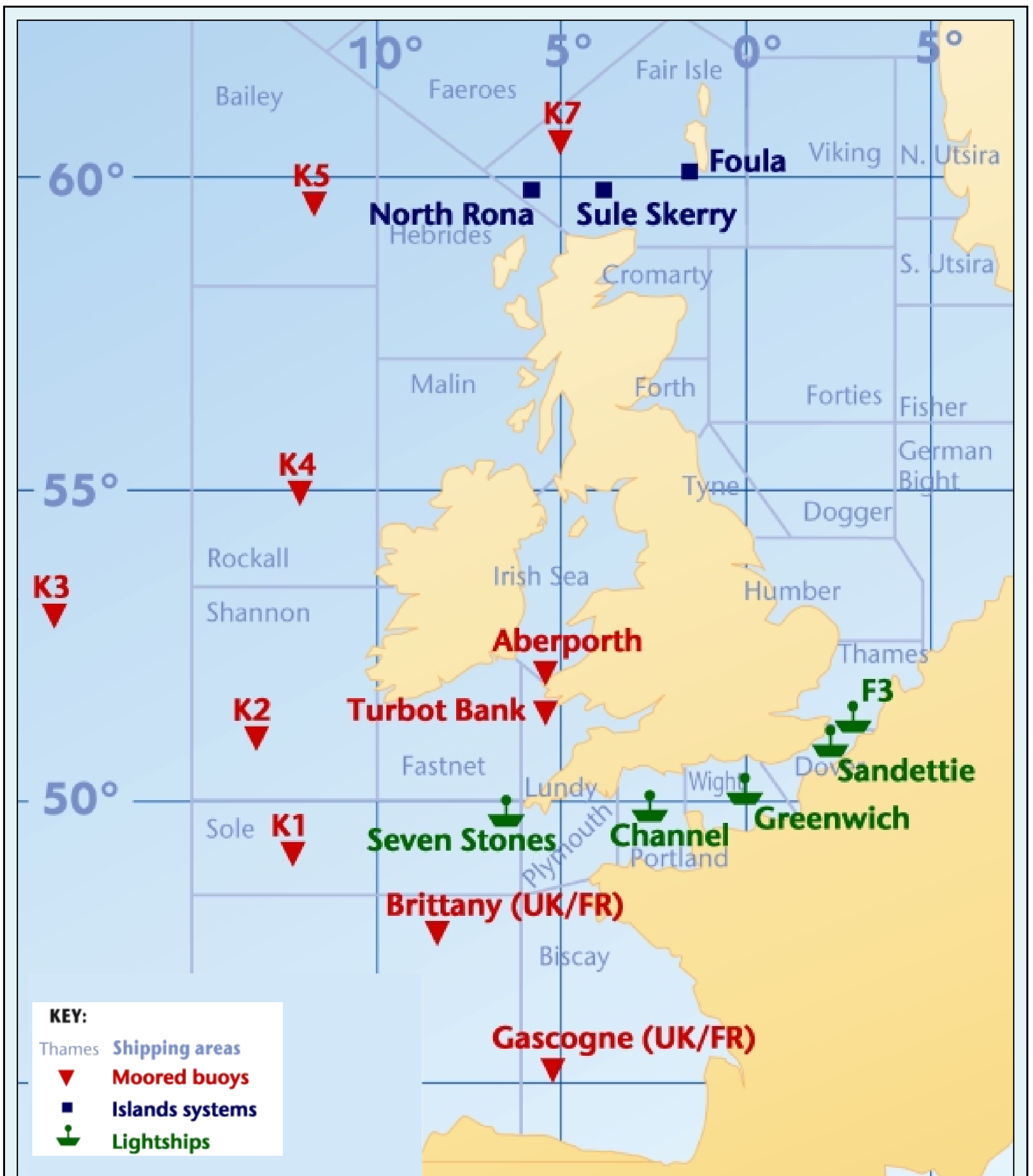


Figure C23 - Met Office Marine Automatic Weather Station Sites

Kilometres

0 50 100 200 300 400

Map Designed and Produced by ABPmer

BERR | Department for Business Enterprise & Regulatory Reform

Atlas of UK Marine Renewable Energy Resources

- Notes
1. Data sourced from the Met Office.
 2. March 2008, Version 2.0.
 3. © Crown copyright, All rights reserved.

Appendix D

Wave

Appendix D. Wave

D1. The Met Office Second Generation Wave Model

The Met Office runs a second-generation (2G) spectral wave model, with both global and nested regional configurations. Spectral models work by calculating the levels of wave energy that can be assigned to a two-dimensional frequency-direction domain (termed the wave spectrum) used to describe motion of the sea-surface under waves (the sea-state). Essentially the spectrum decomposes a given sea-state into a set of constituent sine waves, each with a different direction, period (inverse of frequency) and amplitude (energy).

Field experiments have established families of wave spectra appropriate to different forcing circumstances, and upon which spectral wave models have been based. In the instance of the Met Office 2G model, the spectra used are those derived from the JONSWAP experiment that recorded wave growth over a fetch in the North Sea (Hasselmann, 1973).

From the two-dimensional frequency-direction spectrum standard integrated parameters representing wave conditions are generated (e.g. significant wave height, wave peak and zero-upcrossing period, principal wave direction). With knowledge of wind strength and direction, these integrated parameters can also be assigned to wave field components defined as wind-sea or swell.

D1.1 Summary of the 2G Wave Model Scheme

The wave models are forced using hourly wind fields generated in Met Office Numerical Weather Prediction (NWP) models, which include observational data from satellite, ship and data buoy networks in their assimilation schemes. Based on the local wind speed and direction, energy is input to waves through a parameterisation of the exponential growth of existing wind-sea energy (linear growth in the early development stage). Wind-sea spectral peakedness and peak frequency are used to select an appropriate member of the JONSWAP family of spectra to describe the growing wind-sea energy distribution in frequency space. Directional distribution of wind-sea energy is defined using a cosine squared distribution about the mean wind-sea direction. Frequency dependency for the rate of turn of wave energy in response to turning wind is also parameterised.

As the waves grow, a balance is reached between parameterisations for the input, nonlinear transfer between frequencies and dissipation of wave energy. This ensures that for a given wind speed, with sufficient fetch and duration, the limiting JONSWAP form (known as the Pierson-Moskowitz spectrum) is reached but not exceeded.

Wave energy is advected through the model domain using a 2nd order Lax-Wendroff scheme. In the Global Wave Model, longer period swell energy direction of propagation is modified to ensure that the energy follows a Great Circle. In shallow water (<200m depth) wave group

speed depth dependency, bottom friction and depth refraction are represented in the model physics. The UK Waters Wave Model additionally includes the effects of time-varying currents on the UK continental shelf, taking hourly currents from the 12km Storm Surge model. Model grid and forcing data

The model runs on prescribed regular latitude-longitude spatial grids. Parameter values are derived at collocated positions corresponding to grid cell centre (i.e. the grid is not staggered). Cell types comprise 'sea points', where the full set of calculations for wind-sea growth/dissipation and wave energy advection are applied; 'land points' where no calculations are performed; and 'coast points', where advective/dissipative schemes only are applied and which act as a buffer zone for the land.

Depth information is held on the model grid using a representative average for each cell. This assumption may prove important in some near coastal grid cells where the average depth (for example taken over a 12km grid cell in the UK Waters model, 60km cell in the global model) may mask bathymetric features affecting the local distribution of wave energy. A cut-off depth is set in the model scheme at 200m, since at depths greater than this value shallow water effects are negligible even for wave energy in the lowest frequency range.

The importance of increased spatial resolution is clearest in the near coastal zone, since this allows a better representation of the coastline itself and will increasingly resolve shallow water bathymetric features. The trade off for making these resolution changes lies in run-time, with shorter calculation timesteps required for increased spatial resolution in order not to violate conditions for energy advection.

The models are calibrated such that they are to be forced to a representative 19.5m mean wind speed and direction, such that for correct wind speed, duration and fetch the wave model will attain the limiting Pierson-Moskowitz wave height. In the operational models this forcing is provided by NWP atmospheric models operated on rotated grids. As a result the wind must first be converted to the regular latitude-longitude grid prior to ingestion by the wave model. In assessing an appropriate wave model spatial grid size, the resolution at which the forcing winds are provided is an important constraint.

D1.2 Operational Configurations

The Met Office suite of operational global and regional nested wave models produces regularly updated wave forecasts with lead times of up to five days. Operationally the models are configured with a spectral resolution of 13 frequency bins and 16 directional bins, representing waves with a range of periods between 25 seconds and 3 seconds (deep-water wavelengths from 975m to 15m).

Wave conditions worldwide are forecast using the Global Wave Model on a 5/9degree latitude by 5/6 degree longitude grid (approximately. 60km square grid at mid-latitudes), with fields output at 3-hourly resolution to a lead time of 5 days (T+120). This model is forced using the Met Office's Global domain NWP 10m wind field and run twice daily based on 0000 and 1200

UTC analysis times. The extent of ice cover at high latitudes is updated daily using NWP global analysis data.

Boundary conditions from the Global Wave Model are used as input to a European Wave Model, based on a 1/4 degree latitude by 2/5 degree longitude grid (approximately 35km) covering the area from 30°.75N to 67°.00N and 14°.46W to 41°.14E and with a forecast range out to 36 hours (T+36). Similarly to the Global Wave Model, this model is forced using the Met Office Global domain NWP 10m wind field and run twice daily based on 0000 and 1200 UTC analysis times.

A further increase in resolution is made for the UK Waters Wave Model, which is nested using boundary conditions from the Global Wave Model. The UK Waters Wave Model uses a 1/9 degree latitude by 1/6 degree longitude grid (approximately 12km) covering the north-west European continental shelf from 12°W between 48°N and 63°N. Two configurations of the UK Waters Wave Model are run. The first configuration is forced by high resolution (~12km grid) Mesoscale NWP 10m wind and includes effects of time-varying currents on the UK continental shelf as generated by the Met Office's operational 12km Storm Surge Model. This model is run four times daily using analysis times 0000, 0600, 1200 and 1800 UTC and provides hourly forecasts out to T+36. The second configuration (Extended UK Waters Wave Model) does not include current effects, and is run twice daily (0000 and 1200 UTC analyses) forced by Global NWP 10m wind to provide 3-hourly forecast data out to T+120.

D1.3 Third Generation (3G) Versus Second-Generation (2G) Models

The 2G model scheme mainly differs from its 3G counterparts (e.g. WAM, WAVEWATCH III) in its use of parameterisation schemes for wave growth, nonlinear transfer of energy and dissipation, whereas the more recently devised 3G models calculate some of these explicitly (details in Holt and Hall 1992). Nevertheless the 2G scheme is still considered robust for operational wave modelling applications and compares favourably with 3G counterparts operated by other meteorological bureau in an ongoing international data exchange (Bidlot *et al.*, 2000, 2002).

D1.4 Output

Data are output from the model and variously retained in commercially available fast-access hindcast archives and research based forecast model archives. Due to data handling constraints two-dimensional (frequency-direction) spectral data are output at specific model points only and are not archived. The hindcast archives are based upon one-dimensional (frequency) spectral data output for all model grid points. These data are used to construct integrated wave parameters including significant wave height, period and direction based on the total spectrum, wind-sea and swell components. The decomposition between swell and wind-sea is made using analyses based upon archived model values of wind speed and direction. Hindcast and forecast integrated parameters (e.g. significant wave height) are generated at model run-time for each model grid point and are retained in the research forecast model archive.

D2. Wave Resource Parameters

D2.1 Calculation of Wave Power

D2.1.1 Background Theory

The quantification of the power transmitted by a wave moving across the sea surface was calculated using methodology similar in format to that described in Tucker and Pitt (2001) and used in the Seapower South West study. Assuming a sinusoidal wave form and applying Pointing's theorem, wave power (P_w , per metre unit along the wave crest) is described by:

$$P_w = 0.125 \rho g H^2 c_g \quad (1)$$

where :

- ρ = water density (kg/m³);
- g = acceleration due to gravity (m/s²);
- H = wave height for a monochromatic wave train (m);
- c_g = wave group speed (m/s, the speed at which wave energy will propagate).

In order to calculate the wave power from the available model integrated parameters, further calculations are required to derive H and c_g . As H_s describes the height of the highest one-third of waves in a given sea-state, a more appropriate statistic is required to describe H for all waves. This statistic is the root mean square wave height (H_{rms}).

The three statistics can be related (following Abramowitz and Stegun, 1965) as follows:

$$H = H_{rms} = \frac{H_s}{1.416} \quad (2)$$

therefore, power is redefined as:

$$P_w = 0.0623 \rho g H_s^2 c_g \quad (3)$$

with c_g is defined as:

$$c_g = 0.5c \left(1 + \frac{2kh}{\sinh 2kh} \right) \quad (4)$$

where :

- h = water depth (m);
- k = wavenumber;
- c = wave phase velocity $c = \frac{\sigma}{k}$ (5)

In Equation (5) $\sigma = 2\pi/T$ for T the wave period (in seconds). Wave group speed can therefore be described as a function of water depth and wave period, but will require an iterative process for the relationship to be solved quantitatively. Within the calculations carried out in this project, a process of 20 iterations were used for each data point based on the model depth and an initial starting value for c of:

$$c = \frac{gT}{2\pi} \quad (6)$$

based on a deep water approximation and using an appropriate value of wave period T . The generally accepted period statistic for wave power calculations is the energy period (T_e) which best represents low frequency wave actions that are most efficiently transmitted to wave power devices. This parameter is defined using:

$$T_e = \frac{m_{-1}}{m_0} \quad (7)$$

D2.1.2 Power Calculations for Primary Component and Full Wave Field Scenarios

In most calculations of wave power resource, the power at any given time is calculated based upon single values for H_s , T_e and direction (i.e. the wave spectra are assumed to be uni-modal). However, for certain locations around the UK the sea-state can often comprise two components; a locally generated wind-wave (generated across the fetch where the wind has blown), and a swell-wave which propagates into the area from a remote source and characteristically has longer periods. It is important to note that the direction of the swell-wave is not necessarily aligned to the direction of the wind-waves. Such conditions are given the term 'crossed-seas'.

In this version of the Atlas the effect of those circumstances where the spectrum describes wind-wave and swell components that are both distinct and significantly energetic (crossed-sea) is assessed by making analyses based on the concepts of two hypothetical scenarios:

- 'Primary Component' resource is defined as the power that is attributed to the most energetic component in a given sea-state. For a uni-directional sea this will be derived from the resultant wave field statistics, but in a crossed-sea will be calculated using the most energetic component of either the wind-wave or swell.
- 'Full Wave Field' resource assumes that in crossed-seas the power available will be the summation of power attributed to both wind-wave and swell components. For uni-directional sea states the power is derived using the resultant wave field.

The Met Office model dataset allows such an analysis to be carried out since it retains information describing both the wind-wave and an averaged swell component.

To perform the analysis the wind-wave and swell components are tested in order to define whether a crossed-sea has occurred. In the instances where a crossed-sea has not occurred wave parameters associated with the resultant wave field are applied to the power calculations. Where a crossed-sea has occurred, the Primary component power is calculated using the most energetic component (wind-sea or swell) only, whilst the full wave field power assumes that both component power values can be added to yield the total output (wind-wave and swell).

Within the Atlas, statistics are provided for both device types. However, a point to note when using the wave height versus period scatter tables for the full wave field power is that under crossed-sea conditions two elements within the table may be populated at any given time. As a result, the full wave field scatter table, whilst provided in a normalised form (in which the frequency of all elements sums to 1.0) is associated with a scaling factor relating to the number of crossed-sea events.

Figure D1 shows the frequency of crossed-sea events in this analysis. This is highly variable with location around the UK, with the majority of events occurring in northern Scotland. The impact of such events on overall power is limited however, being generally less than 5 % (Figure D2). The limited benefit of a device that is optimised to utilise the full wave field is less surprising when it is considered that the extra power gained will be a function of both probability of crossed-seas occurrence and the ratio of energy in the primary and secondary components. For example, if at a given location the probability of occurrence is 20% and the average energy in the secondary component is 50% of that in the primary component, then the overall increase from exploiting the full wave field would be 10%. This value will be further reduced should the majority of cross-seas events be mainly associated with low or moderate energy sea-states.

D2.1.3 Definition of Wave Period

The archived wave model statistic for wave period is zero-upcrossing period (T_z). This statistic is derived using the spectrum second moment and as a result may be sensitive to high-frequency low energy variations in the wave spectrum. As a result the analysis used for the Atlas has adopted the energy period T_e as a basis for calculation.

Whilst T_e is not directly computed by the wave model an approximation can be made based on T_z . The approximation assumes that a standard JONSWAP spectrum is representative of the average wave conditions over time, in this case the NORSOK (1999) recommended design values for γ , σ_a and σ_b ¹ (2.0, 0.07 and 0.09 respectively) for the North Atlantic were applied. T_z and T_e were calculated based on the theoretical spectra for peak periods between 3 and 20 seconds and their ratio determined. The ratio was found to vary between 1.0 and 1.17.

For this version of the Atlas a table of values was created for application to given values of T_z , such that T_e is determined across the UKCS using:

¹ Where γ = peak enhancement of the spectral peak of the wind sea; σ_a and σ_b = the narrowness of the peak

$$T_e \approx C_{TR} T_z \quad (8)$$

where:

C_{TR} is taken from:

	T_z Period Range		
	< 6 seconds	< 10 seconds	> 10 seconds
Wind-wave C_{TR}	1.06	1.12	1.14
Swell C_{TR}	1.05	1.10	1.14

D 2.2 Statistical Analysis of Wave Resource Parameters

To enable a more detailed description of the wave regime a number of standard statistical expressions are provided for H_s , and P_w . Statistical values are contained in the Atlas database for further examination.

The analyses were divided into five components:

- Non-directional wave parameters;
- Significant wave height distribution statistics;
- Significant wave height vs. energy period scatter tables;
- Directional wave analyses; and
- Monthly mean time-series.

These comprise statistics corresponding to the original Atlas which was based upon existing work, including:

- Previous studies such as the EU WERATLAS and Seapower South West; and
- The DTI study carried out by Thorpe (1999).

Each set of statistics was defined not only in terms of annual value (using the 7 year period from June 2000 to May 2007) but also at seasonal and monthly timescales (using appropriate data from the data base) in order to express important variations in wave climate occurring during an annual cycle. Specifically these can be described as:

- Non-directional wave and power statistics; e.g. mean, median and inter-annual variability of wave height and power (Table D1). These statistics allow a simple inter-comparison of the bulk differences in wave and wave power climate between sites over the UKCS when visualised in map form. For power, two additional statistics are provided that aim to assess the practicality of exploiting the resource on a year round basis. These are a seasonal variability index that shows the ratio between summer and winter power yields; and a performance index that compares the power estimate

for a device that exploits energy for 100% of the time, versus a device that shuts down and yields no power during the lowest 2.5% of events and the highest 2.5% of events.

Table D1. Non-directional wave parameters

Parameter	Mean	Median	Seasonal Variability	Inter-Annual Variability	Performance Index
H _s - wave height (m)	Available	Available	N/A	Available	N/A
Power - Primary component (kW/m ²)	Available	Available	Available	Available	Available
Power - Full wave field (kW/m ²)	Available	Available	Available	Available	Available

- Significant Wave Height Distribution statistics. Normalized frequency statistics that show the proportion of time for which a given significant wave height class is expected over a prescribed period (Table D2). These values are useful in assessing the amount of time for which wave conditions fall within a given operating range, and may also be useful for comparison of many sites when visualized in map form. It should be noted however, that these data have not been analysed with the intention of providing any form of design statistic and as such are not recommended for this purpose.

Table D2. Significant wave height distribution intervals

H _s (Wave Height) (m)
<1.0
<2.0
<3.0
<4.0
<5.0
<6.0
<7.0
<8.0
<9.0
<10.0
>10.0

- Wave height versus period scatter tables (Table D3). Normalized frequency tables comparable with those used for wave power calculations in other studies, and useful in assessing the time for which wave height and periods fall within an appropriate operating range. The data bins were chosen to provide an optimal balance between representing the data distribution in a format familiar to wave power device developers and conserving data volumes. Scatter tables provided for the full wave field power are accompanied by a conversion factor that allows the normalised distribution to be compared directly against the distribution for a Primary component power i.e. the full wave field power may comprise more than 100% of events since under ‘crossed-sea’

conditions wind-wave and swell will populate the scatter table in two categories at the same time.

Table D3. Significant wave height vs. energy period scatter tables

		Period (s) (Less Than Unless Stated)															
H _s (m)		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	>18
<1.0	Frequency values (in % units)																
<2.0																	
<3.0																	
<4.0																	
<5.0																	
<6.0																	
<7.0																	
<8.0																	
<9.0																	
<10.0																	
>10.0																	

- Directional wave and power statistics (Tables D4a and D4b). Unless wave power devices can be driven from all directions, they will be dependent upon waves propagating from a prevailing direction. The statistics in these tables aim to allow assessment of the degree of 'directionality' in the wave climate at given sites. Two statistics are available: the first provides frequency and mean parameter (wave height and power) information through 12 directional sectors (Table 6a); the second is a wave 'rose' showing a distribution of wave height through 12 directional sectors.

Table D4a. Directional wave analyses (using 12 direction sectors)

Parameter	Normalised Frequency	Mean
H _s (m)	Available	Available
Power - primary component (kW/m)	Available	Available
Power - full wave field wave device (kW/m)	Available	Available

Table D4b. Significant wave height rose (using 12 direction sectors)

Parameter	Normalised Frequency			
H _s (m)	< 2m	< 4m	< 6m	> 6m

- Time series describing monthly mean significant wave height and wave power (primary component and full wave field) throughout the 7 year analysis period are available for each point in the Atlas.

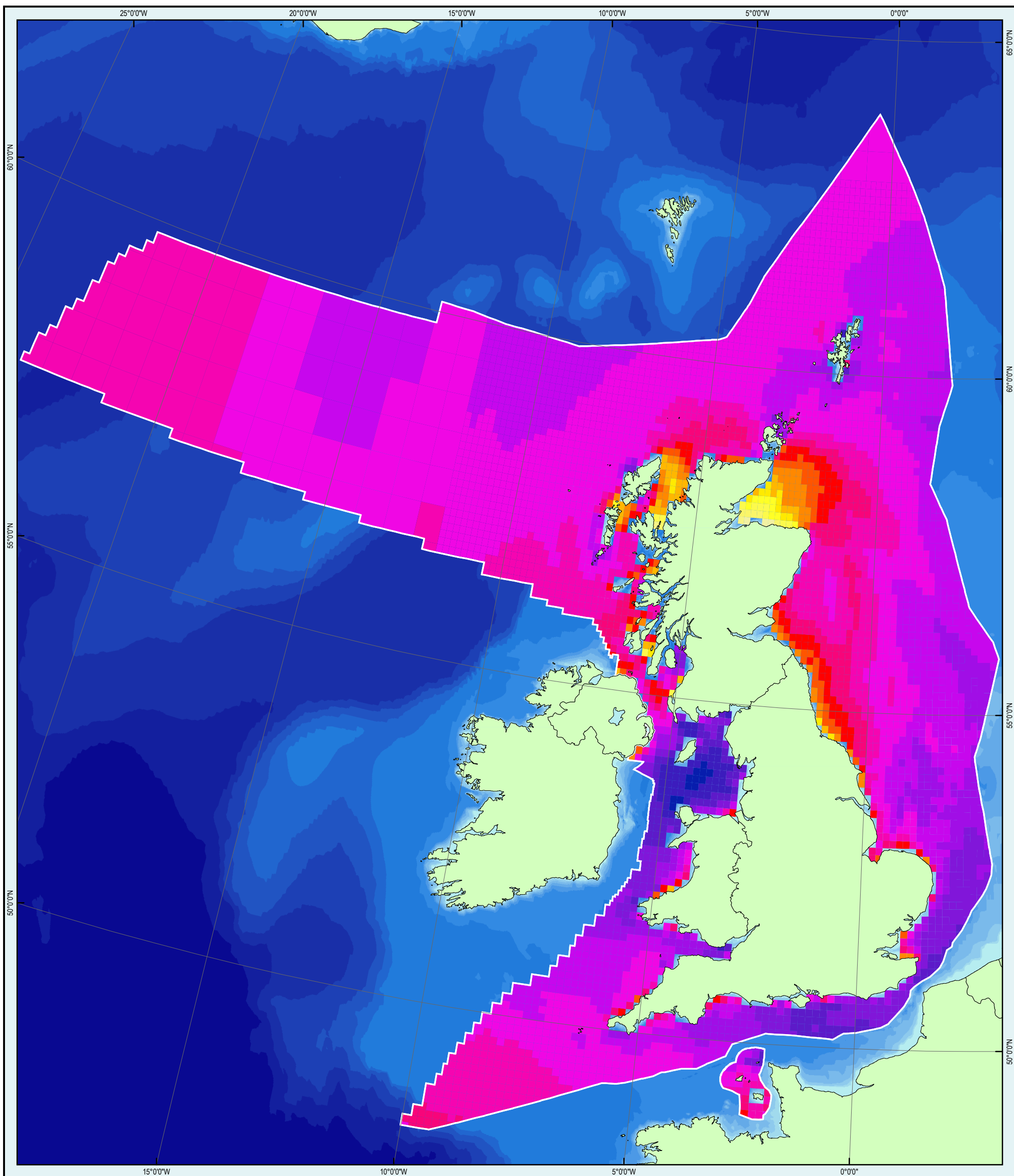


Figure D1 - Frequency of Crossed-Sea Events



Projection Transverse Mercator
WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
when printed A3

Map Designed and Produced by ABPmer Ltd.

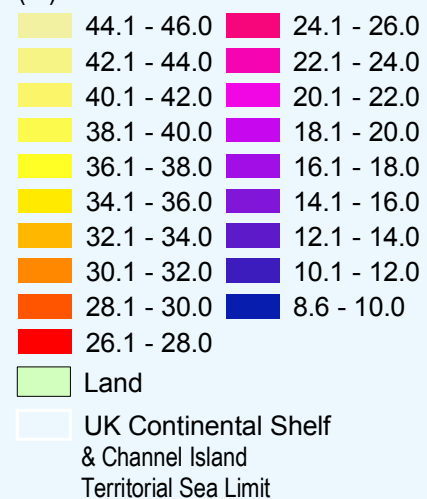
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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Crossed-sea events are defined when wind-wave and swell wave components are present.
5. Wave power is calculated for each horizontal metre of wave crest using the energy period calculation (T_e).
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Frequency of crossed-sea events (%)



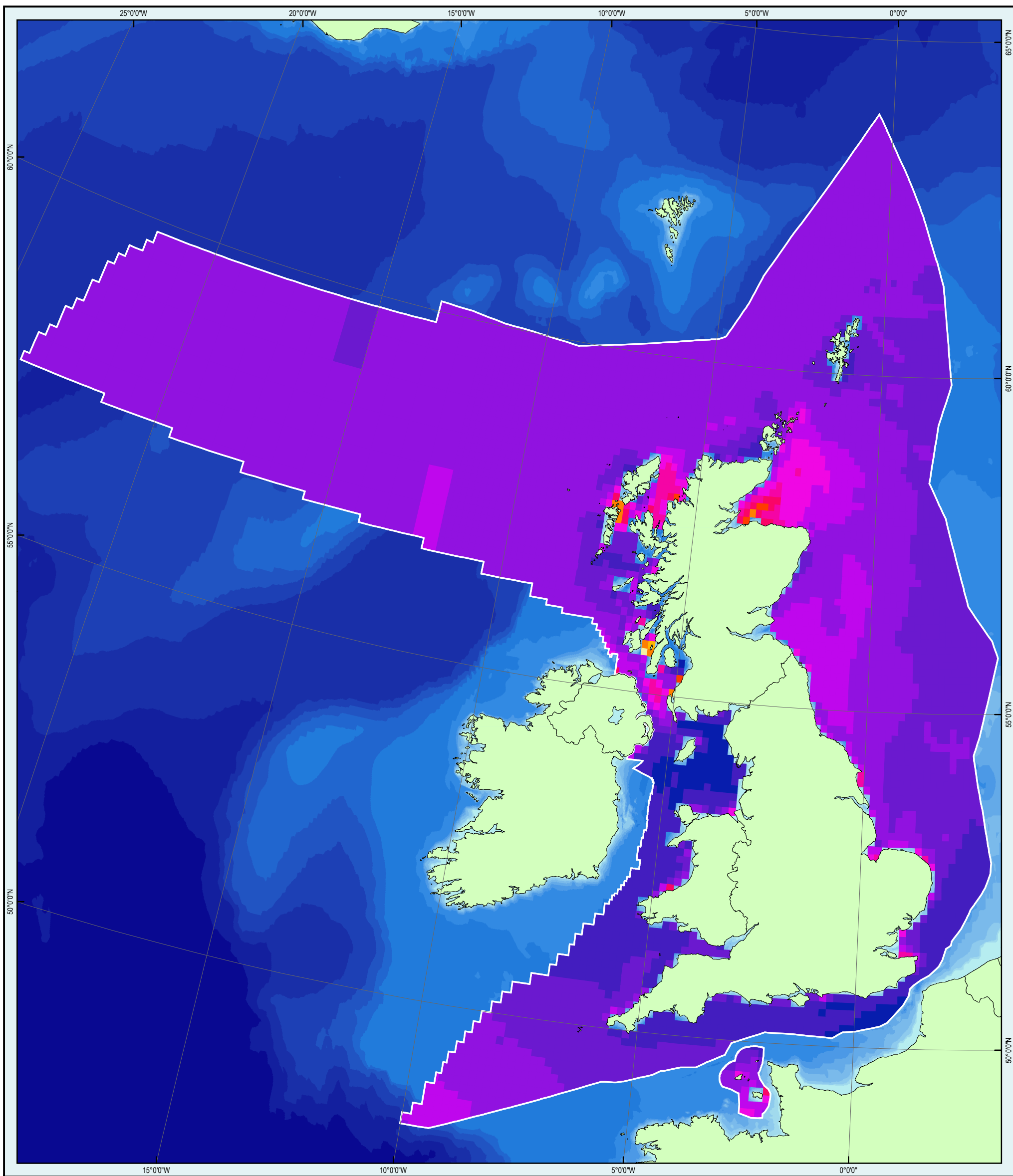
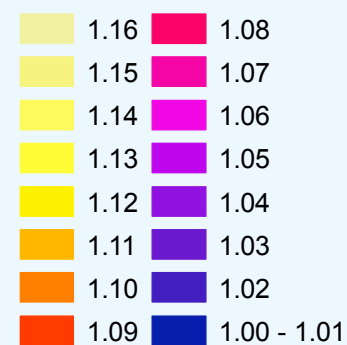


Figure D2 - Ratio of Annual Mean Full Wave Field Power to Primary Component Power

Full Wave Power:Primary Component (ratio)



Land
 UK Continental Shelf & Channel Island Territorial Sea Limit



Projection Transverse Mercator
 WGS 1984 UTM Zone 31 N

Scale 1:6,250,000
 when printed A3

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Notes

1. North of 63° N and West of 12° W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Full Wave Field Power is calculated using the summation of wave power attributed to wind-wave and swell components. Primary Component Power is calculated from maximum component (either wind-wave or swell).
5. Wave power is calculated for each horizontal metre of wave crest using the energy period calculation (T_e).
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D3. Validation of the Wave Data

Validation of both wind and wave data aims to assess the following issues:

- Over the defined climate period, does the distribution of wave model data represent a measured spread of wind and sea-state conditions well?;
- Does the sourced data broadly represent long-term variations in wave climate?; and
- Is the performance of the sourced model data better or worse for specific regions of the UKCS?

The validation exercise was undertaken in two parts. To test validity against a measured source and geographic variation in performance, the UK Waters Model and observation time-series data from in-situ wave and meteorological measurement platforms were compared. To determine how the sourced data compare to longer term assessments in the climate over the UKCS the archive of Met Office European Wave Model data was utilised. This data source extends over 15 years, and comparisons were made between the whole 15 year period and the Atlas' specific 7 year analysis period.

D3.1 Comparison Between Met Office UK Waters Model and Observations

A comparison between the UK Waters Wave Model dataset and long term observations from a network of offshore observing platforms has been used to indicate the level of confidence that might be placed in the Atlas at various locations around the UK.

As with the wind data validation (Appendix C3) observation time-series data were selected from sites comprising the Met Office Marine Automatic Weather Station (MAWS) Network (Figure C23, Table D5) in order to undertake the validation exercise.

Table D5. Met Office Marine Automatic Weather Station (MAWS) sites used in validation study

Station Name	WMO Number	Station Position		Station Type	Water Depth (Model* m)
		Latitude	Longitude		
K5	64045	59° 04' N	11° 25' W	Buoy	> 200.0
RARH (3 years)	62106	57° 00' N	09° 54' W	Buoy	> 200.0
Aberporth	62301	52° 17' N	04° 30' W	Buoy	31.0
Turbot Bank	62303	51° 37' N	05° 09' W	Buoy	40.0
Seven Stones	62107	50° 04' N	06° 04' W	Lightship	73.0
Lyme Bay (2.5 years)	62101	50° 37' N	02° 44' W	Buoy	33.0
Greenwich	62305	50° 25' N	00° 00' E	Lightship	54.0
K17 (3.5 years)	62026	55° 25' N	01° 10' E	Buoy	69.0
K16 (3.5 years)	62109	57° 00' N	00° 00' E	Buoy	84.0

These sites provide observations of both marine wind and wave parameters, specifically significant wave height and wave period. Locations were chosen to provide a spread of data around the UKCS and are summarized in Table D5. Where possible the time-series used for comparison have provided a match between model and observed data over the entire 7 years

of the Atlas dataset. However, some of the buoys were decommissioned during this period, in which case the analysis period in years is noted in Table C2.

The chosen parameters for comparison are the significant wave height (H_s) and 'resultant wave power'. Since the wave observations are derived from the resultant sea-state only (i.e. there is no breakdown of the wave field into components), the wave power examined in this section does not have a direct map to the 'Primary Component' or 'Full Wave Field' powers presented in the Atlas. Instead this is a separate calculation used to test model versus observed data in as consistent a manner as possible.

Five measures for comparison are used:

- Annual mean values;
- Mean in-year variability (standard deviation);
- RMS Error for monthly averages;
- Significant Wave Height and Wave Power Exceedence distributions; and
- Monthly Significant Wave Height Averages.

Distributions are presented in Figures D3 to D11. Comparison statistics are provided in Tables D6 and D7.

Annual mean significant wave height is well estimated (within 10%) at open seas sites (K5, RARH, Seven Stones, K17 and K16), plus the coastal site at Aberporth. This should be considered relative to a likely observation accuracy of 5-10%. Data distributions show that in general, any differentials at these sites occur at the lower end of the wave height distribution, with the model slightly overestimating the frequency of conditions in the 1-2m range. The in-year variability of significant wave height is also well estimated at these sites, and show a variability that is relatively high compared to the mean (due to changes in storminess between winter and summer). Monthly wave height plots and RMS error (a direct comparison between model and observation values by month) indicate that model performance is variable for given months of the year at individual sites within this subset. For example, at K5 and RARH the winter month significant wave height averages have a higher differential than summer month values. This may be due to model under-representation of the most extreme storm events.

Model versus observed value differentials are significantly higher for the Lyme Bay and Greenwich sites. At Greenwich, this particularly high differential is likely due to both shortcomings in model and the observation platform used. In this case the platform is a light vessel, which would be less responsive than a buoy in the low wave height short period wave conditions prevalent in this area. Examining the distribution of significant wave height averages through the year, Greenwich is the only site that shows a systematic overestimate. The overestimate by the model in Lyme Bay is most likely due to the model not correctly representing shallow water effects on dissipation and swell propagation for this area. The distribution of significant wave height averages through the year at Lyme Bay implies that the overestimate generally results from an overprediction of wave conditions during the stormiest months in autumn and winter.

Table D6. Annual wave statistics for validation sites

Station Name	H_s Mean (m)			H_s Std. Dev. (m)			H_s RMS Error (m)
	Model	MAWS	% ^e	Model	MAWS	% ^e	
K5	3.27	3.47	-6	1.68	1.78	-6	0.62
RARH	3.08	3.19	-3	1.68	1.65	2	0.63
Aberporth	1.20	1.25	-4	0.77	0.82	-6	0.32
Turbot Bank	1.63	1.73	-6	1.15	1.12	3	0.40
SevenStones	2.29	2.11	9	1.39	1.34	4	0.76
Lyme Bay	1.12	0.96	17	0.86	0.69	25	0.39
Greenwich	1.35	0.89	52	0.84	0.74	14	0.61
K17	1.87	1.75	7	1.00	0.96	4	0.38
K16	1.97	1.95	1	1.06	1.07	-1	0.42

^e Error calculated as a percentage using (Model/MAWS - 1)*100 values. Negative values show an underestimate, positive values an overestimate

Table D7. Annual wave power statistics for validation sites

Station Name	Resultant Power Mean (kW/m)			Resultant Power Std. Deviation (kW/m)		
	Model	MAWS	% Error ^e	Model	MAWS	% Error ^e
K5	60.61	72.88	-17	82.94	101.24	-18
RARH	54.68	61.75	-11	85.20	87.42	-3
Aberporth	6.59	7.59	-13	11.14	14.42	-23
Turbot Bank	15.34	17.75	-14	29.40	30.96	-5
Seven Stones	29.34	37.50	-22	49.10	62.49	-21
Lyme Bay	6.95	4.07	71	14.09	9.21	53
Greenwich	7.85	5.60	40	12.97	13.83	-6
K17	15.64	13.98	12	21.87	21.19	3
K16	18.04	18.11	0	26.17	26.74	-2

^e Error calculated as a percentage using (Model/MAWS - 1)*100 values. Negative values show an underestimate, positive values an overestimate

Wave power differentials result from differences in both significant wave height and period as modelled and observed. With respect to this, all sites save for Lyme Bay and Greenwich show reasonable agreement between model and observations, with average power and in-year variability estimates generally within 20% of each other. As for significant wave height, the sites most open to Atlantic swell (K5, RARH, Aberporth, Turbot Bank and Seven Stones) are characterised by a model underestimate relative to observations. Power exceedence curves for these sites show the main differential in the 5-40 kW/m range. At Greenwich and Lyme Bay this trend is reversed.

Concluding from these results:

- Modelled and observed data show generally good agreement to within 10% of significant wave height and 20% of wave power.
- The exceptions to the previous statement are two sites within the English Channel. At Lyme Bay the larger difference may be due to the model representation of shallow water effects close to the coast. At Greenwich these issues are likely to be compounded by the nature of the measurement platform and it's response to low wave conditions.
- For the open ocean sites in particular, differences are noted in the model performance relative to the observations for different times of the year; i.e. as a result of changing levels of storminess between summer and winter.

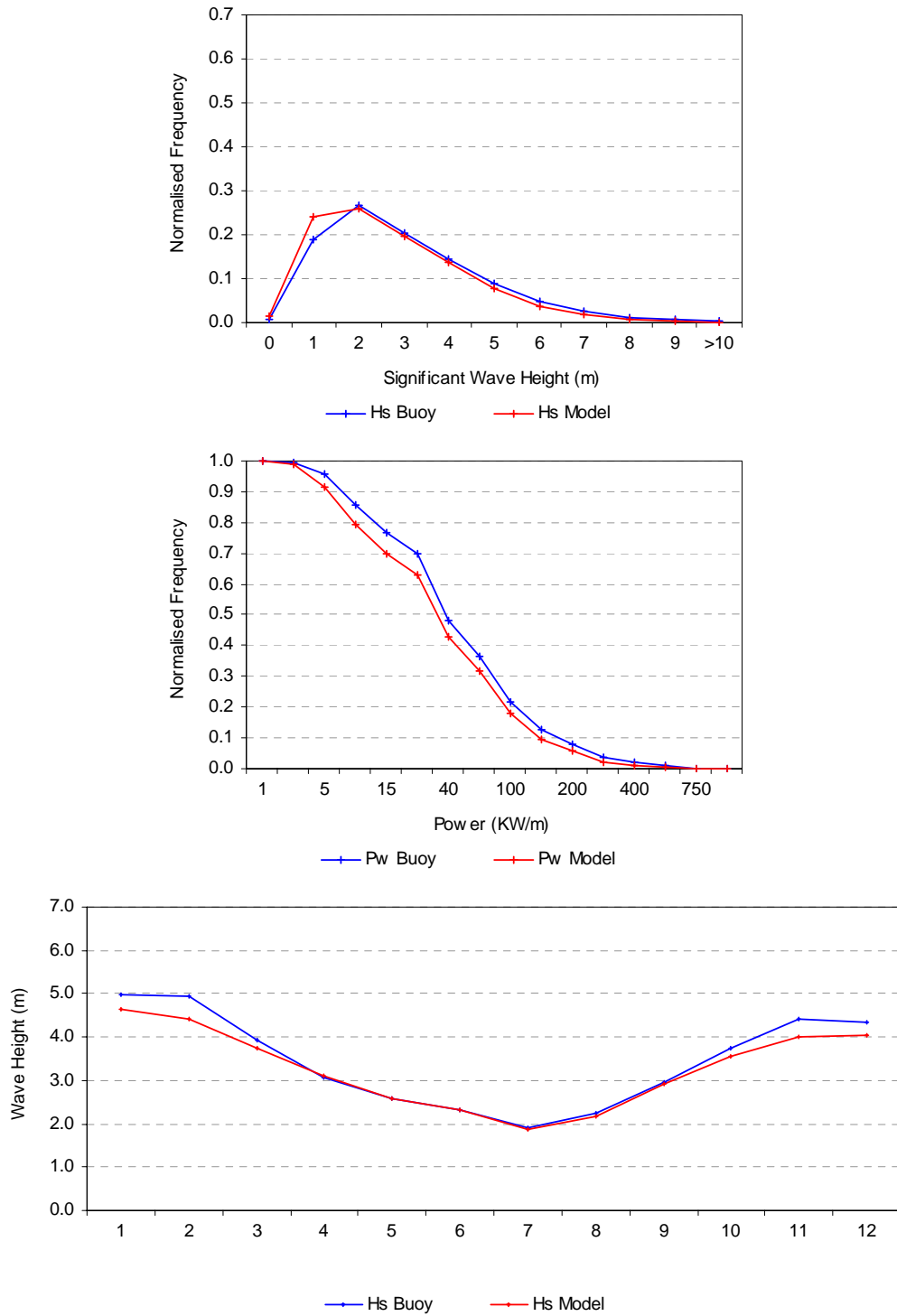


Figure D3. K5 MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

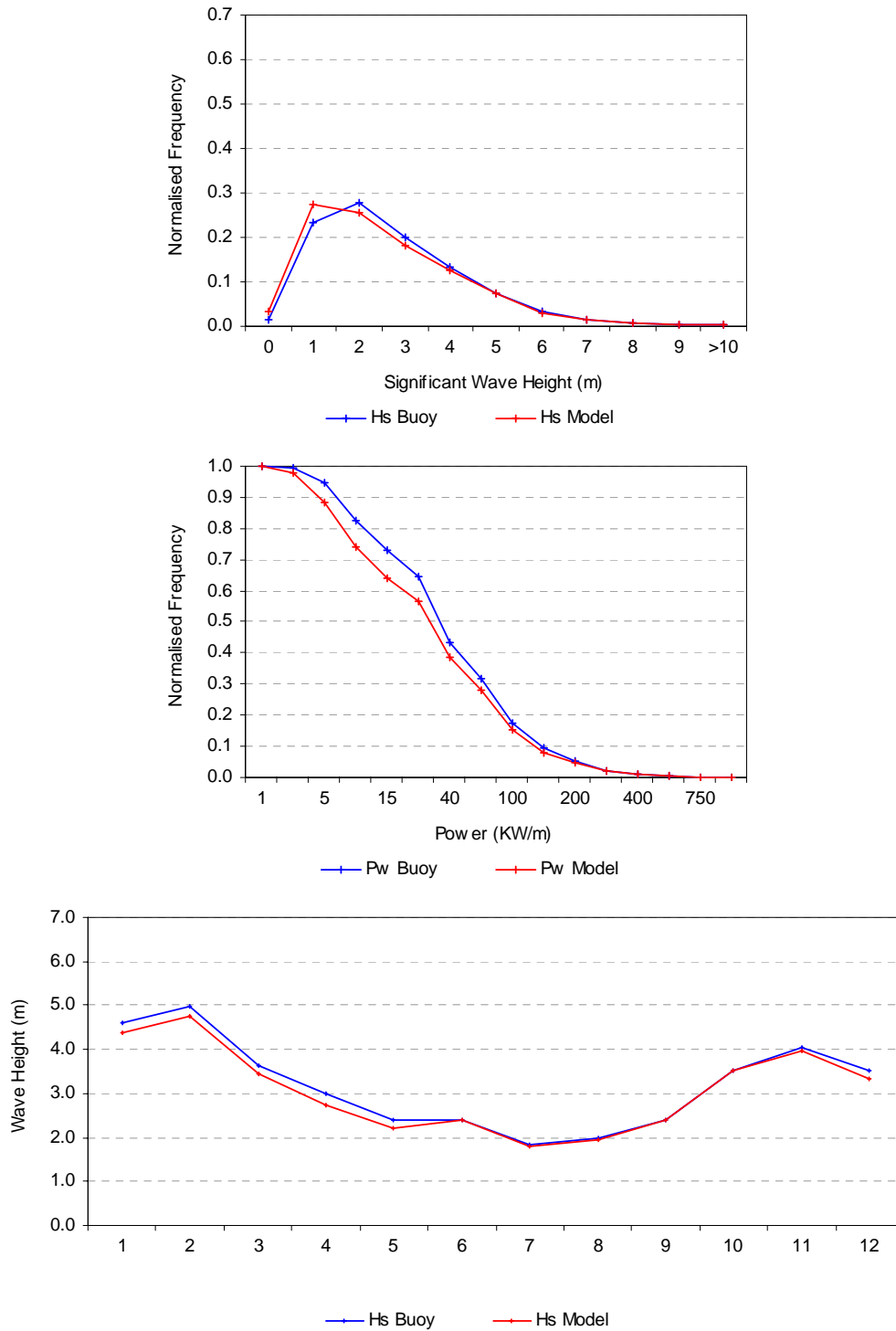


Figure D4. RARH MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

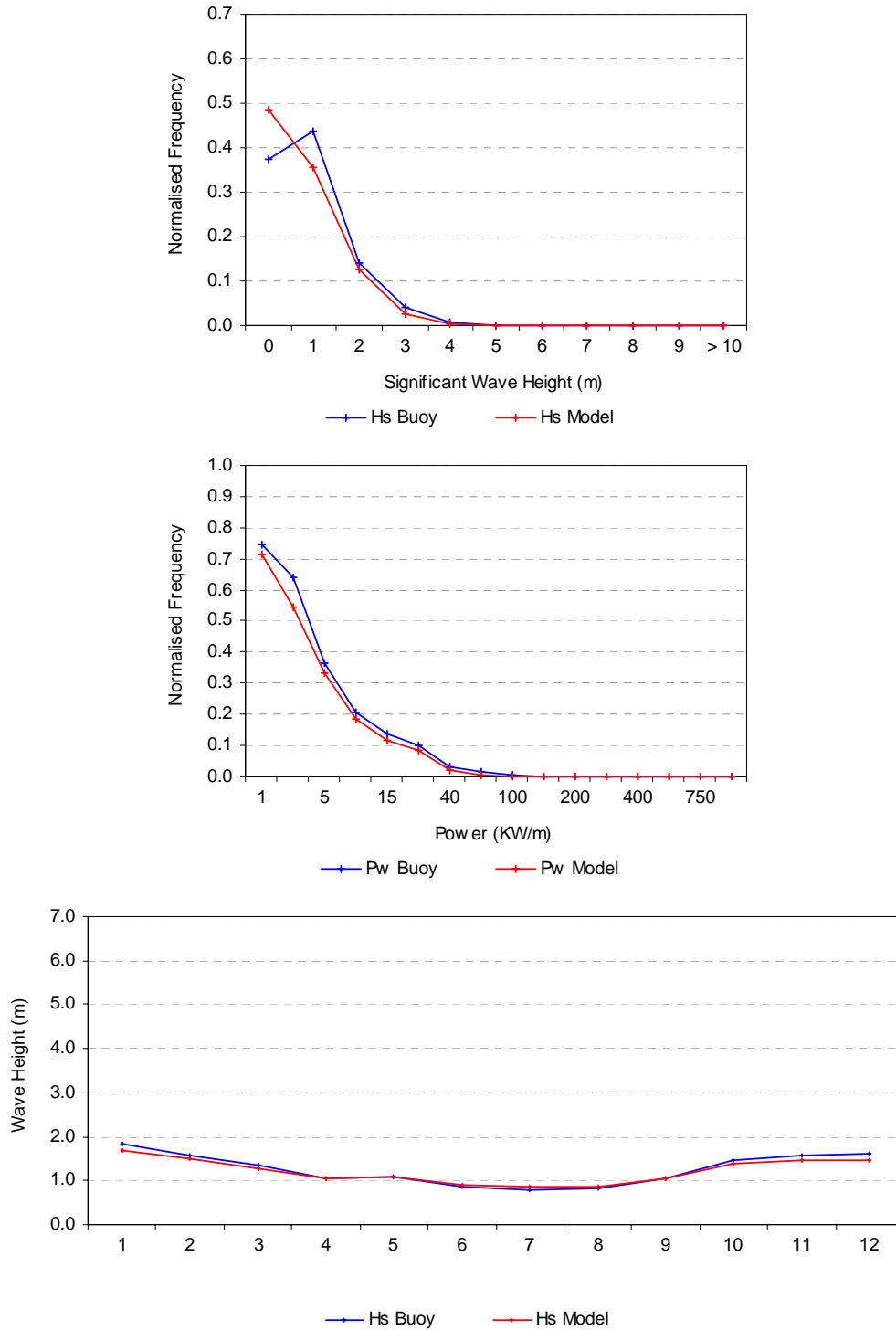


Figure D5. Aberporth MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

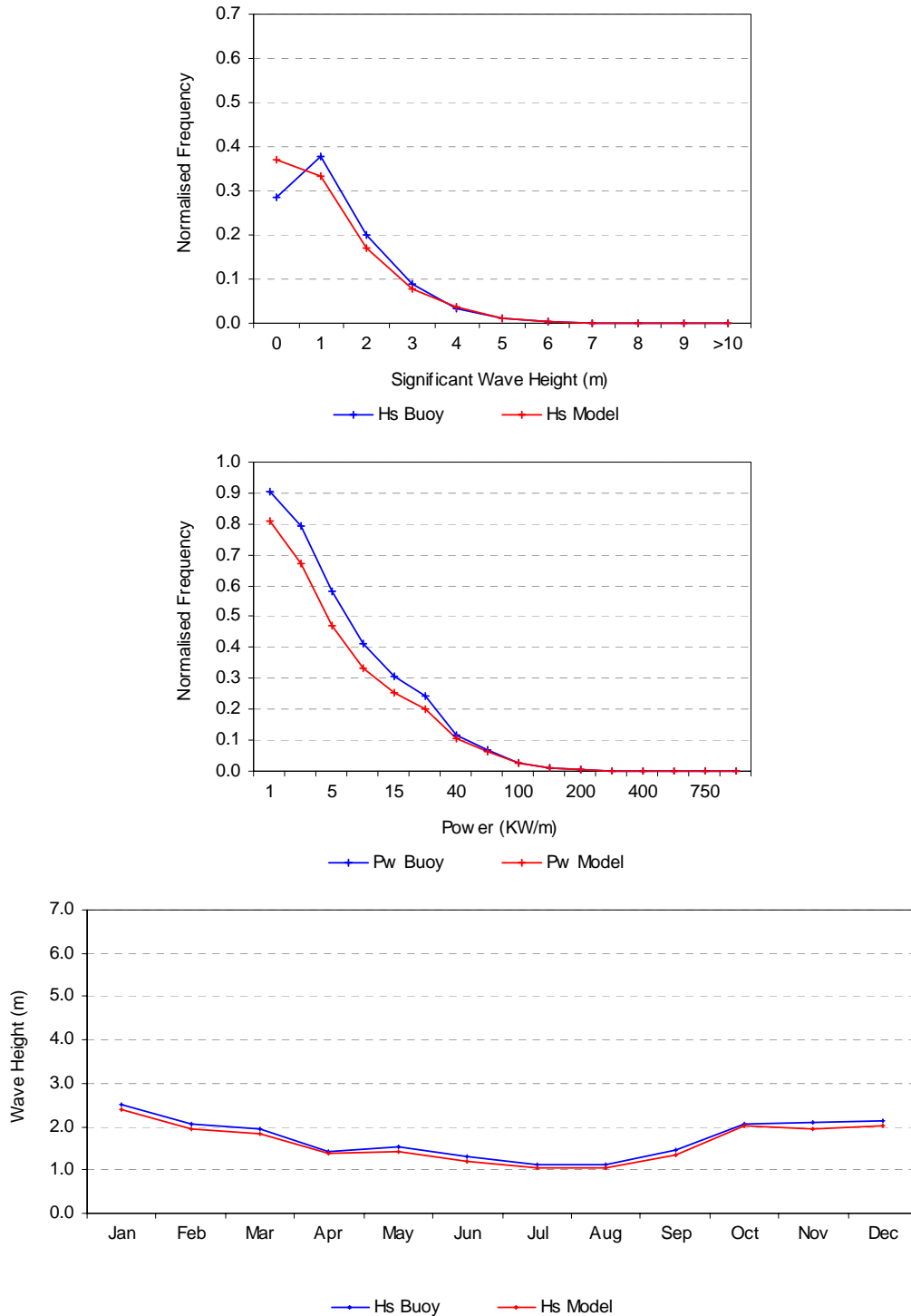


Figure D6. Turbot Bank MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

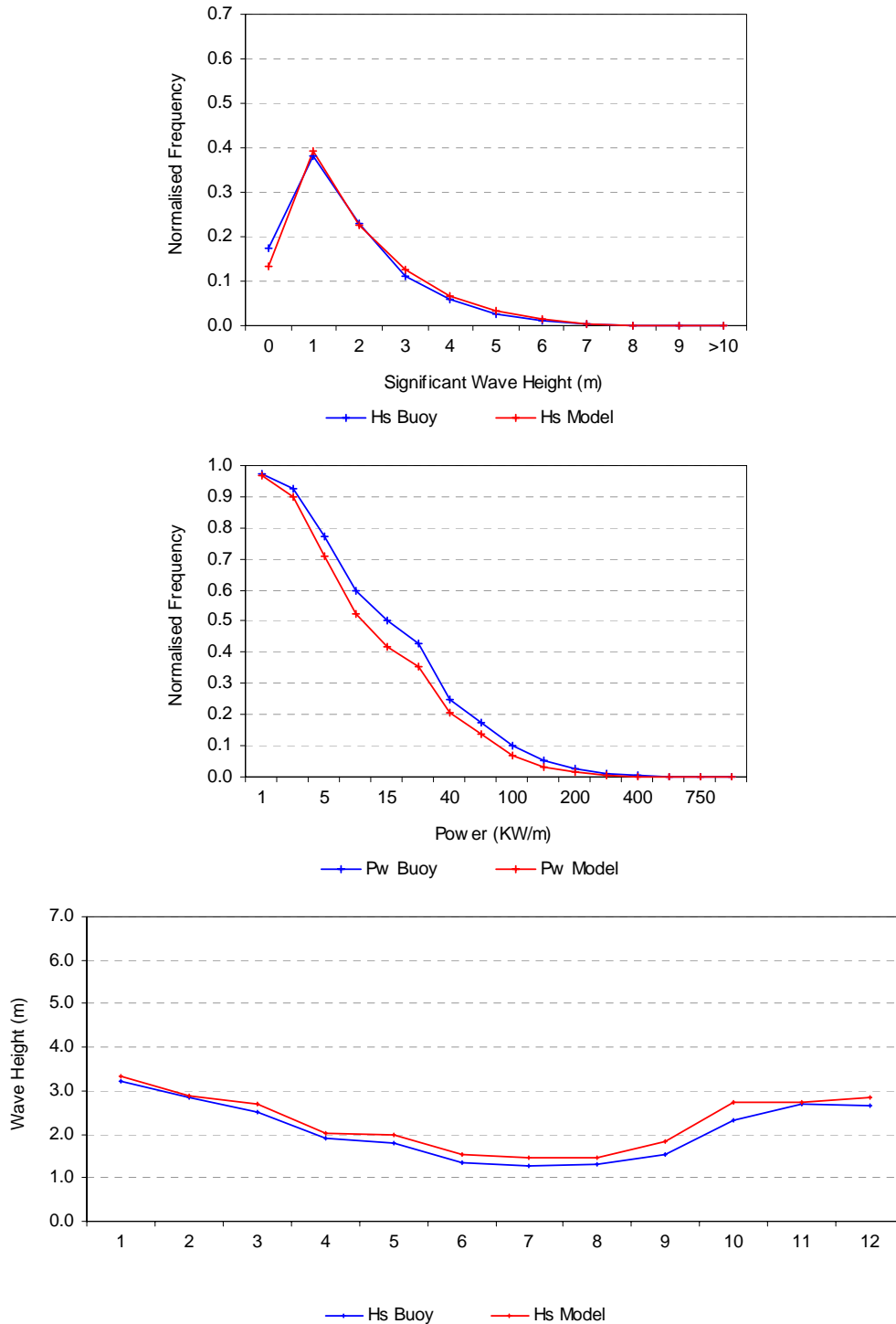


Figure D7. Seven Stones MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

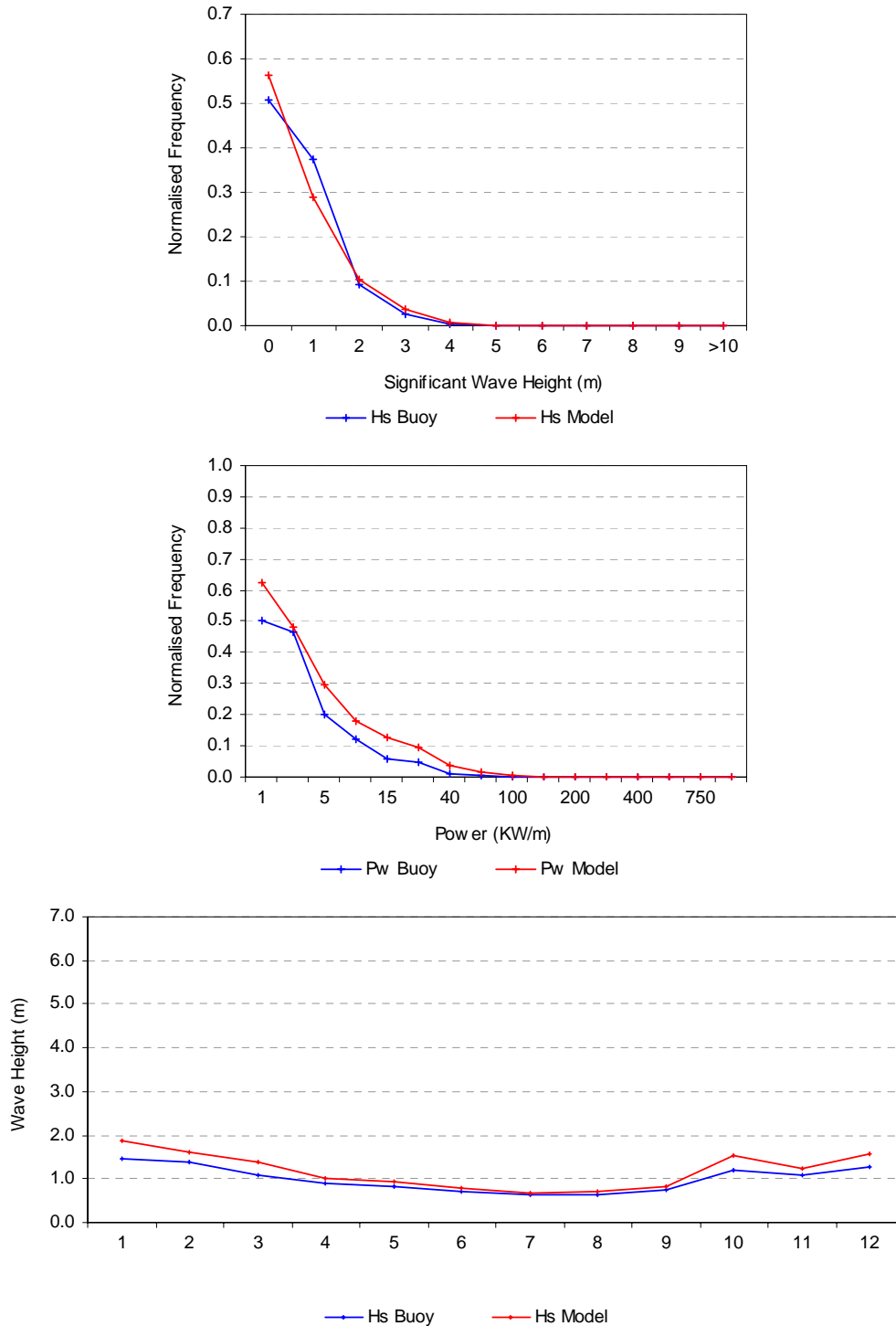


Figure D8. Lyme Bay MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

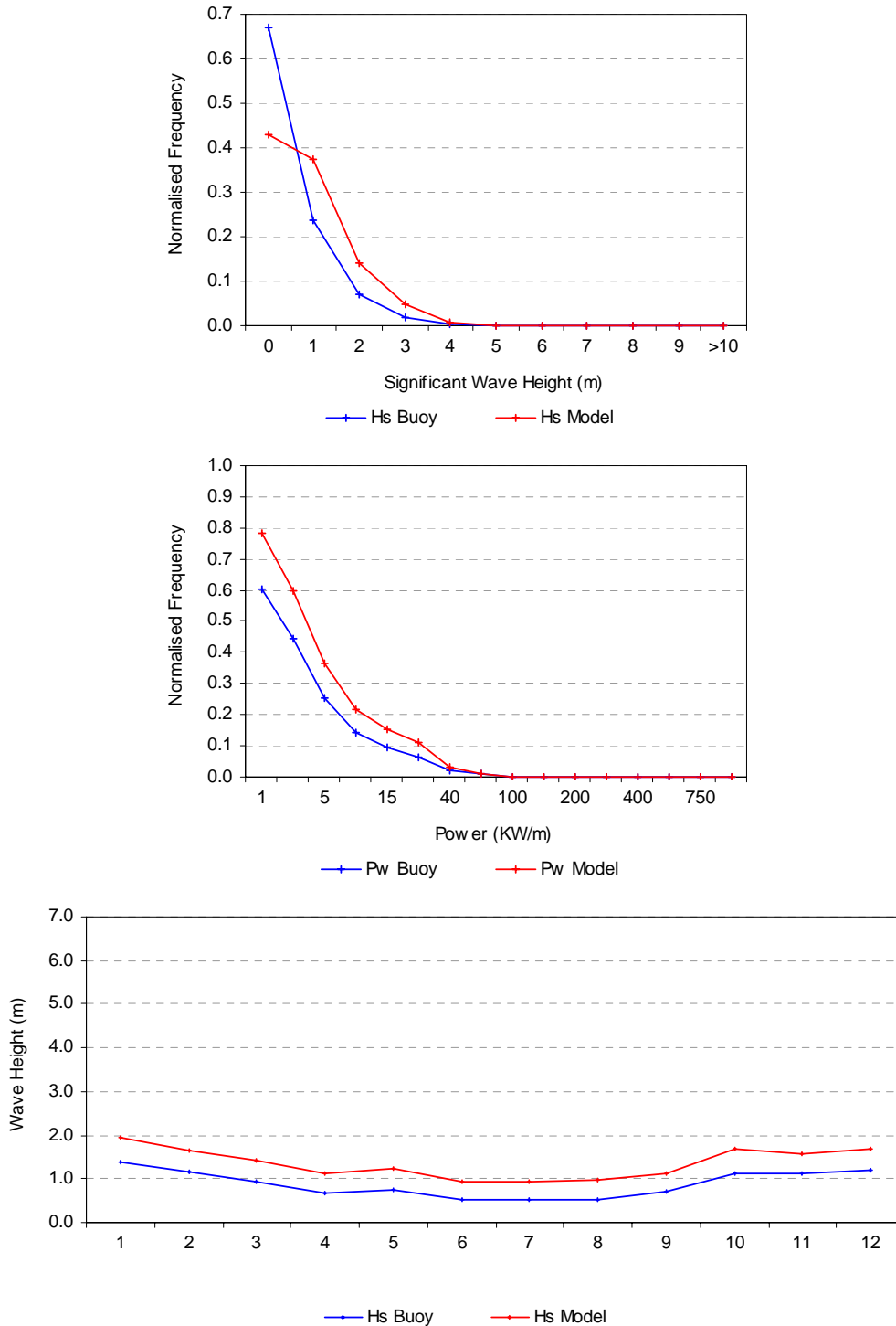


Figure D9. Greenwich MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

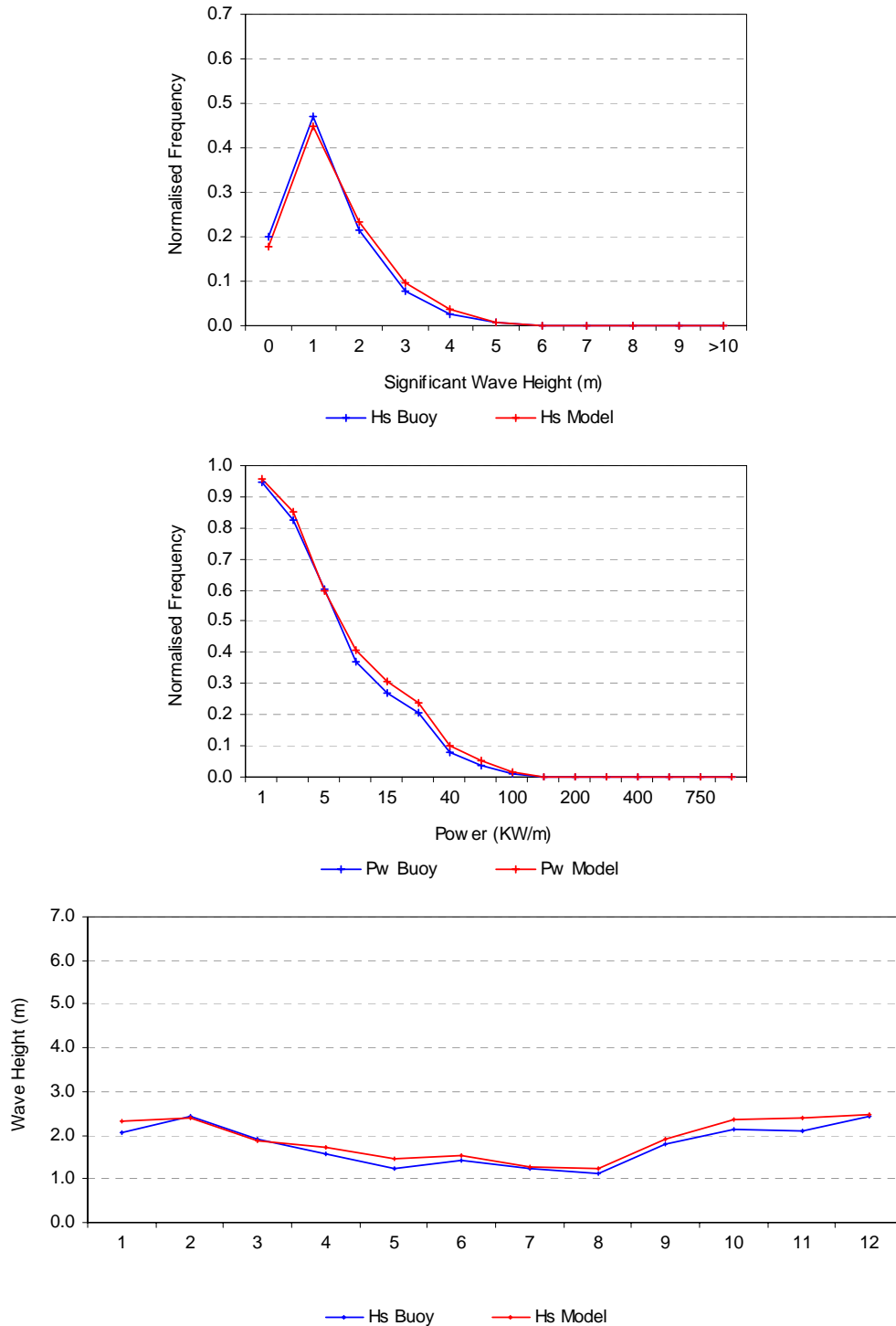


Figure D10. K17 MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

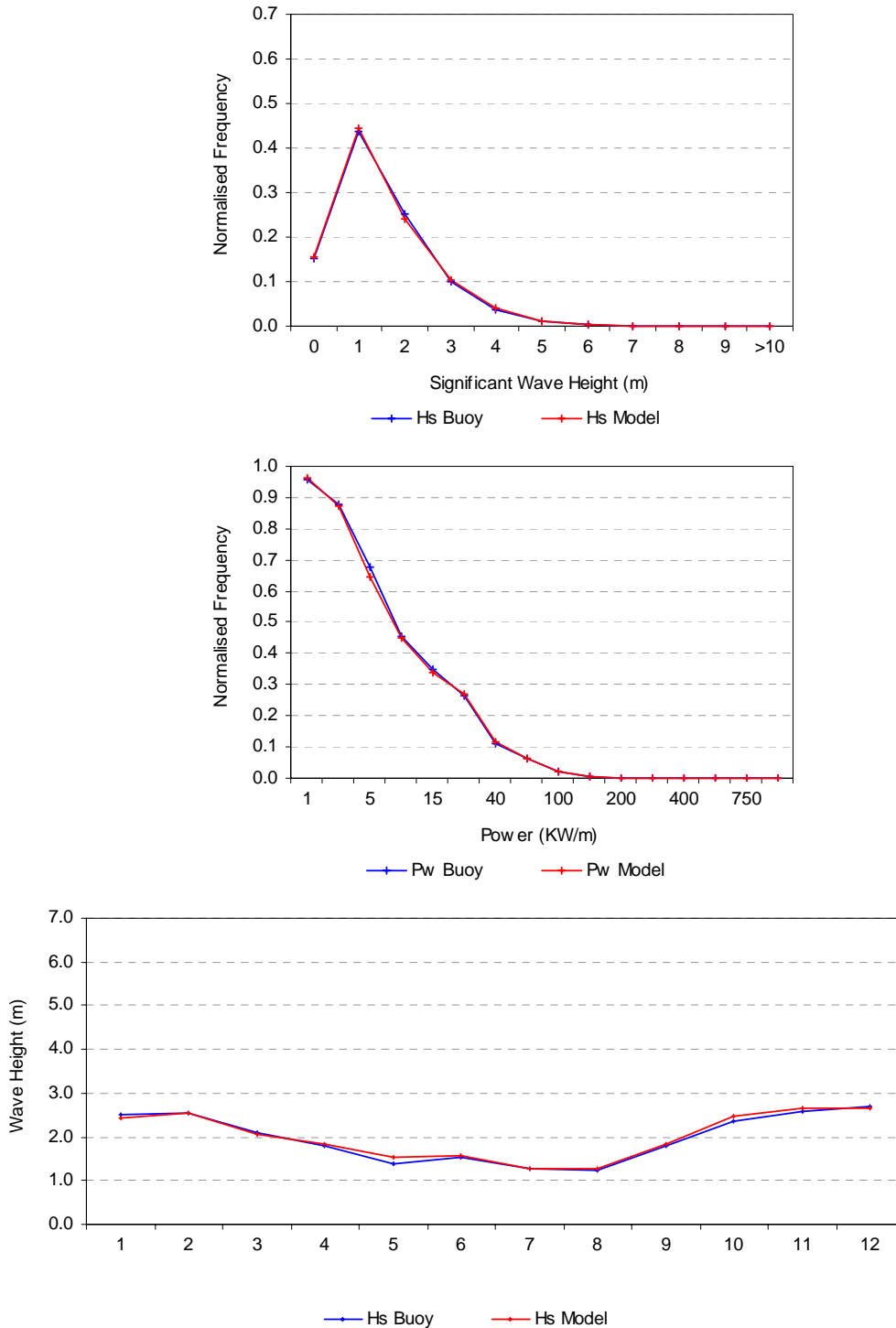


Figure D11. K16 MAWS Station modelled and observed; significant wave height and resultant wave power distributions; monthly mean significant wave heights

D3.2 Short Versus Long Term European Wave Model Comparisons

This analysis compared the Atlas analysis period (7 years, June 2000 to May 2007) with a longer analysis period (15 years June 1992 to May 2007) in order to assess the impact of using a longer time-series. In order to eliminate possible inconsistencies resulting from comparing different model formulations, both the data samples were obtained using data from the Met Office 35km resolution European Wave Model. However, to afford some cross-referencing of this study with the validation of mode performance versus observations, this analysis is tested at the MAWS locations described previously (Figure C23, Table D8).

Table D8. Location of MAWS sites for the European model

Site Name	Closest European Model Point (deg WGS84)	
K5	59.00°N	11.26°W
RARH	57.00°N	10.06°W
Seven Stones	50.00°N	06.06°W
Turbot Bank	51.50°N	05.26°W
Lyme Bay	50.50°N	02.86°W
Greenwich	50.50°N	00.06°W
Aberporth	52.25°N	04.46°W
K17	55.50°N	01.14°E
K16	57.00°N	00.06°W

The statistics used for comparison comprise:

- Annual mean significant wave height and resultant wave power;
- Mean in year variability (standard deviation) of significant wave height and resultant wave power; and
- Significant wave height and resultant wave power exceedence distributions.

Results are presented in Tables D9 and D10 and Figures D12 to D20.

In almost all cases the results show a good agreement between the 7 year and 15 year results, with all significant wave height and almost all resultant wave power mean statistics falling within 10% or less. No significant differences occur in the distributions derived from the 7 and 15 year datasets.

The minor exceptions that in these data are at K5 where the 15 year dataset provides a 21% higher mean power, and in the distributions of wave power at Turbot Bank, K17 and K16. At K5 the wave power distributions are well matched until power exceeds 40 kW/m; implying that in the 15 year period may have been subject to a slightly higher frequency of high energy storms. At Turbot Bank, K17 and K16 the 7 year period shows a higher exceedence of power thresholds in the 1-40 kW/m range. This is matched by a slight increase in frequency of wave heights in the 2-4m band, suggesting that storm tracks during the most recent 7 year period

allowed slightly more energetic wave activity in the Bristol Channel and North Sea areas in more recent years.

Table D9. Comparison of 7 vs 15 year significant wave height (H_s) statistics for validation sites

Station Name	H_s Mean (m)			H_s Std. Deviation (m)		
	15 years	7 years	% Error ^e	15 years	7 years	% Error ^e
K5	2.77	2.64	5	1.83	1.61	14
RARH	3.14	3.15	0	1.79	1.69	6
Aberporth	1.64	1.66	-1	1.08	1.06	2
Turbot Bank	2.46	2.64	-7	1.65	1.61	2
Seven Stones	2.35	2.38	-1	1.47	1.43	3
Lyme Bay	1.29	1.27	1	0.88	0.85	3
Greenwich	1.26	1.25	1	0.84	0.79	6
K17	2.46	2.64	-7	1.62	1.61	1
K16	18.04	18.11	0	26.17	26.74	-2

^e Error calculated as a percentage using (15 year/7 year - 1)*100 values. Negative values show an underestimate, positive values an overestimate

Table D10. Comparison of 7 vs 15 year wave power statistics for validation sites

Station Name	Wave Power Mean (m)			Wave Power Std. Deviation (m)		
	15 years	7 years	% Error ^e	15 years	7 years	% Error ^e
K5	48.77	40.46	21	88.63	64.73	37
RARH	57.72	55.57	4	84.07	78.42	7
Aberporth	15.14	15.09	0	26.83	25.80	4
Turbot Bank	40.86	44.42	-8	75.84	75.48	0
Seven Stones	31.81	31.25	2	53.15	49.23	8
Lyme Bay	8.36	8.02	4	14.99	13.82	8
Greenwich	7.13	6.70	6	12.66	11.19	13
K17	37.32	41.29	-10	68.30	68.70	-1
K16	37.74	40.74	-7	67.45	67.48	0

^e Error calculated as a percentage using (15 year/7 year - 1)*100 values. Negative values show an underestimate, positive values an overestimate

To conclude from this element of the wave study, the 7 year period used by the Atlas can be considered generally representative of the wave climate measured during the last 15 years.

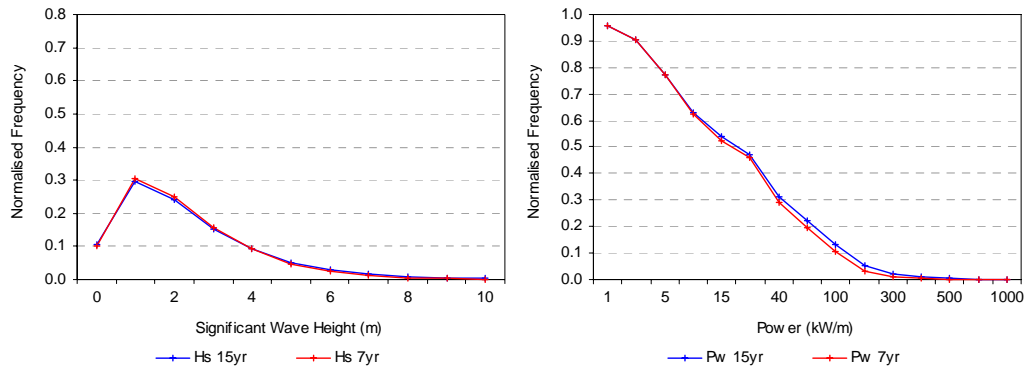


Figure D12. K5 15 year versus 7 year significant wave height and resultant wave power distributions

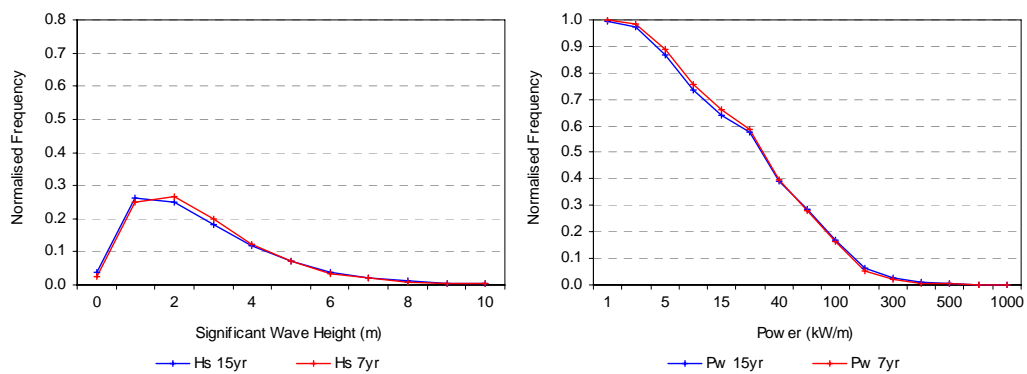


Figure D13. RARH 15 year versus 7 year significant wave height and resultant wave power distributions

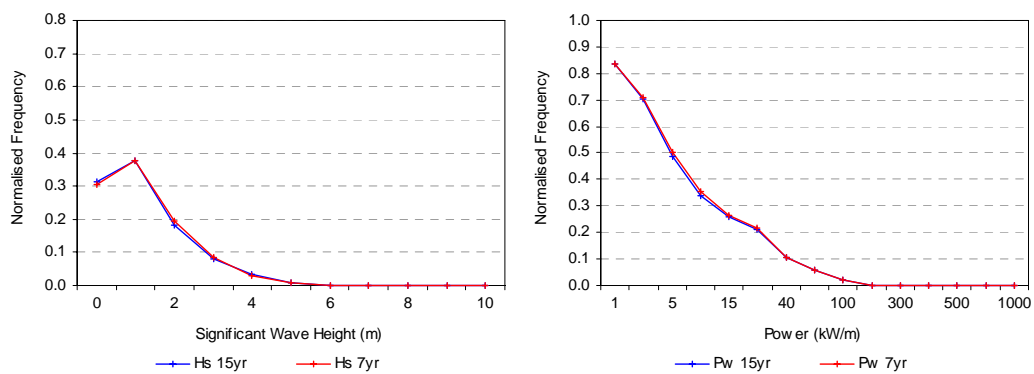


Figure D14. Aberporth 15 year versus 7 year significant wave height and resultant wave power distributions

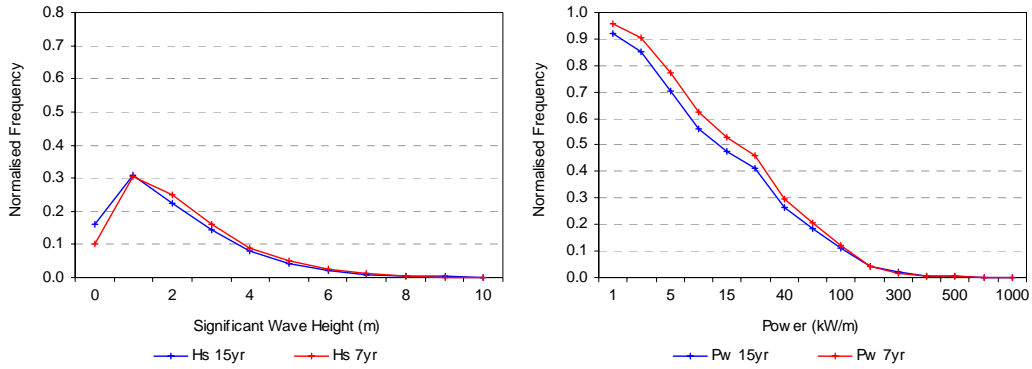


Figure D15. Turbot Bank 15 year versus 7 year significant wave height and resultant wave power distributions

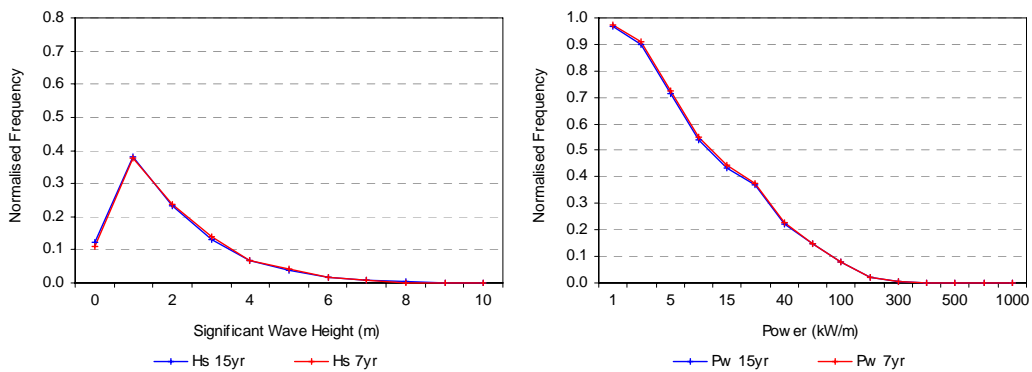


Figure D16. Seven Stones 15 year versus 7 year significant wave height and resultant wave power distributions

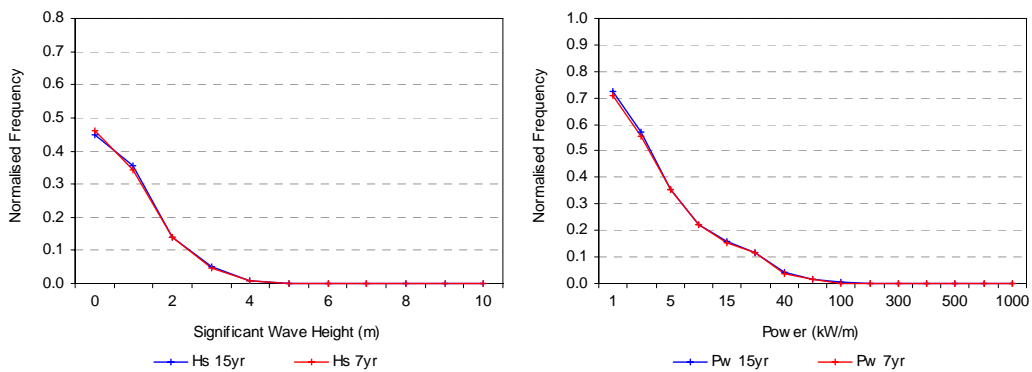


Figure D17. Lyme Bay 15 year versus 7 year significant wave height and resultant wave power distributions

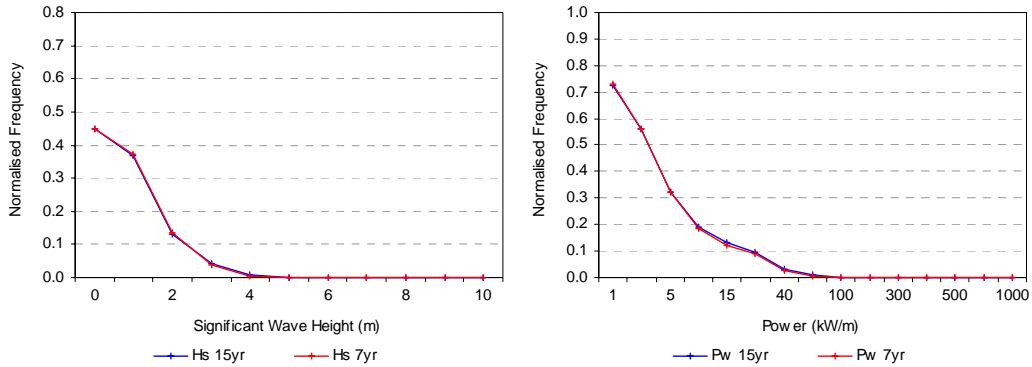


Figure D18. Greenwich 15 year versus 7 year significant wave height and resultant wave power distributions

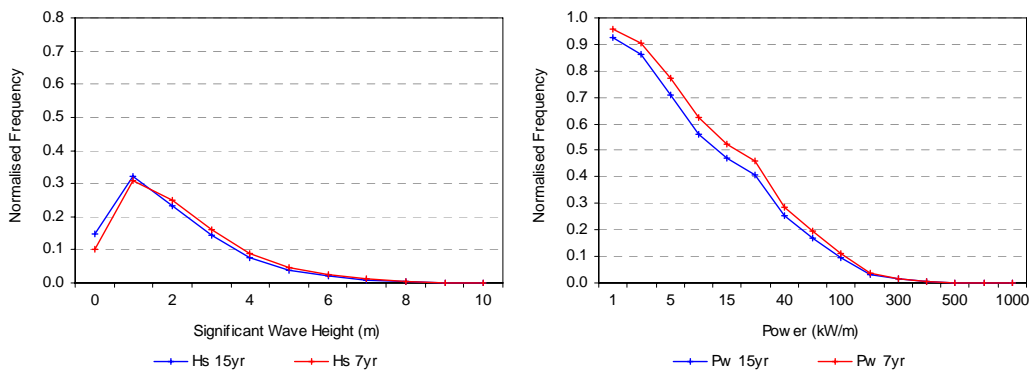


Figure D19. K17 15 year versus 7 year significant wave height and resultant wave power distributions

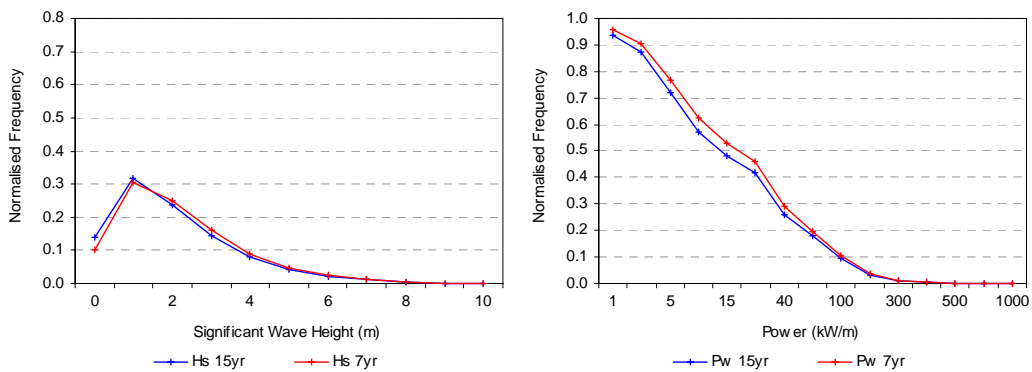


Figure D20. K16 15 year versus 7 year significant wave height and resultant wave power distributions

D.4 Discussion of the Atlas Wave Resource

D4.1 Wave Model Performance

Met Office wave models use a well-established second generation spectral scheme, which has been developed over the past 20 years to produce a robust and generally highly reliable source of wave prediction for offshore regions. The UK Waters Model, from which the Atlas database is sourced, is the most recent development in these models' evolution.

An important part of the modelling process is day-to-day validation of the model focusing on predictive capacity. For purposes of the Atlas database, this validation study has attempted to provide some insight into the behaviour of a UKCS wide model dataset as an indicator of climatology through some simple data comparisons carried out over a small selection of sites where reliable observed marine data is available. A more complete examination of the model data may well be possible through comparison with existing larger geographical datasets (e.g. from satellite observations) but in terms of time and cost falls outside of the remit of this project. Nevertheless results from this study, allied to some general 'health warnings' associated with the well established models from which the Atlas data was sourced, does allow a valid discussion of the integrity of the Atlas wave resource.

Results of the wave resource validation indicate that whilst modelled mean statistics are generally within 5-20% of the observations, the model data performs best at 'open sea' sites, i.e. away from the near coastal zone. In particular, very good results were achieved at the North Sea stations. The Atlantic stations, which are exposed to extremely energetic and long fetch storms, showed a slight tendency to underestimate the most energetic wave conditions.

That the model performed best in open seas is not entirely surprising since closer to the coastline a number of physical processes become important that, although included in the model scheme, can be affected by changes in bathymetry occurring below the scale of the model grid. Specifically these include bottom friction, sheltering and refraction effects that may decrease (or possibly increase) the amount of swell energy reaching a site, and can have considerable local variations (for example in leeward or more open ends of bays). The recommendation is to treat the near coastal zone carefully, making full use of available bathymetric charts and local observations where possible in any decision making. Data from points further offshore in the Atlas should provide a robust guide as to the nature of wave energy incident to the near coastal zone.

Recent developments in use of, and operations occurring in, the near coastal zone have highlighted the need for improved modelling of such areas. Model technology for near coastal areas is well established, ranging from fairly simple refraction models to spectral schemes such as SWAN. However, studies tend to be commissioned piecemeal for specific sites and as such provide a similarly sparse resource in geographic terms to long term observational data. With

improvements in computer capacity however, improving the resolution of more regional or UKCS-wide models is a likely development in the foreseeable future.

D4.2 Long Term Variability in Wave Climate and the North Atlantic Oscillation

Variability in the occurrence frequency and track of storms across the North Atlantic toward Europe is commonly termed as the 'North Atlantic Oscillation' (NAO). The NAO varies on both inter-annual and seasonal timescales, but usually discussion focuses on annual variations of the winter NAO, since this is when storms are most common. Two distinct patterns of NAO are most common, with either frequent strong storms tracking north-eastward and termed a 'high' NAO, or less frequent and weaker storms tracking directly east and into Mediterranean Europe ('low' NAO). These changes will impact wave heights on the UKCS in terms of maximum wave heights experienced, frequency of extreme conditions, and, in the case of more sheltered locations, the potential exposure to remotely generated swell waves.

NAO variability is presently described using indices based on the difference between sea level pressures measured near Iceland and the Azores/Iberian peninsula (e.g. Jones *et al.*, 1997). Using such an index, high NAO periods are linked with a positive NAO index, and conversely low NAO periods with a negative index. Over the last 30 years, the NAO index has taken a positive value for the majority of winters, indicating that the most common storm track influencing waves on the UKCS is north-eastward. In terms of the most recent years used in the Atlas, NAO index values have been generally weak to moderate, although stronger positive NAO values have occurred in the last few years (2004-2007) relative to the period used for the original Atlas dataset (2000-2003).

D5. References

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Appendix E

Desktop GIS Tools

Appendix E. Desktop GIS Tools

E1. Introduction

A desktop GIS based system allows the interrogation of the full tide, wave and offshore wind resource data layers. In order to allow these functions to be undertaken, the tide, wave and offshore wind parameters have been incorporated into a structured database, accessible via the GIS system (as summarised in Figure E1). This system is intended for use on an ArcGIS 9.2 platform and requires the appropriate licence for such software. The features of the system are described in the following sections.

E1.1 Resource Assessment

The Atlas desktop has been developed to allow the regional assessment of marine resources for use as a support tool within the BERR SEA process. The main Desktop GIS tools are:

- Graph Manager; and
- Criteria Selector.

These tools were designed following industry consultation prior to the publication of the first Atlas in 2004 and were re-visited using an on-line questionnaire (see Appendix A) to check present day applicability.

E1.2 Resource Assessment Using the Graph Manager

Each cell held within the resource database can be interrogated to show and compare tide, wave and offshore wind parameters using a bespoke facility in the GIS called the Graph Manager. This enables the user to visualise temporal, directional and vertical changes in the wind, wave and tidal resource parameters which cannot be conveyed easily using conventional two-dimensional thematic mapping. Selected parameters are illustrated in a graphical form which can be exported from the GIS system to allow incorporation into a data summary report. The graph options included are listed in Table E1. All parameters provided in the Atlas are listed in Table E2.

Figure E1

Schematic of Atlas of UK Marine Renewable Energy Resources

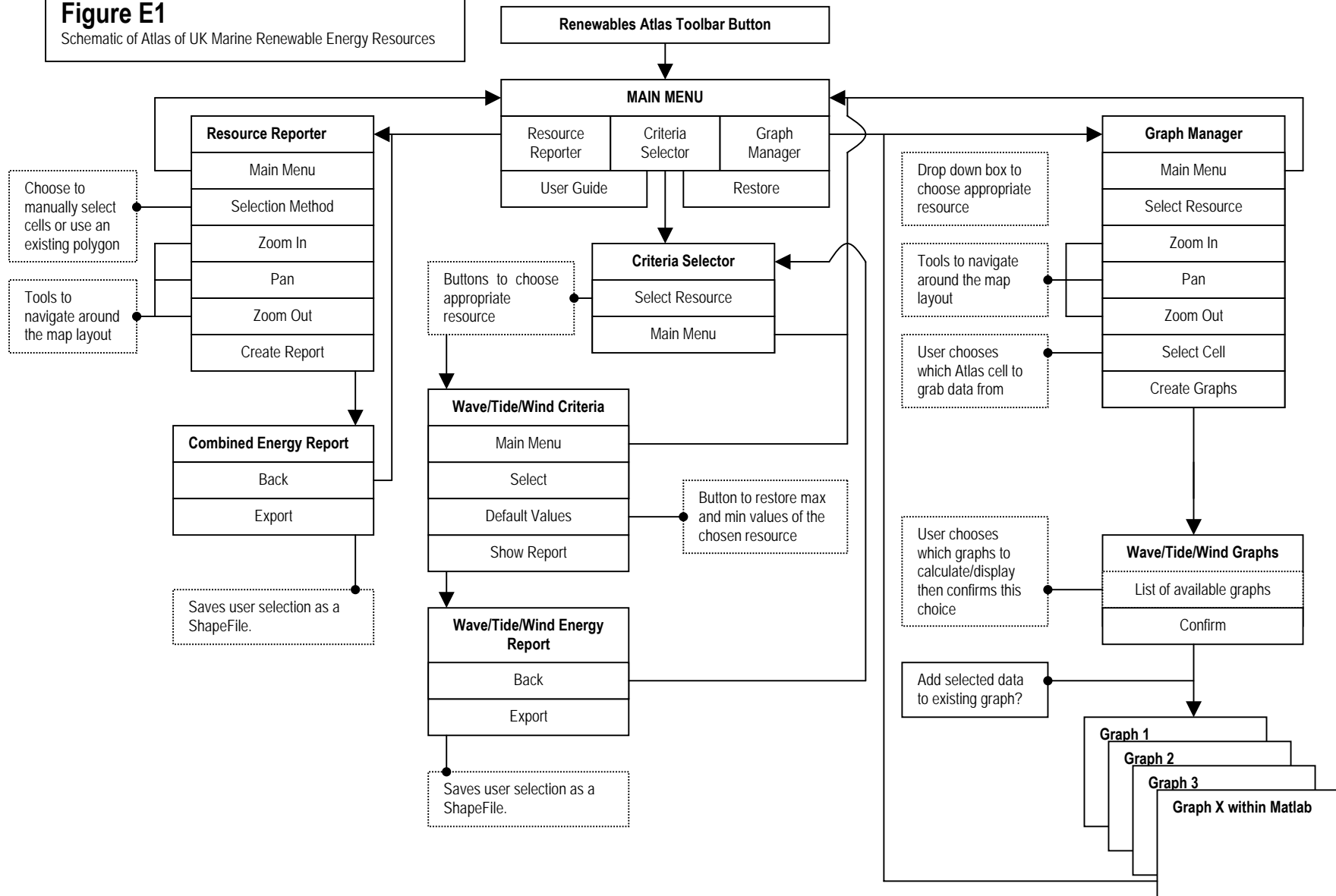
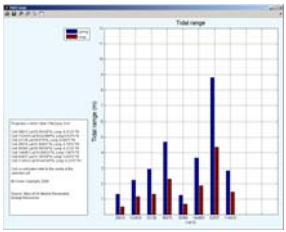
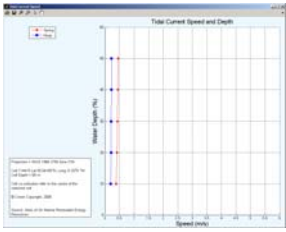
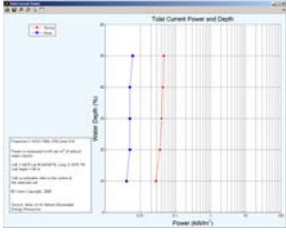
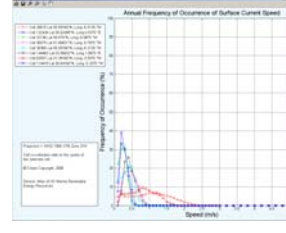
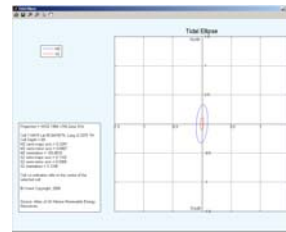
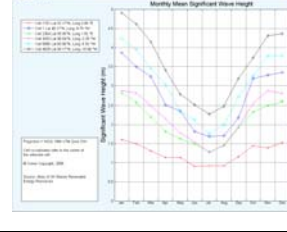
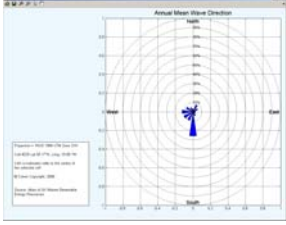
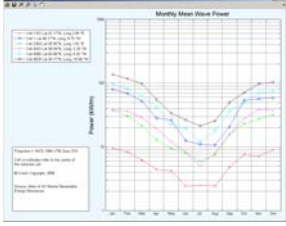
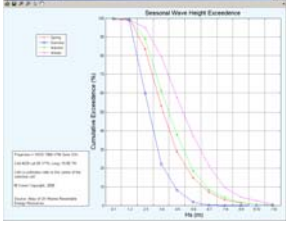
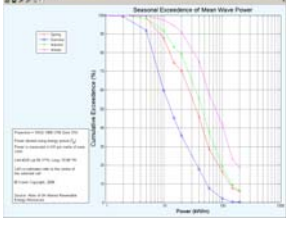
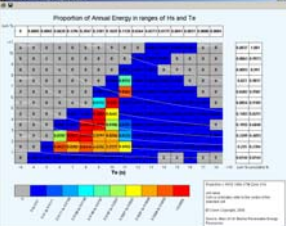
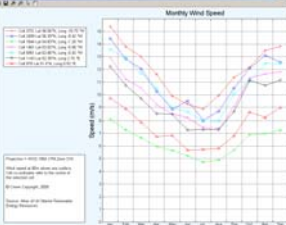


Table E1. Graphical presentation of resource assessment

Energy Resource	Parameter/ Graph	Description	Example
Tidal	Range	Tidal range is shown for both the spring and neap tides for a maximum of nine locations per graph. The presentation of the data in a bar chart format clearly allows comparison between sites, as shown in the example here.	
	Current speed	Current speed for spring and neap tides are shown at 10% depth intervals throughout the water column from 50-90% below the sea surface. One site is shown per graph.	
	Current power	Current power for spring and neap tides are shown at 10% depth intervals throughout the water column from 50-90% below the sea surface. One site is shown per graph.	
	Current speed exceedance at surface	Frequency of occurrence of the average annual current speed. These are shown for a maximum of nine locations per graph.	
	Tidal ellipse	Tidal ellipses are presented for the M ₂ and S ₂ components of the tide (see Appendix B2). One location per graph is shown. The peak spring tidal velocity can be determined from the ellipses from the addition of the M ₂ and S ₂ .	
Wave	Wave height	Significant wave height can be presented in both monthly and seasonal graphs for a maximum of nine locations per graph.	

Energy Resource	Parameter/ Graph	Description	Example
	Wave direction	Wave direction is presented for annual and seasonal periods for a total of eight sectors, each representing 30 degrees. Only one location is shown per graph.	
	Wave power	Wave power is presented both monthly and seasonally for a maximum of nine locations per graph.	
	Wave height exceedance	Wave height exceedance is presented for monthly, seasonal and annual periods. This is shown for a maximum of one location per graph.	
	Wave power exceedance	Wave power exceedance is presented for monthly, seasonal and annual periods. This is shown for a maximum of one location per graph.	
	Wave power, described in ranges of H_s and T_e	Wave power is also displayed as a function of H_s and T_e . Bands are shown illustrating the power available for a combined range of these parameters. Occurrences of various combinations at one site are shown as counts and coloured with red representing high counts and blue low counts.	
Wind	Wind speed	Wind speed is presented both monthly and seasonally for a maximum of ten locations per graph.	

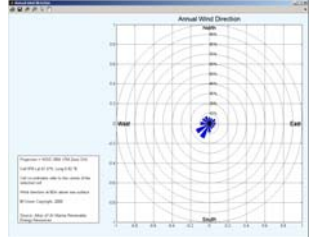
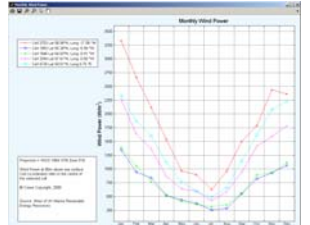
Energy Resource	Parameter/ Graph	Description	Example
	Wind direction	Annual wind frequency, speed and direction is provided for eleven locations within the UKCS.	
	Wind power	Wind power is presented both monthly and seasonally for a maximum of ten locations per graph.	

Table E2. All parameters in the Atlas database

Energy Resource	Parameter	Temporal Resolution	Units
Tidal	Tidal Range	Spring and neap	m
	Current speed	Spring and neap	m/s
	Current speed exceedance	Spring and neap	% frequency
	Ellipse Semi-major axis	Spring and neap	non-dimensional
	Ellipse Semi-minor axis	Spring and neap	non-dimensional
	Ellipse Orientation	Spring and neap	deg. clockwise
	Phase of ellipse	Spring and neap	+/-
Wave	Tidal power density	Annual, spring and neap	kW/m ²
	Significant wave height	Monthly, seasonal and annual	m
	Wave period	Monthly, seasonal and annual	sec
	Wave direction	Seasonal and annual	deg. N
	Wave power	Monthly, seasonal and annual	kW/m
	Significant wave height exceedance	Monthly, seasonal and annual	Cumulative %
Wind	Wave power exceedance	Monthly, seasonal and annual	Cumulative %
	Wind speed	Monthly, seasonal and annual	m/s
	Mean power density	Annual	W/m ²
	Direction	Annual	deg. N

For those parameters unsuitable for presentation in a graphical form, the GIS interface will display it in tabular form as either a value or coloured cell. An example of this is given in Table E1 showing wave power, described in ranges of H_s and T_e .

E1.3 Resource Assessment Using the Criteria Selector

The criteria selector enables rapid identification of locations that meet specific tidal, wind or wave resource thresholds as well as other parameters including both and distance from land. The tool offers the user a standard form to input constraint values of certain parameters (Table E3) which are both generic (e.g. distance from shore) and resource specific (e.g. wave height). The results of the selection are highlighted on the map and key statistics such as number of selected cell and area are also returned. The tool also include an export function wish allows the user to export the selection to a new layer which can be stored for future use.

Table E3. Criteria selector parameters

Resource	Parameters
Tidal	Water column position, water depth, distance from shore, tidal power, current speed, tidal range
Wave	Season, wave height, water depth, distance from shore, wave power
Wind	Season, device height, water depth, distance from shore, wind speed

E2 User Guide

E2.1 Overview of ArcGIS MXD Documents

The Atlas of UK Marine Renewable Energy Resources GIS is designed to be accessed from two ArcGIS *.mxd projects. These can be found in the default folder **C:\Program Files\UK_MRER_ATLAS**. Project 'Atlas_Resource.mxd' provides tools to visualise wind, wave and tidal resource parameters for the United Kingdom continental shelf, which cannot be conveyed easily using conventional two-dimensional thematic mapping. This project also provides custom tools for interrogating and reporting wind, wave and tidal resource parameters. (Note: The use of 'Atlas_Resources2.mxd' and 'temp.mxd' are explained in Section 3.5).

E2.2 Data

All of the data used in the GIS can be found in the folder **C:\Program Files\UK_MRER_ATLAS\Data**. All of the vector and tabular data is stored in layers within ArcGIS Geodatabases called Atlas.mdb, Wind.mdb, Wave.mdb and Tide.mdb. Please note that although this file shares the same extension as a Microsoft Access database it is not designed, and therefore should not be opened, using this software. Each of the layers in the Geodatabases contains many attributes recording detailed information about the wind, wave and tidal resources. Each attribute name is limited to ten characters. To make attribute information more accessible each attribute has been assigned an alias that is used as a column header in the attribute table if the layer is loaded into ArcMap. **For more information about the and their attributes please refer to the Metadata pdf document in the C:\Program Files\UK_MRER_ATLAS\Documents folder.** The bathymetry dataset that is used within the Atlas is stored as a raster ArcGIS grid layer and therefore cannot be loaded into the

geodatabase. This dataset is also located in the Data folder and can be accessed using ArcGIS.

E2.3 GIS Layer Files

The data stored in the geodatabase and the bathymetry grid can be coloured to display different attributes. This information can be saved as an ArcGIS layer (*.lyr) file enabling the colour palette and banding to be recalled if the dataset is loaded into a different ArcGIS project. As part of the Atlas project, data from the geodatabase has been coloured to highlight useful attributes that present important resource parameters. This information has been saved into layer files that are located in the **C:\Program Files\UK_MRER_ATLAS\Layers** folder. These layers can be added to any existing or new ArcMap document. Please note that these layers reference the data in the geodatabase and therefore are dependent on it remaining in the same relative file path location to the layer files.

E3 Atlas Resource Project

E3.1 Introduction

The Atlas resources project is located at **C:\Program Files\UK_MRER_ATLAS\Atlas_Resources.mxd**, and can be accessed through Windows Explorer or the 'Open' menu in ArcMap. This project provides tools to visualise wind, wave and tidal resource parameters for the UKCS, which cannot be conveyed easily using conventional two-dimensional thematic mapping. It also provides custom tools for interrogating and reporting wind, wave and tidal resource parameters.

Please note that Microsoft Excel must not be open whilst using the Atlas.

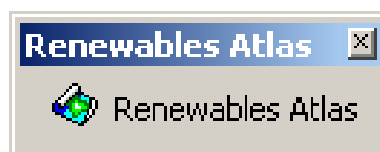


Figure E2. UK Marine Renewable Atlas Toolbar

This project opens with all the required data displayed. Click the 'Renewable Atlas' toolbar (Figure E2) to activate the main menu (Figure E3). If this toolbar disappears go to View > Toolbars and click Renewables Atlas. The menu has links to the four tools contained within the resources section of the Atlas GIS.

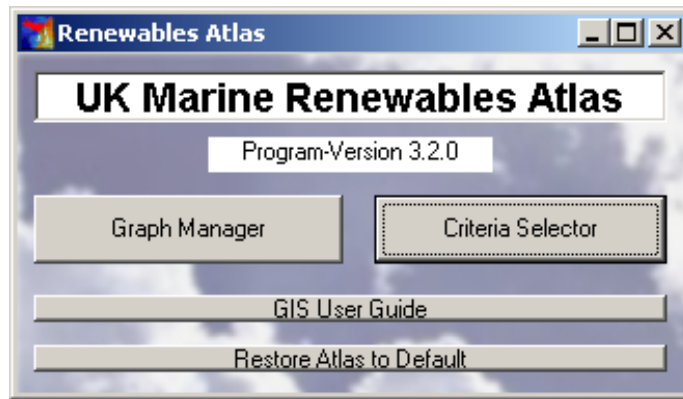


Figure E3. UK Marine Renewable Atlas main menu

E3.2 Graph Manager

The Graph Manager allows the user to view complex information about the resources that is not suited to conventional mapping. The Graph Manager tool is accessed from the main menu. Instructions for this tool are provided below.

- 1) Use the dropdown list to choose a resource. Please note that separate resources cannot be graphed together.

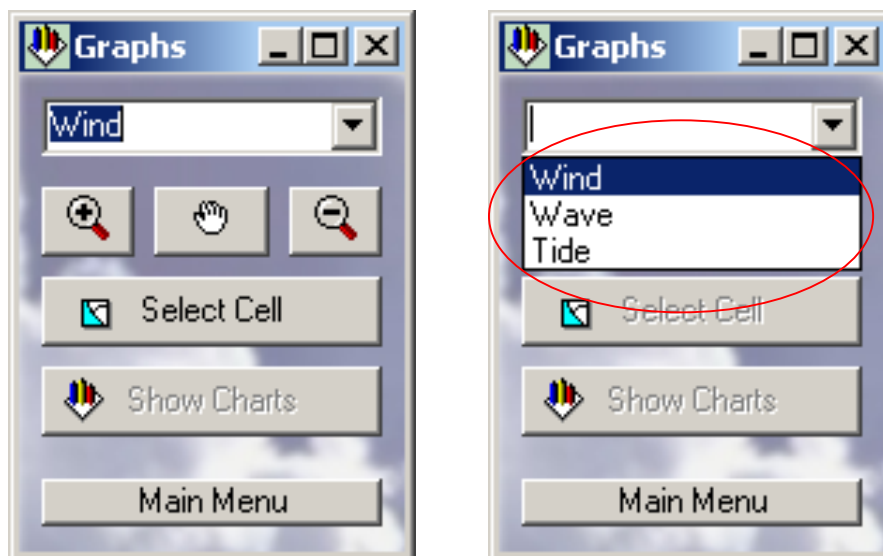


Figure E4. Graph Manager form

- 2) The displayed map will refresh to show the chosen resource. Use the Zoom and Pan tools on the Graph Manager form to locate your area of interest.
- 3) Click the Select button then click on the map to pick a resource cell. Please note that initially only one cell should be selected and if more than one is selected then graphs will be created from the selection which comes first in the resource attribute table.
- 4) Click the Show Charts button to initiate graph calculations. You will be prompted with a list of available graphs in a window (Figure E5). Choose the graphs you wish to view and **Confirm** your choices. The graphs from the chosen resource cell will be loaded into new graph windows.

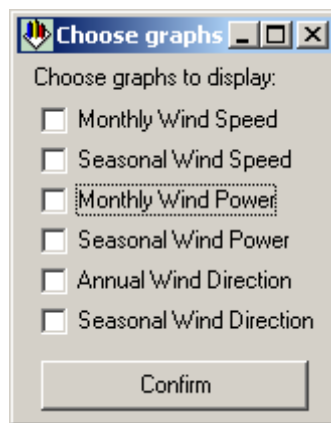


Figure E5. Graph Manager choice menu

- 5) Some of the graphs can support data from up to 9 cells. To add data from a new cell to the existing graphs simply select a different cell and click **Show Charts**. When prompted (Figure E6) click **Yes** to indicate that you wish to add the data from the new selection to the existing graph.

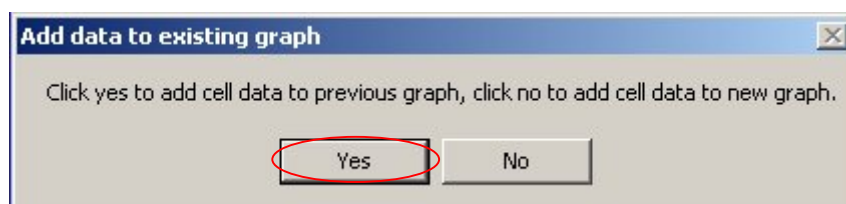


Figure E6. Message box prompting the addition of extra data a current graph

- 6) Click **No** to add the data from the new cell to a fresh version of the graph window. Existing data retrieved will be overwritten at this point.
- 7) Each graph has Print, Save (to .TIFF format), Export and Zoom functionality accessibly along the toolbar at the top of the graph window.
- 8) A further button to Export the underlying data of the graph to a .CSV file also exists.
- 9) To select a graph from a different resource, close the graph window and return to the dropdown list in point 1.

E3.3 Criteria Selector

The Criteria Selector selects cells from a resource based upon criteria defined by the GIS user. As an example, this tool could be used to select areas that are suitable for the deployment of a particular technology based upon minimum resource criteria being exceeded, and maximum resource criteria not being reached. The Criteria Selector tool is activated from the main menu (Figure E3). Instructions of use are provided below.

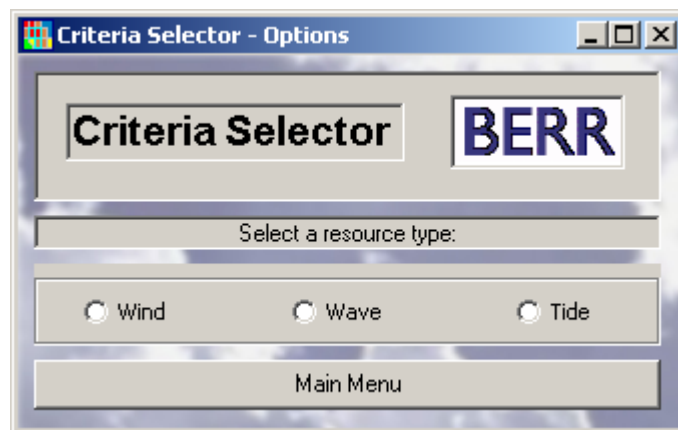


Figure E7. Criteria Selector menu

- 1) Criteria can be selected from one resource at a time. The resource is chosen from the Criteria Selector menu (Figure E7).
- 2) For each resource there are fixed parameters that can be selected using the dropdown lists provided (Figure E8).
- 3) When these criteria have been selected the remaining user-definable criteria boxes are populated with the maximum and minimum values for each parameter.

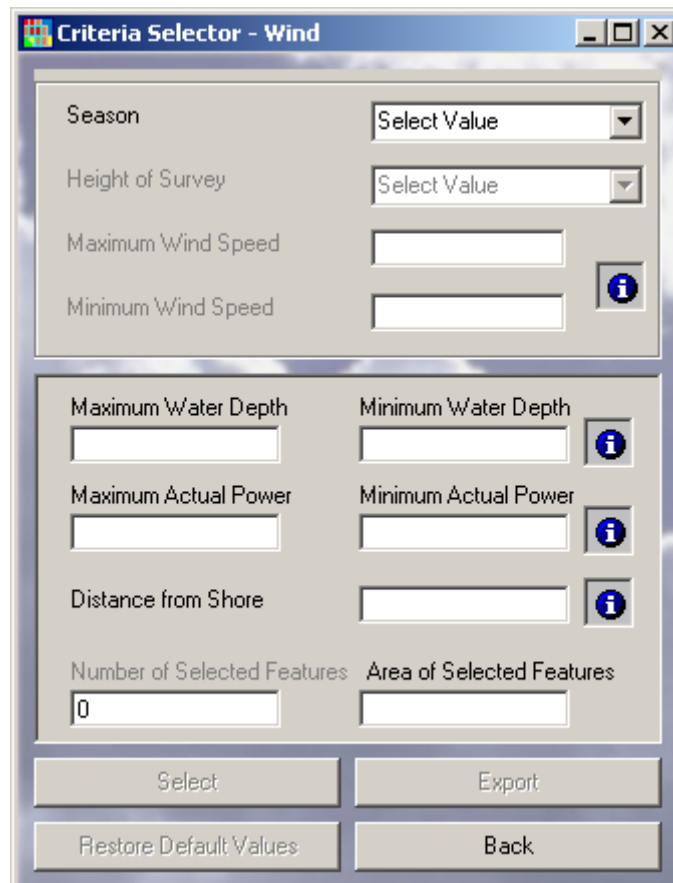



Figure E8. Criteria Selector - Wind menu

- 4) The user can customise the selection criteria by entering new values. If a value is entered that is outside of the maximum or minimum range for selected resource, the user is notified and the value reset. If the default maximum and minimum values are required again these can be restored by clicking on the **Restore Default Values** button. Further information about the criteria is available by clicking on the information button  next to each box.
- 5) Following the entry of the desired criteria the **Select** function will perform a selection. The results displayed are highlighted in light blue in the map window. The number of cells that have been selected is displayed in the bottom left corner of the Criteria Selector window. The Criteria Selector is based upon an 'and' statement, therefore all of the criteria must be met in order for a cell to be selected. Please note that selections based upon the tidal resource will take longer due to the high resolution of this dataset.

- 6) The **Show Report** function allows the user view statistics concerning the selected cells. The user is then given an **Export** function which saves the selection to a new geodatabase layer. The geodatabase is by default located at `C:\Program Files\UK_MRER_ATLAS\Data\Atlas_Selections.mdb`. The user is required to enter a layer name, please note that this name can only contain numbers, letters and underscores and must be unique.
- 7) The exported selection can be added to the current map or recalled by loading the layer from the `C:\Program Files\UK_MRER_ATLAS\Data\Atlas_Selections.mdb` geodatabase into any ArcMap project.

E3.4 GIS Guide and Resetting the Atlas

Details of the two other buttons on the main Atlas menu (Figure E3) are provided below.

- 1) GIS User Guide:
A link to a User Guide which explains the Atlas functionality.
- 2) Restore Atlas to Default:
This uses `C:\Program Files\UK_MRER_ATLAS\Atlas_Resources2.mxd` to reset the Atlas back to how data was displayed upon installation, creating a temporary file in the process. 'Atlas_Resources2.mxd' should **not** be altered. This function is useful if the Atlas has been used and altered (such as adding/removing layers or zooming to a specific site) and then these alterations have been saved, consequently the Atlas will reopen with these alterations and may confuse a new user.

E3.5 Changing Data Sources

The following section requires knowledge of GIS terminology and an understanding of ArcGIS tables.

Users may hold their own data in their own database, or move the existing Atlas data to this database.

If using their own data users must have the field names in their tables the same as field names in existing tables used by the Atlas, as it is these names that are looked for when data is retrieved by the tool.

Alternatively to move an existing Atlas dataset to a different database simply import all the files in `C:\Program Files\UK_MRER_ATLAS\Data\Atlas.mdb` to the database. To then change the data source of the Atlas open the application in the normal way and follow the instructions below.

The Atlas must be saved after a change has been made to ensure new data sources remain.

- 1) After opening the Atlas right-click on the name of a resource (e.g. Wind) in the Table of Contents, and choose **Properties**.

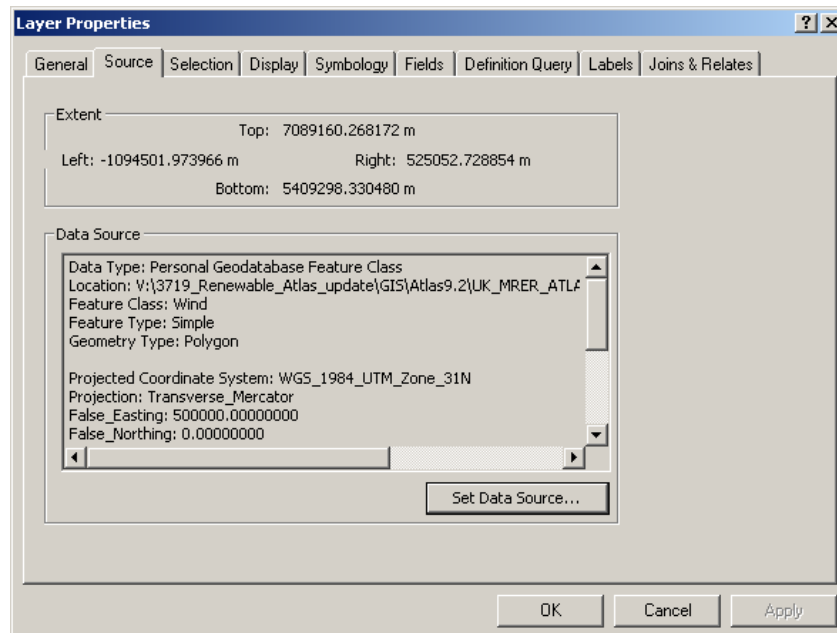


Figure E9. A typical ArcGIS layer properties window

- 2) Locate the **Source** tab and click the **Set Data Source...** button and then navigate to the appropriate to become the new dataset and add it as the new data source. This process must be done for each data file in the Atlas geodatabases. The Atlas must then be saved to remember the change in data sources. Resetting the Atlas back to its default setting will also reset data source links.
- 3) A point to note is that the way the Atlas is designed means it requires the above datasets to always be labelled 'Wind', 'Wave' and 'Tide', etc. in the Table of Contents, regardless of what the actual filename in the database is. Changing data sources as described above should not change this requirement and should keep the names in the Table of Contents as the Atlas needs them to be. But if the user changes the name of a dataset in the Table of Contents then the Atlas will no longer recognise it as belonging to that resource.

E3.6 Troubleshooting

Information about potential GIS problems and associated solutions are provided below.

E3.6.1 Error Selecting

- Question: Is there already a selection active within the target layer?
Solution: Clear the selection by using the Selection -> Clear Selected Features menu option.
- Question: Is selection enabled in the target layer?
Solution: Enable selections to be made from the target layer by using the Selection -> Set Selectable Layers... menu.
- Question: Is there no selection in the polygon layer that the selection is to be based upon?
Solution: Make a selection in the polygon layer using the selection tool.

E3.6.2 Error Saving or Exporting

- Question: Is the Geodatabase Read only?
Solution: Check the `C:\Program Files\UK_MRER_ATLAS\Data\Atlas_Selections.mdb` (or other selected file destination) using Microsoft Windows Explorer and amend in necessary.
- Question: Is the Feature Class name unique?
Solution: Use ArcCatalog to navigate to the `C:\Program Files\UK_MRER_ATLAS\Data\Atlas_Selections.mdb` and review Feature Class names already stored.
- Question: Is the prefix name unique?
Solution: Use ArcCatalog to navigate to the `C:\Program Files\UK_MRER_ATLAS\Data\Atlas_Selections.mdb` and review prefixes already used.

E3.6.3 Renewables Atlas Button Missing

If the button to load the Renewables Atlas disappears, select **Tools > Customise..** and look under the **Commands** tab for **Renewables Atlas Commands** under the **Categories** list (Figure E10). If this is not present click the **Add from file..** button and browse to the 'Atlas' folder in the Renewables Atlas set-up folder (default `C:\Program Files\UK_MRER_ATLAS`). In the 'Atlas' folder should be a file called `UK_MRER_ATLAS.dll`. Add this and a screen similar to Figure E10 should appear. With this present left-click on **Renewables Atlas** in the **Commands** list and drag it to the Renewables Atlas toolbar. Close the Customise window.

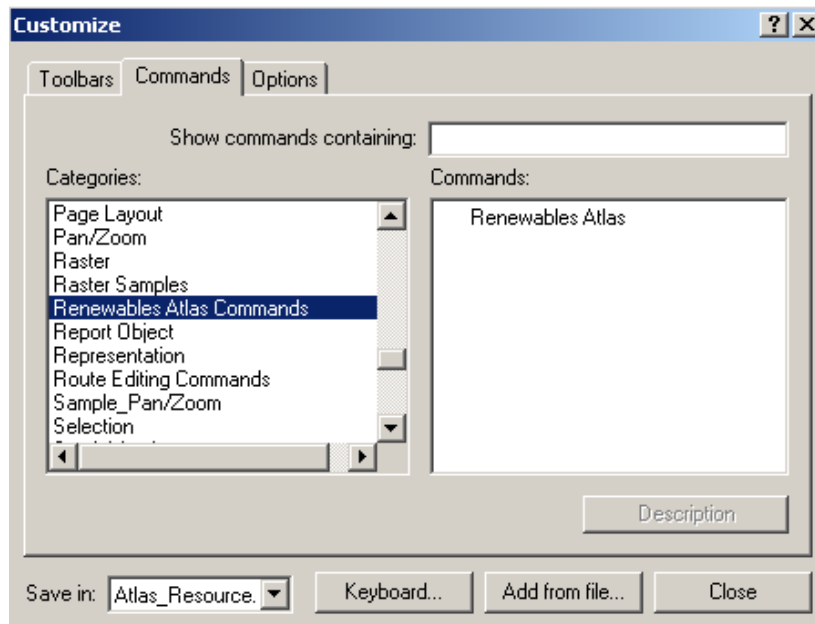


Figure E10. ArcMap Customise window

If the above procedures fail uninstall the Atlas then navigate to the Atlas installation path and delete the folder **UK_MRER_ATLAS**, then reinstall the Atlas again.



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