The Scottish Shelf Model. Part 2: Pentland Firth and Orkney Waters Sub-Domain

Scottish Marine and Freshwater Science Vol 7 No 4

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The Scottish Shelf Model. Part 2. Pentland Firth and Orkney Waters sub-domain

Marine Scotland

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Document history

The Scottish Shelf Model. Part 2: Pentland Firth and Orkney Waters sub-domain

Marine Scotland

This document has been issued and amended as follows:

Version	Date	Description	Created by	Verified by	Approved by
1.0	04/03/2013	Draft report including only data review section.	Maurice McCabe, Fiona McLay, Darren Price	Hakeem Johnson	John Debenham
1.1	21/6/2013	Draft including initial model calibration	Darren Price	Hakeem Johnson	John Debenham
1.2	8/11/2013	Draft including barotropic model validation	Darren Price	Hakeem Johnson	John Debenham
1.3	28/02/2014	Added section on wave model setup and calibration.	Hakeem Johnson		
1.4	28/3/2014	Added skeleton sections for wave simulations, and wave and tidal energy	Darren Price/Caroline Stuiver		
1.5	10/6/2014	Added sections on wave simulations and wave energy resources	Hakeem Johnson Caroline Stuiver		
1.6	28/8/2014	Update PFOW calibration for 10 layer model	Darren Price		
1.7	24/11/2014	Added section on effect of wave-current interaction	Hakeem Johnson Caroline Stuiver		
1.7a	10/12/2014	Incorporates comments from Marine Scotland on issue 1.7.	Caroline Stuiver	Hakeem Johnson	
1.8	03/01/2015	Climatology and tidal energy analysis added	Caroline Stuiver	Darren Price	

1.9	26/06/2015	Final version. Summary and conclusions added. Minor changes as a result of general editing.	Darren Price Caroline Stuiver	Hakeem Johnson	John Debenham
1.10	04/09/2015	Minor changes based on comments from Marine Scotland.	Caroline Stuiver	Hakeem Johnson	John Debenham

The Scottish Shelf Model. Part 2: Pentland Firth and Orkney Waters sub-domain.

Authors: Darren Price, Caroline Stuiver, Hakeem Johnson, Alejandro Gallego, Rory O'Hara Murray.

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The FVCOM model has been developed by the Marine Ecosystem Dynamics Modeling Laboraotry at the School for Marine Science and Technology, University of Massachusetts, Dartmouth, led by Dr Changsheng Chen. We would like to acknowledge Dr Chen for authorising the project team to use FVCOM for the development of the Scottish Shelf Model.

We would like to thank the SSM Steering Group for their contribution. In particular, Tracy McCollin (Marine Scotland) as the Project Manager, John Debenham (CH2M HILL) and Alan Hills (Scottish Environment Protection Agency). Daniel Pendrey and Kate Smith (Marine Scotland) and Andrew Berkeley (SEPA) also participated in the Steering Group.

We also wish to acknowledge the contribution of Fiona McLay, Maurice McCabe, Ilektra Apostololidou and Elysia Ward (CH2M HILL).

The Grid2Grid freshwater runoff data were supplied under contract by the Centre for Ecology and Hydrography. We would like to thank Robert Moore and his colleagues at CEH for those data. The waves model boundary data were supplied under contract by the UK Met Office from their European, UK Waters and Wave Watch II models.

Many individuals and organisations, too numerous to list individually, made data and data products used in the development of this model available free of charge. All relevant data sources are acknowledged through the text of these reports and we refer the readers to that information.

Contents

Abbreviations

Abbreviation	Meaning
ABPmer	Associated British Port Marine Environmental Research
ADCP	Acoustic Doppler Current Profiler
AMM	Atlantic Margin Model
BODC	British Oceanographic Data Centre
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CEH	Centre for Ecology and Hydrology
CTD	Conductivity, Temperature and Depth instrument
DHI	Danish Hydraulic Institute
DTM	Digital Terrain Model
ECLH	East Coast of Lewis and Harris
ECMWF	European Centre for Medium range Weather Forecasting
EMODNet	European Marine Observation and Data Network
EMEC	European Marine Energy Centre
FVCOM	Finite Volume Community Ocean Model
G2G	Grid-to-Grid
GEBCO	General Bathymetric Chart of the Oceans
GSHHS	Global Self-consistent, Hierarchical, High-resolution Shoreline
ICES	International Council for the Exploration of the Sea
MHW	Mean High Water

Abbreviation	Meaning
MHWS	Mean High Water Spring
MS	Marine Scotland
MSL	Mean sea level
NGDC	National Geophysical Data Centre
NOAA	US National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre
NOC-L	National Oceanography Centre - Liverpool
NODB	National Oceanographic Database
NOOS	Northwest European Shelf Operational Oceanographic System
NTSLF	National Tide and Sea Level Facility
ODYSSEA	Ocean Data analYsis System for SEA
OS	Ordnance Survey
PFOW	Pentland Firth and Orkney Waters
PFOWSA	Pentland Firth and Orkney Waters Strategic Area
POL	Proudman Oceanographic Laboratory
POLCOMS	Proudman Oceanographic Laboratory Coastal Ocean Modelling System
POL HRCS	Proudman Oceanographic Laboratory High Resolution Continental Shelf
SEPA	Scottish Environment Protection Agency
SMB	St Magnus Bay
SSS	Sea Surface Salinity

Abbreviation	Meaning
SST	Sea Surface Temperature
SWAN	Simulating Waves Nearshore
UKHO	United Kingdom Hydrographic Office
WLLS	Wider Loch Linnhe System
WOA	World Ocean Atlas
WVS	World Vector Shoreline

1 Introduction

1.1 Background

Halcrow Group Ltd. (a CH2M Company) was commissioned by Scottish Ministers to develop a ‗Hydrodynamic model of Scottish Shelf waters'. The contract was commissioned under the Scottish Government Framework Contract for the Provision of Strategic Environmental Assessment, Appropriate Assessment and Marine Planning Services and Advice to Support Sustainable Economic Development in Scottish Marine Waters (REF: 177895) – Call Off Number 11 - Provision of a Hydrodynamic Model of Scottish Shelf waters – 16 May 2012. The project is managed on behalf of the Scottish Ministers by Marine Scotland.

The Scottish Government is committed to the development of a successful marine renewable energy industry in Scotland, which is currently also the largest producer of farmed Atlantic salmon in the EU and third largest globally. To achieve the sustainable development of both the offshore renewable energy industry and the aquaculture sector, Marine Scotland has adopted a planning approach to identify potential developmental areas.

Both of these factors are drivers for the development of a regional hydrodynamic model of the Scottish Shelf Waters and four more localised models which will be used to inform their planning approach. Marine Scotland will take ownership of the hydrodynamic models at the end of the study enabling them and other community organisations they work with, to undertake simulations and further development to meet their planning and research needs.

This report forms part of a series of reports that were produced during the lifetime of this project.

1.2 Study areas

The overall study area includes all of the Scottish shelf waters out to the 200m depth contour at the edge of the continental shelf. The shelf waters model is used to simulate the hydrodynamic conditions in three-dimensions, including meteorological and tidal forcings.

Within this region-wide shelf waters model, four local three-dimensional models are setup providing higher resolution to resolve key bathymetry, coastline and physical processes over smaller more local areas. These four model areas have been defined as case studies and cover the following regions:-

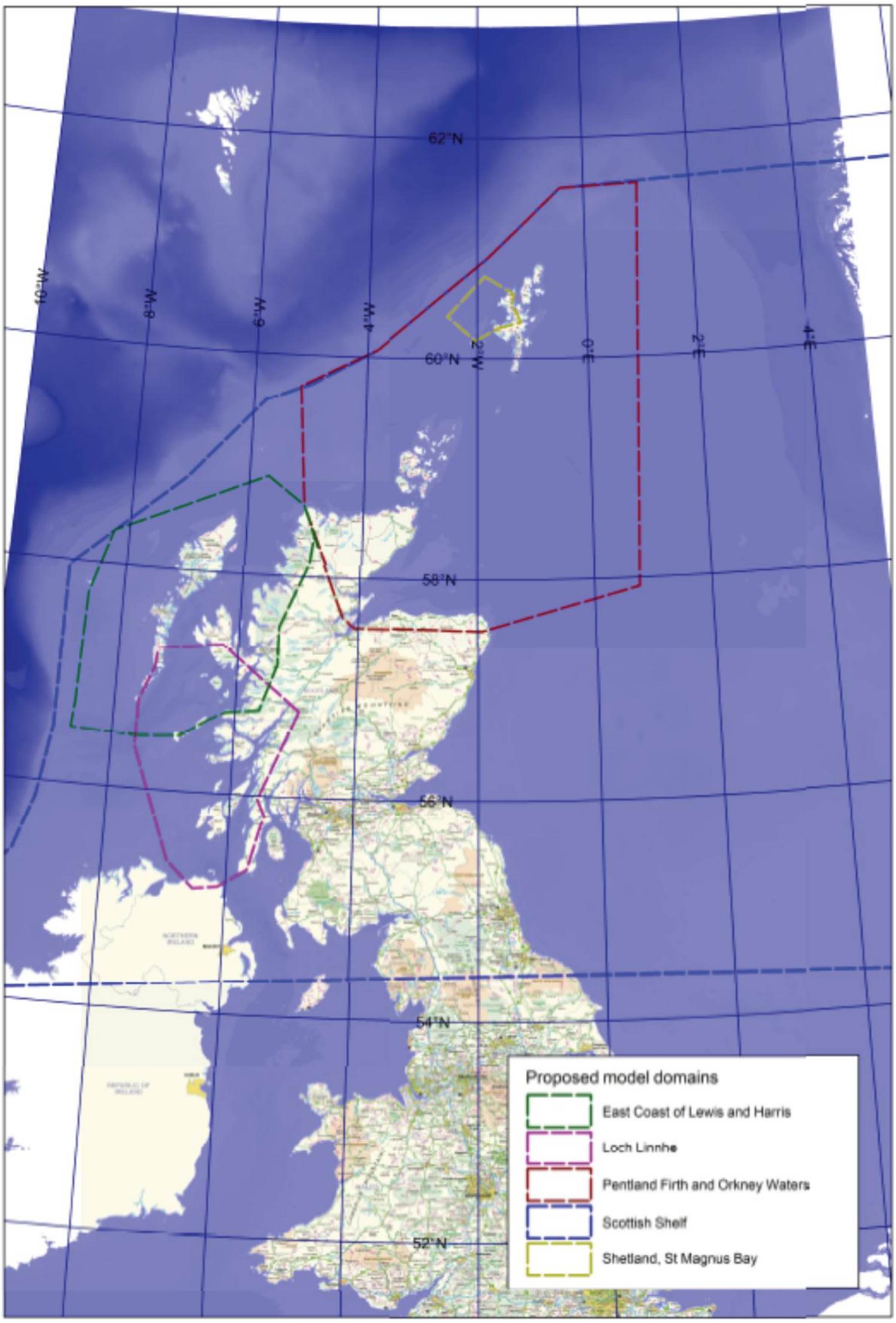
Case Study 1: Pentland Firth and Orkney Waters (PFOW)

Case Study 2: Wider Loch Linnhe System

Case Study 3: East Coast of Lewis and Harris

Case Study 4: Northwest Shetland mainland – St Magnus Bay area

The locations and proposed areas of these models are shown in Figure 1-1, note that these model domains are not the final model domains but an approximation.



Client	Consulting Engineer	Project:	**Figure 1-1**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location of the Shelf and individual case study model domains

1.3 Aims and scope of numerical modelling works

The main aims of the project are to: 1) develop a validated three dimensional hydrodynamic model for the Scottish shelf waters; 2) develop a validated three dimensional hydrodynamic model for each of the four identified case studies. In addition, to develop a validated wave model for the Pentland Firth and Orkney Waters (Case Study 1); and 3) integrate the case study sub-models into the wider domain shelf model.

The modelling study is aimed at providing a quantitative description of marine currents and water properties for the whole of Scottish waters on a range of spatial scales. The outputs of this study comprise validated hydrodynamic models (shelf model and local case study models) capable of predicting tidal and non-tidal currents for the whole of the Scottish shelf and inshore waters; a more accurate assessment of the connectivity of different regions; and the available energy resources (wave and tidal energy) in the Pentland Firth and Orkney Waters. It also include description of methods for assessing the impact of extracting some of that energy upon the physical environment.

The modelling is undertaken using an open-source three-dimensional (3D) hydrodynamic model called FVCOM. One of the reasons behind the choice of this modelling software is that the models developed in this project will be freely available to others at the end of the Project. Marine Scotland have a vision that the models will be used and developed further by Marine Scotland staff and the marine modelling community as more data becomes available and/or other needs are identified.

1.4 Project Team

The project team delivering this study consists of:

- Halcrow Group Ltd as the main contractor, responsible for co-ordination of team and development of the hydrodynamic models for the four case studies.
- National Oceanography Laboratory, Liverpool (NOC-L) as subcontractor, responsible for development of the Scottish shelf model.
- Centre for Ecology and Hydrology (CEH) responsible for delivering river outflow discharge data covering the entire Scottish waters and Northern Ireland using the Grid to Grid model.

- Prof. Chen of University of Massachusetts, USA, responsible for providing technical support on the application of the FVCOM software.

- Prof Christina Sommerville of University of Stirling, UK, responsible for providing technical support on sea lice and development of connectivity indices.

1.5 This Report

This report documents the work carried out in developing the Pentland Firth and Orkney Waters (PFOW) model. This work includes: data collated and/or identified for the numerical modelling, setup and calibration of the flow and wave models, and the longer term simulations required for this study. It is noted that the data section in this report is a summary of the overall Data Review report (Halcrow, 2012) that is relevant to the PFOW area. This report is Volume 1 of the PFOW model report. A companion volume (Volume 2) contains additional details on model development (data preparation, mesh generation, preparation of model setup files, how to run the model, etc.).

1.6 Datums

Unless explicitly stated otherwise the following reference datums are used in this study:

- All horizontal co-ordinates are referenced to latitude and longitude.

- All vertical levels are relative to MSL.

1.7 Acknowledgments

We gratefully acknowledge with thanks the contributions of the following organisations and individuals to this project.

- Marine Scotland (Alejandro Gallego, Rory O‘Hara Murray, George Slesser and Berit Rabe) for providing, requesting and collecting available data.
- UKHO for the bathymetry datasets provided.
- BODC/NOC-L for the wide range of oceanographic data and metadata; this is a great source of data. Thanks to Polly Hadziabdic at BODC for helping us with our enquiries.
- SEPA for providing tide gauge data, which has been very useful for this study.

- CEH (Robert Moore and team) for providing river discharges data using the Grid-to-Grid model for this study.
- CEFAS for the provision of wave data from their WAVENET website. Thanks to David Pearce at CEFAS for his help with clarifying the terms of use of these data.
- Dr Susana Baston Meira and Dr David Woolf at Heriot-Watt University for their help with obtaining ADCP data in the Pentland Firth.
- Professor Chen at the University of Massachusetts (Dartmouth) and his team.
- We also acknowledge with thanks the owners of the internet websites mentioned below for the valuable data downloaded from them for this study.
- Tide gauge data (class ‗A‘) from the National Tide and Sea Level Facility (NTSLF – available from http://www.ntslf.org/) will be downloaded and used for calibration purposes.
- ICES database (http://ocean.ices.dk/) which proved to be a good source of data.
- Bathymetric metadata and Digital Terrain Model data products have been derived from the EMODNet Hydrography portal - http://www.emodnet-hydrography.eu. This portal was initiated by the European Commission as part of developing the **European Marine Observation and Data Network** (EMODNet).

2 Available data for model development

2.1 Introduction

In order to carry out the numerical modelling works for the Pentland Firth and Orkney Waters (PFOW), the following data have been collated and/or identified:

- Bathymetry data, required for creating the bathymetry for the numerical model.
- Forcing data, required for specifying the forcing conditions in the numerical wave and flow models.
- Calibration and validation data, required for calibrating and validating the numerical models.

This section of the report describes the data collated/identified for the Pentland Firth and Orkney Waters (PFOW) model area. Where appropriate, reference is made to the overall project data review report (Halcrow, 2012). Note that the proposed model domains shown are not the final model domains but an approximation.

2.2 Bathymetric Data

2.2.1 Coastline Data

Two coastline data sets have been obtained for use in this study the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) distributed by National Geophysical Data Centre (NGDC) in the US, and Ordnance Survey Mapping.

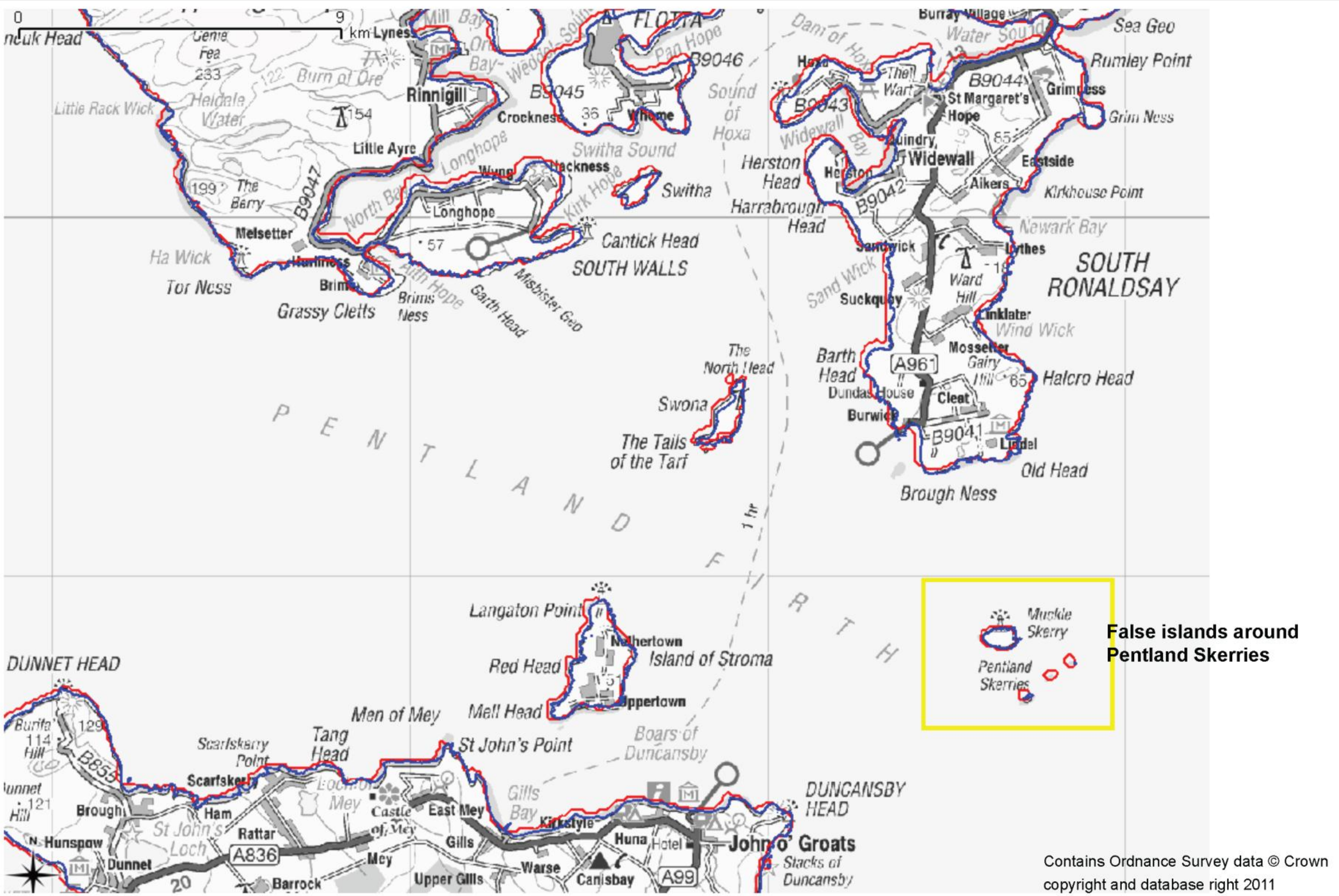
The GSHHS coastline comes in different resolutions. For the UK, the best resolution available is the World Vector Shoreline (WVS) designed to be used at a resolution of 1:250,000. The GSHHS coastlines have been data processed to ensure they are free of internal inconsistencies such as erratic points and crossing segments.

The Ordnance Survey (OS) Vector Map District contains tidal boundary polylines, which are at Mean High Water Spring level (MHWS) in Scotland and MHW in England and Wales. These are at higher spatial resolution than the GSHHS shoreline dataset. Figure 2-1 shows both the OS Vector Map District tidal boundary and the GSHHS shoreline dataset for the Pentland Firth area. False islands occur over the Pentland Skerries in the GSHHS shoreline data set, which are shown as lying between the MLWS and MHWS boundaries in the Ordnance

Survey Vector Map District dataset. The GSHHS data is considered appropriate for use in areas where the model resolution is coarse, the OS vector map district MHWS line was used in areas of higher resolution, such as for the Pentland Firth and Orkney Waters.

2.2.2 Global/Regional Gridded Data Sets

Three existing coarse resolution bathymetry data sets have been identified which cover the study area the GEBCO_08, the ETOPO-1 grid and the EMODnet grid. These are described briefly below. Details regarding these datasets are provided in Halcrow (2012).



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-1		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	OS Vector Map District MHWS (blue) and GHSS coastlines for the Pentland Firth (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012

2.2.2.1 General Bathymetric Chart of the Oceans (GEBCO)

The GEBCO_08 data set is a global DTM at 0.5 minute resolution generated from a database of bathymetric soundings with interpolation between soundings guided by satellite-derived gravity data. The dataset is produced by GEBCO (http://www.gebco.net).

Known errors or discontinuities in the data set occur between regions where data is derived from satellite data and detailed bathymetric survey – this is evident in a grid pattern in the Southern North Sea Region, and a discontinuity at 0°E. Marine Scotland has highlighted errors where false banks occur on the shelf around the Shetland Island (Hughes, 2014).

Figure 2-2 shows the GEBCO_08 bathymetry for the British Shelf and the source of the data. The discontinuity at 0°E and the grid pattern in the North Sea are clearly visible.

2.2.2.2 ETOPO-1

ETOPO-1 is a global DTM at 1 minute resolution produced by NOAA National Geophysical Data Center. The documentation states that this uses the GEBCO_08 data set for the British Shelf. Due to the lower resolution this dataset has not been considered further.

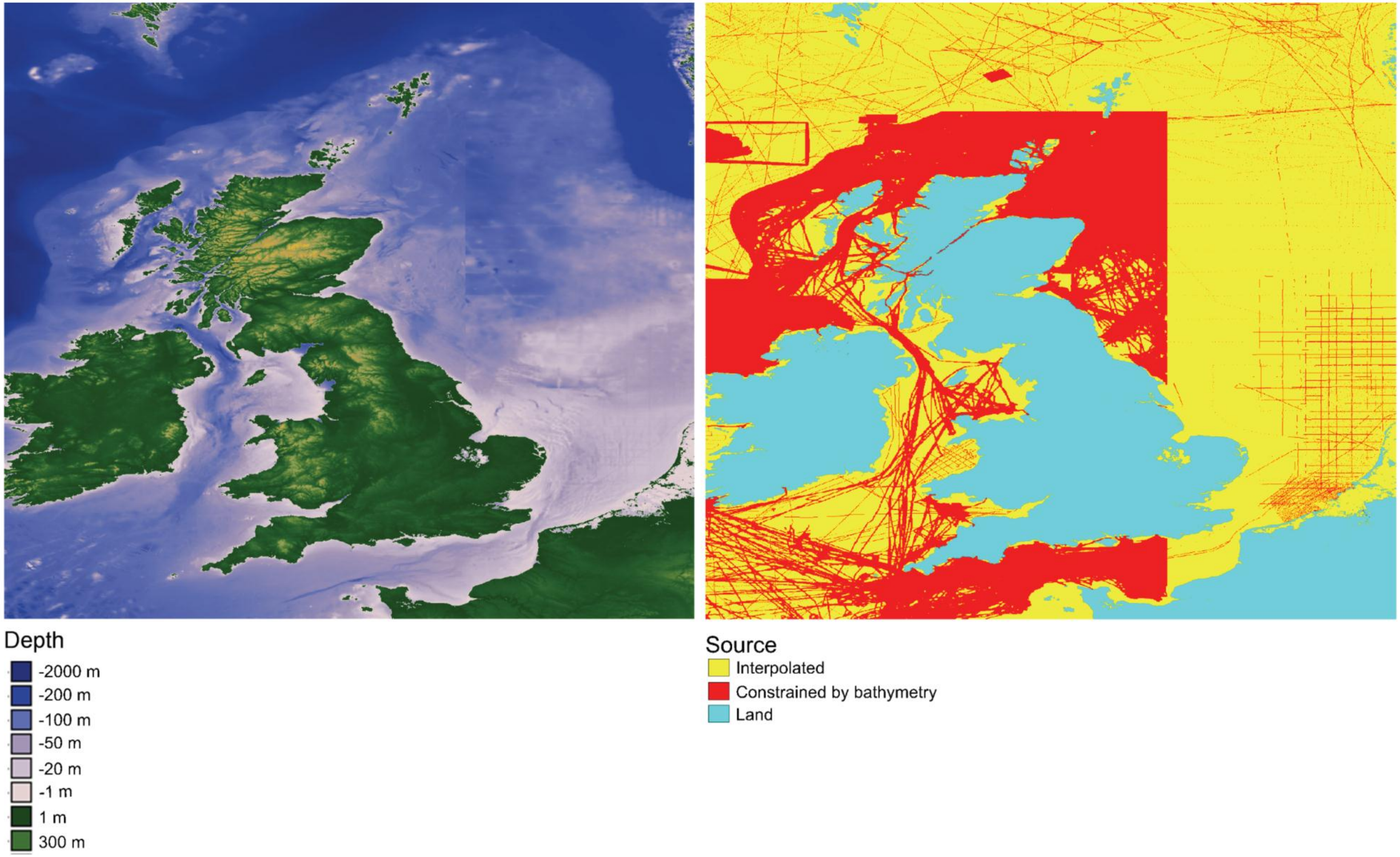
2.2.2.3 European Marine Observation and Data Network (EMODnet)

The European Marine Observation and Data Network (EMODnet) have produced DTMs for the Greater North Sea and Celtic Seas at 0.25 minute resolution (about 250m east-west direction and 450m north-south directions). The grids are based on bathymetric surveys and terrain models developed by external data providers including the UK Hydrographic Office (UKHO), and the GEBCO_08 Grid 0.5 minute resolution dataset where no other data is available. Data sets are made available through the EMODnet website http://www.emodnet-hydrography.eu/

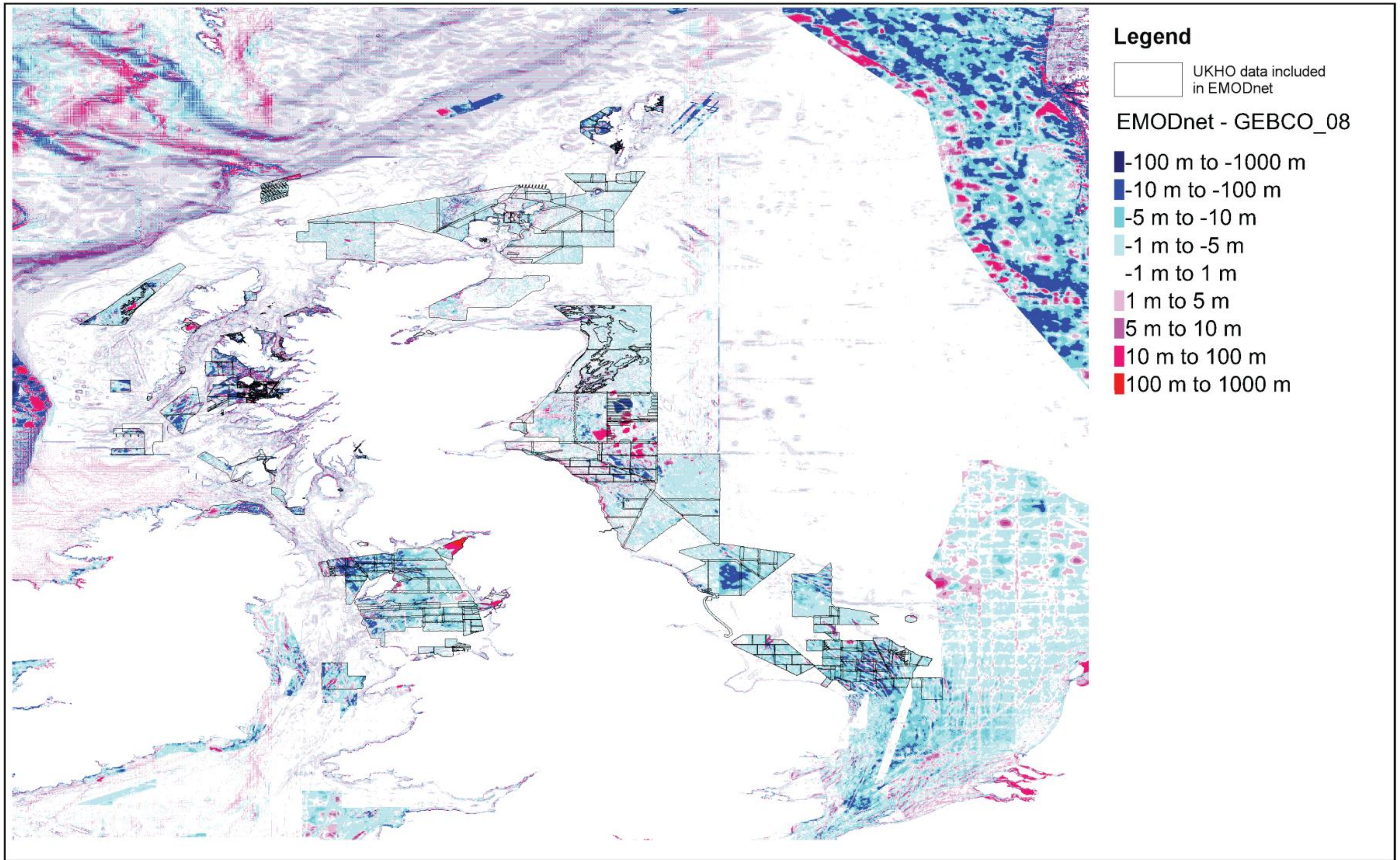
Further details of EMODnet are provided in Halcrow (2012).

Figure 2-3 shows where UK Hydrographic office data has been incorporated into the EMODnet dataset and the differences between the EMODnet and GEBCO_08 bathymetry. Comparison of the EMODnet and GEBCO_08 data sets shows significant differences where the data from the UKHO and other hydrographic offices has been included. Differences are generally greater in areas where the GEBCO_08 has been interpolated, and the UKHO data has been used in the EMODnet bathymetry, for example around 1.5°W 56.3°N, due east of the Firth of Tay. The large differences west of Norway are due to incorporation of Norwegian hydrographic office data. There are also differences north west of the British Shelf around Iceland, where the EMODnet data is sourced from the GEBCO_08 grid. However these have not been investigated as they are not considered important for the study area.

Due to the inclusion of the majority of the UKHO data, ***the EMODnet bathymetry is considered appropriate for use as the base bathymetry for model construction in areas where the resolution was in the order of one kilometre.*** Higher resolution bathymetry data is however required in areas where the model mesh is finer to represent bed or flow features. Therefore other datasets are required as described below.



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-2		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Data sources used in the GEBCO data set.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012



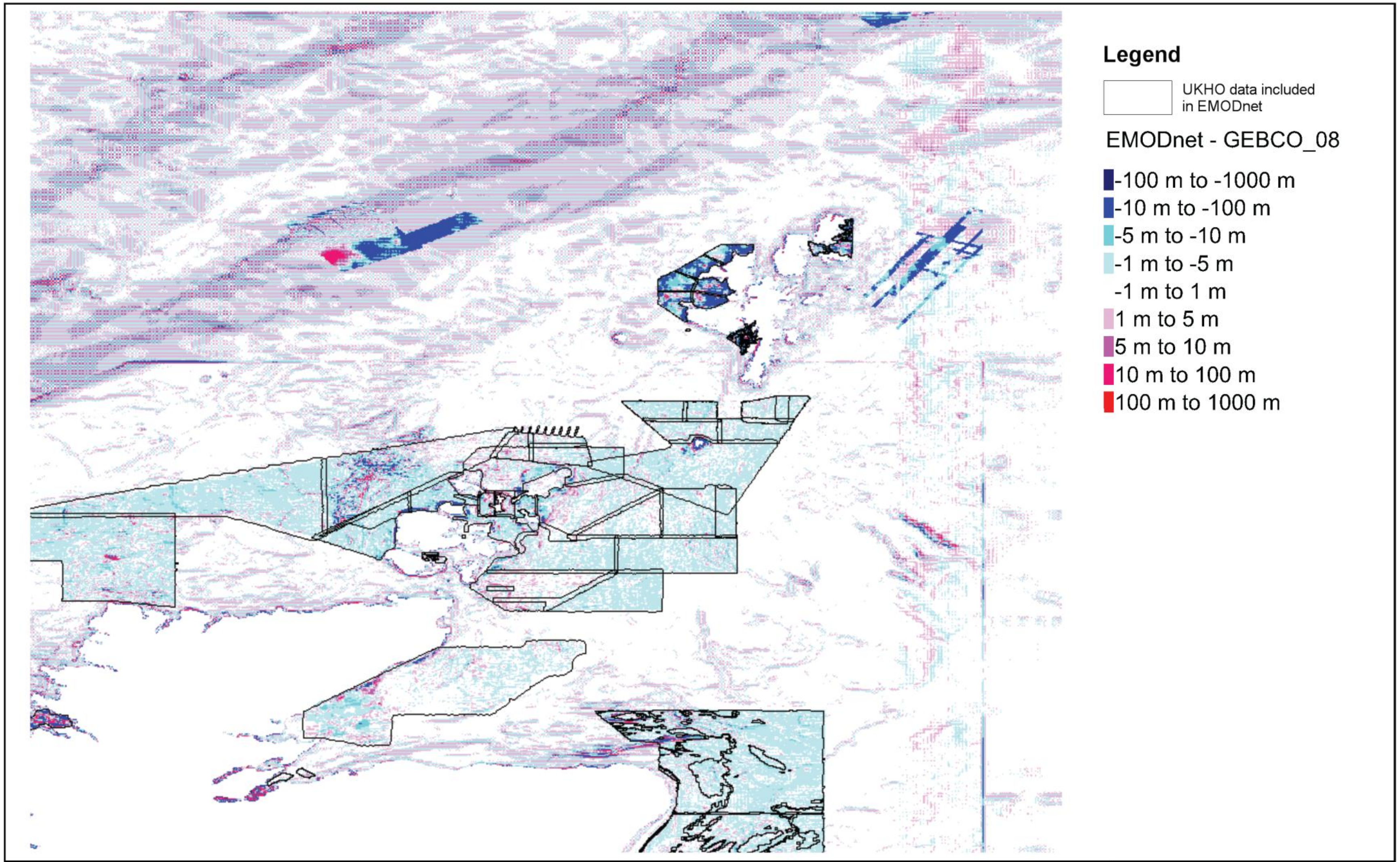
Client	Consulting Engineer	Project:	Figure Title:	Figure 2-3		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	EMODnet data sources and difference between EMODnet and GEBCO_08 bathymetry.	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed: FML	Drawn	Date: 14/112012

2.2.3 Hydrographic Data

Three sources of hydrographic survey data have been identified; the United Kingdom Hydrographic Office (UKHO), the International Council for Exploration of the Sea (ICES) and Marine Scotland's data sets.

The UKHO have a memorandum of understanding with Marine Scotland making their high resolution bathymetric survey available. Most of these data have already been incorporated into the EMODnet bathymetry, however further data has since become available. The location of the UKHO data is shown in Figure 2-3 (also Figure 2-4 for smaller areas of sea). Marine Scotland has carried out recent bathymetric surveys for the Pentland Firth which are not listed in the UK Hydrographic office data sets.

The ICES surface dataset holds over 100 years of ship based observations, including soundings. There are over 2 million data points in the ICES data set within the study area, providing a good coverage over most areas. The ICES website (http://ocean.ices.dk/) states that data are quality controlled by contributing organisation and visually inspected by experienced staff to further improve the quality of these data. However it is expected that due to the age of some of the sounding data and the differences in measurement methods, data logging and processing that there may be significant differences or scatter between the soundings. Marine Scotland used the ICES dataset to identify and correct anomalies in the GEBCO_08 data set off the coast of Shetland. See Halcrow, 2012, for more detail regarding hydrographic data and the differences observed between datasets.



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-4		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Bathymetry data for the Pentland Firth and Orkney Waters model	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed: FML	Drawn:	Date: 14/112012

2.2.4 NOOS 1.0

NOOS 1.0: A gridded dataset for the UK continental shelf at 1 arc-minute resolution was produced under the aegis of NOOS (an operational oceanography organisation for the NW European Shelf (see Halcrow, 2012 for more information). The NOOS bathymetry incorporates local datasets made available by oceanographic institutions in countries around the North Sea, however no detailed source attribution information is available for the bathymetry, and it was last revised in 2004. Bathymetric surveys collected by the UKHO post 2004 are therefore not incorporated in to the bathymetry, and it is uncertain to what extent earlier UKHO and other national hydrographic office datasets were incorporated.

The NOOS bathymetry as gridded in the NOC-L high resolution continental shelf model (1.5 minute by 1 minute resolution) was compared with ICES ship track soundings and the EMODnet bathymetry. The NOOS bathymetry does not have a discontinuity in the North Sea at 0°E and is more consistent with the ICES ship track soundings than the EMODnet bathymetry east of 0°E. The false islands in the EMODnet and GEBCO bathymetry east and north east of Shetland are not present in the NOOS bathymetry. It is therefore considered more appropriate to use the NOOS bathymetry than the EMODnet bathymetry for the PFOW and the shelf model in the North Sea east of 0°E, except in areas where it is known that UKHO data has been incorporated into the EMODnet bathymetry. Where UKHO data has been incorporated into the EMODnet bathymetry the difference between the EMODnet bathymetry and the ICES ship track soundings is less than for the NOOS bathymetry. As the EMODnet bathymetry is also at higher resolution it is not considered appropriate to use the NOOS bathymetry east of 0°E where it is known than hydrographic office data has been incorporated into the EMODnet bathymetry.

However, south east of Shetland (0.1°W,59.6°N to 0.2°E 60°N) the NOOS bathymetry is shallower than the EMODnet bathymetry and less consistent with the ICES ship track soundings, and comparison with chart data is needed in this region. Differences between the NOOS bathymetry and the ICES ship track soundings are also larger than for the EMODnet bathymetry for the west of Scotland, including the Inner and Outer Hebrides. It is therefore not considered appropriate to use the NOOS bathymetry west of 0°E.

2.2.5 Other data sources

Other identified data sources include digital Admiralty charts (C-MAP) and SeaZone. However, these datasets were not used for this study due to licensing restrictions as discussed fully in Halcrow (2012). A licence enabling Halcrow to digitise the required Admiralty Charts was obtained from the Hydrographic Office and the digitising undertaken. This allows the data to be used into the future for this project without paying a licence fee every year. The digitised Admiralty Charts are used to fill the gaps in the digital bathymetry data available for the PFOW model.

2.2.6 Summary of bathymetry data availability for the Pentland Firth and Orkney Waters Area

This section summarises the availability of bathymetry data for PFOW area.

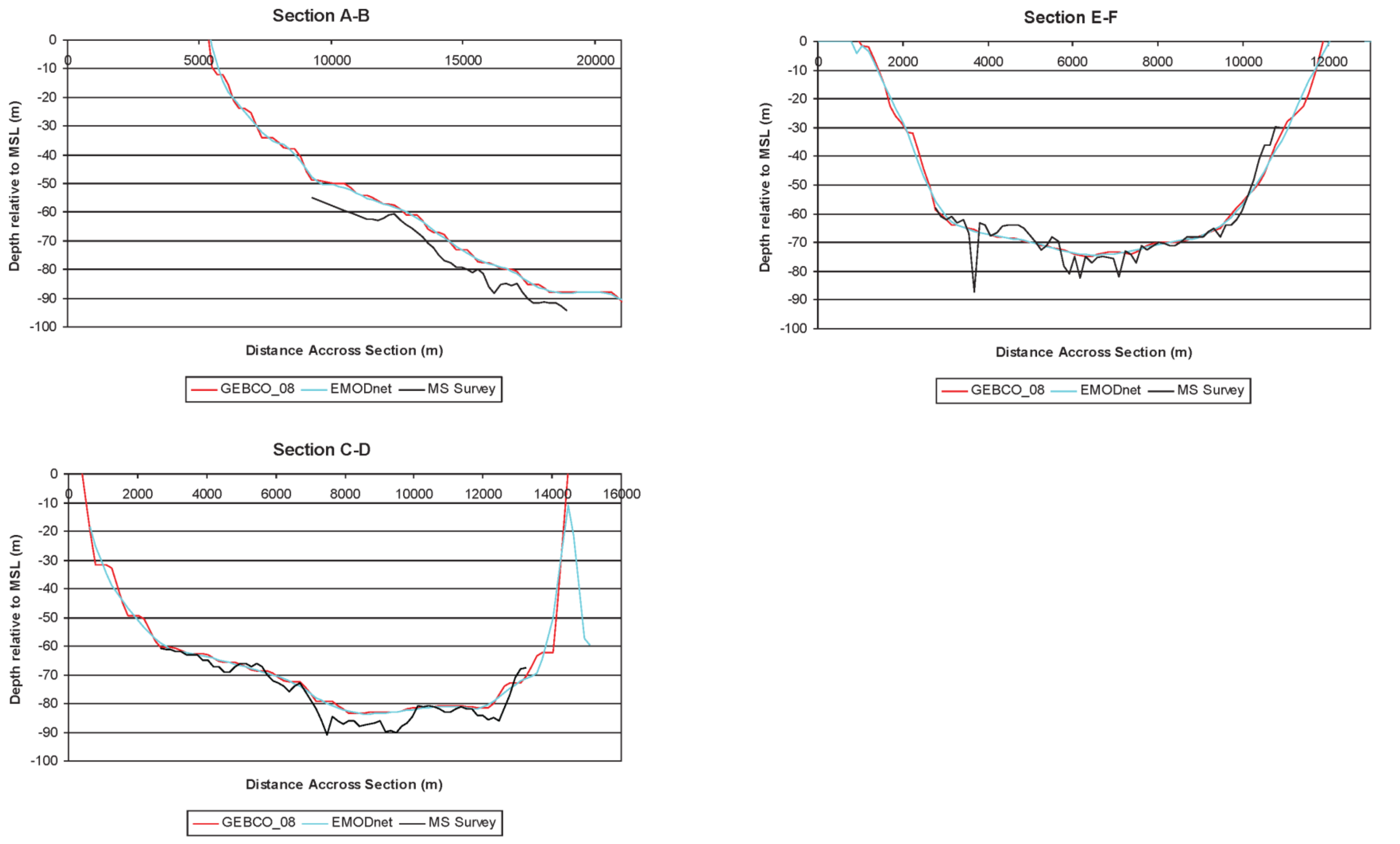
High resolution bathymetric data is available, for most of the core study area of the Pentland Firth and Orkney Islands. Figure 2-4 shows the availability of bathymetric data for the Pentland Firth and Orkney Waters model (excluding Admiralty Charts). EMODnet formed the base bathymetry with the NOOS data providing depths to the east of longitude 0°E. The small areas of coloured bathymetry shown in Figure 2-4 show higher resolution data obtained from the UKHO.

Figure 2-5 shows a comparison of bathymetry profiles from Marine Scotland surveys and EMODnet data at three sections A-B, C-D and E-F. The locations of these sections are indicated in Figure 2.4. The Armadale bathymetry (section A-B) is offset by 10m from the GEBCO_08 dataset, however agreement between the Pentland Firth survey (sections C-D and E-F) and the GEBCO_08 dataset is good.

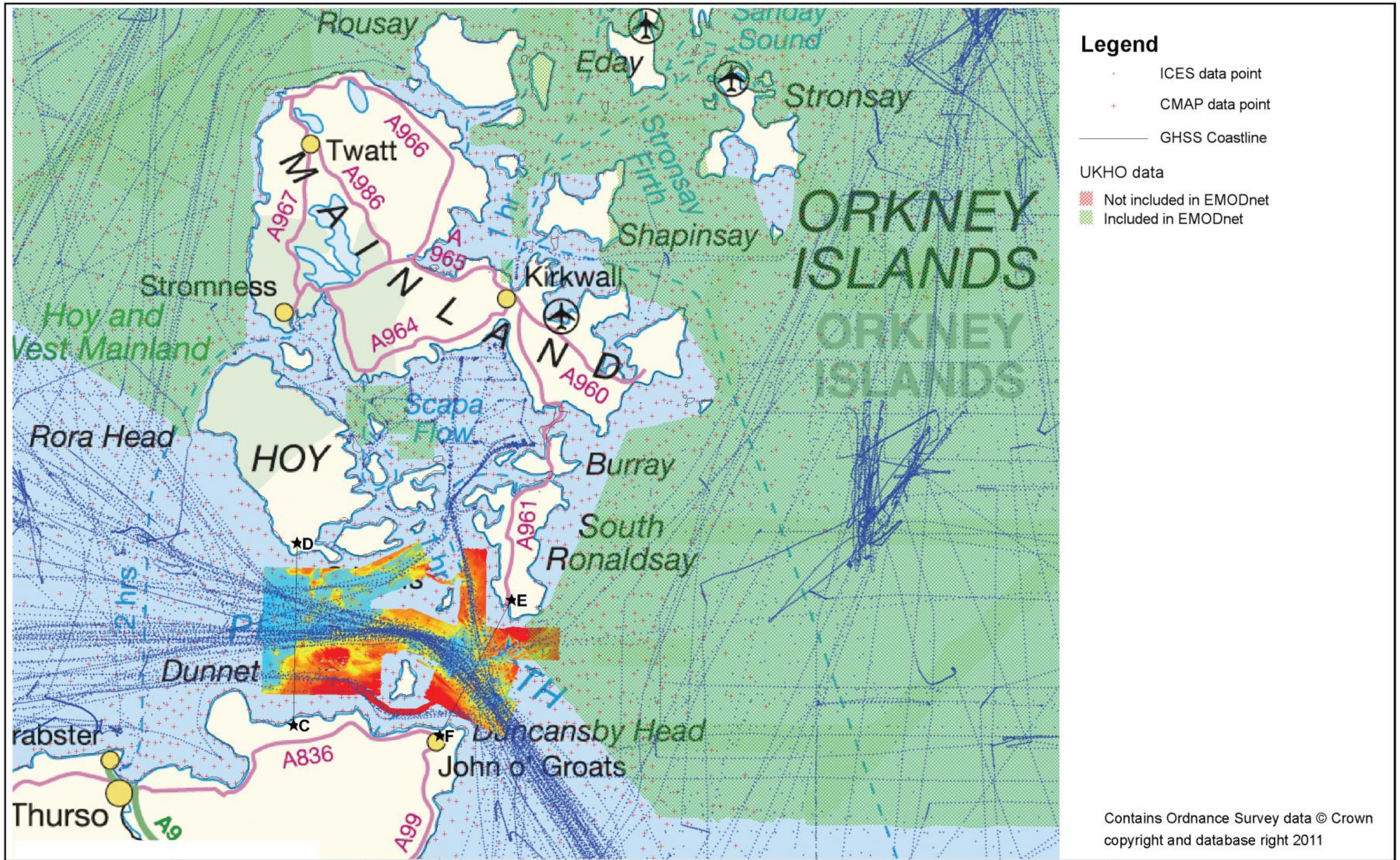
A detailed map of data availability for the Orkney Islands and Pentland Firth is shown in Figure 2-6. Detailed bathymetric survey data is missing between the shore and 3000 m to the east of South Ronaldsay, Burray and the mainland, to South West of Hoy and for many of the passages between the islands. It is the areas with a blue background that was supplemented with digitised Admiralty Chart data.

A detailed map of data availability for the Shetland Islands in the north of the proposed model domain is shown in Figure 2-7. For the Shetland Islands there is no high resolution data east of the Mainland and through the Yell Sound. This data was supplemented with digitised Admiralty Chart data.

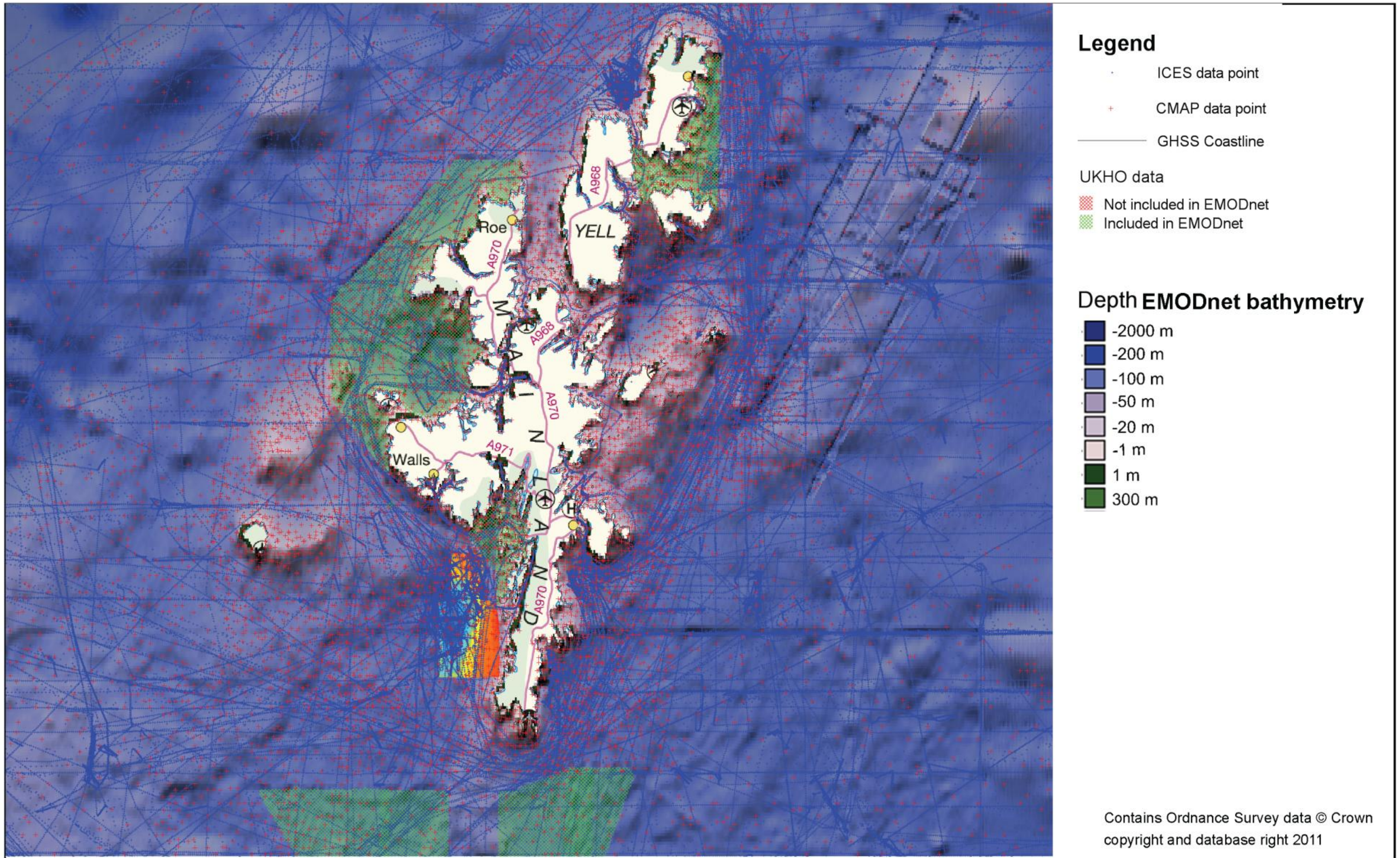
To summarise, there appears generally to be sufficient bathymetry data in the open water areas, however there is limited data in the channels within the islands of Orkney and Shetland as well as in the shallow areas of these islands. These gaps have been filled with data obtained by digitising the appropriate Admiralty Charts (after first obtaining a licence to do so from the Hydrographic Office).



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-5		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Cross sections through sections A-B, C-D and E-F on figure 2-4.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-6		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Detailed view of available bathymetry for the Pentland Firth and Orkney Islands.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-7		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Detailed view of available bathymetry for the Shetland Islands.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012

ch2m Halcrow

2.3 Forcing Data

2.3.1 Introduction

Forcing data is required for a one year climatological model run of the PFOW flow model and for calibration using observed data for approximate 1 month periods. The following forcing data is required;

- meteorological - including wind speed/stress, atmospheric pressure, surface heat flux, precipitation and evaporation
- hydrological - river flux
- oceanic open boundaries – including temperature, salinity and velocity
- tides

In addition, surface winds and offshore wave boundary data are required for the wave model.

2.3.2 Meteorological forcing

2.3.2.1 UK Met Office Model Data

Two data streams from the Met Office forecast models have been archived at NOC-L for operational modelling:

- for operational tide-surge modelling on the continental shelf, using the 2d tide-surge model (CS3 and CS3X).
  - These data comprise of surface wind and atmospheric pressure only, at 1-h intervals, from May 1991 to present. From 1991 to 1995 the data is at 50 km resolution, post 1995 the data is at 12 km resolution.
- for Irish Sea Observatory operational modelling system, running the 3d baroclinic hydrodynamic model, POLCOMS, on (i) the Atlantic Margin Model (AMM, ~12km) and (ii) the nested Irish Sea model (IRS, ~2km). The data comprise the following, from 2004 to 2007 with some gaps, and continuously from 2007 to 2011, all at 12 km resolution:
  - Global model output for the Atlantic at 6-hour intervals – 10m wind (E and N components); sea level pressure; low, medium and high level cloud coverage; specific humidity at 1.5m, air temperature at 1.5m; total accumulated precipitation; sensible heat flux
  - Mesoscale model output at 3-hour intervals – same variables

2.3.2.2 Climatological Forcing

Climatological forcing was derived from the ERA40 and ERA-Interim datasets, which were used to force the POLCOMS AMM (~12km) model for the 45 year hindcast (1960-2004). See Wakelin et al. (2012) and Holt et al., (2012). A licence to use these data has been provided by the European Centre for Medium range Weather Forecasting (ECMWF) for this study.

A detailed description of the methodology used to derive the forcing for the 1-year climatology run is provided in the Scottish Shelf Waters Model report (Wolf et al. 2015). A brief description is given as follows: 1) The initial and boundary conditions were taken from a mean of the AMM climatology run; 2) The river climatology data was provided by CEH; 3) The tides were included as a mean tidal year and 4), while the met forcing climatological data was calculated as monthly mean wind-stress, pressures, heating and evaporation minus precipitation from the ERA40 and ERA-Interim datasets.

2.3.3 Meteorological observations

The Marine Scotland Science survey vessel MV Scotia undertook two surveys for this project, one in St Magnus Bay, Shetland (October 2012) and the other in the Hoy Sound, Orkney (Dec, 2012). During these surveys wind measurements were made from the vessel.

2.3.4 Hydrological Data (Fresh Water Inflows)

In order to simulate the effect that river flow has upon salinity in coastal waters, river flux data are required. The Centre for Ecology and Hydrology (CEH) Grid-to-Grid (G2G) model is used to supply freshwater inflows to the various coastal models for this study. For the PFOW model the G2G model was extended to provide conditions for the Shetland Isles which were not available in the available dataset at the onset of this project.

The G2G model output provided by CEH are:

1. River discharge data (time series data) at all coastal locations in Scottish waters. The data cover 1 March 2007 to 30 September 2010 at 15 minute intervals.

2. River discharge data (time series data) at all coastal locations around Shetland and Northern Ireland. The data cover 1 March 2007 to 30 September 2010.
3. River discharge climatological data (long term daily/seasonal discharge data) at all coastal locations for Scotland (including Shetland) and Northern Ireland. Daily averaged data was provided, the averaging period covered 1962-2011.

2.3.5 Waves

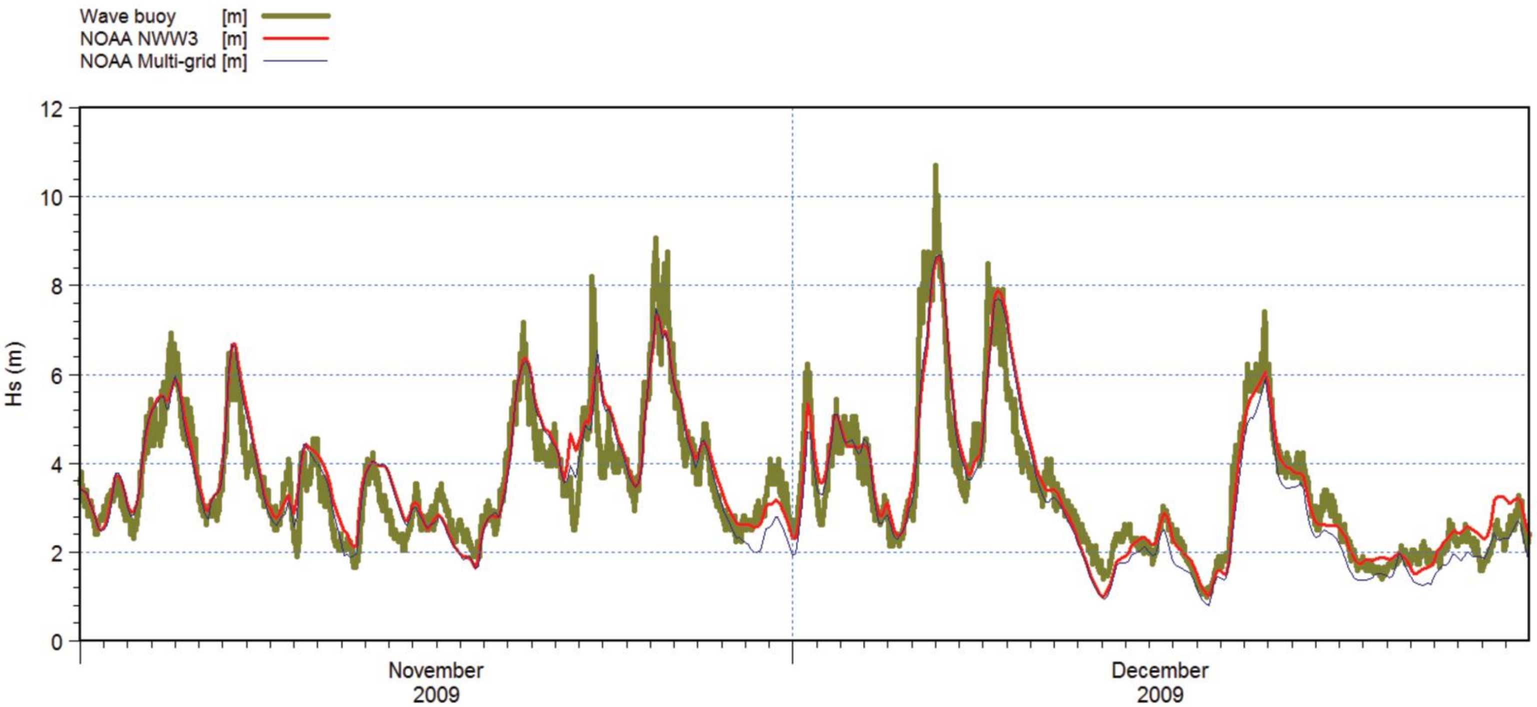
Two sources of offshore wind and wave data were identified, namely 1) US National Oceanic and Atmospheric Administration (NOAA) data; 2) UK Met Office data.

The NOAA data is freely available, however comparisons with measured wave data showed that this dataset significantly underestimates wave heights during storms, see Figure 2-8. The data also underestimates the wave climate from the north and overestimates waves from the west-southwest, see Figure 2-9a.

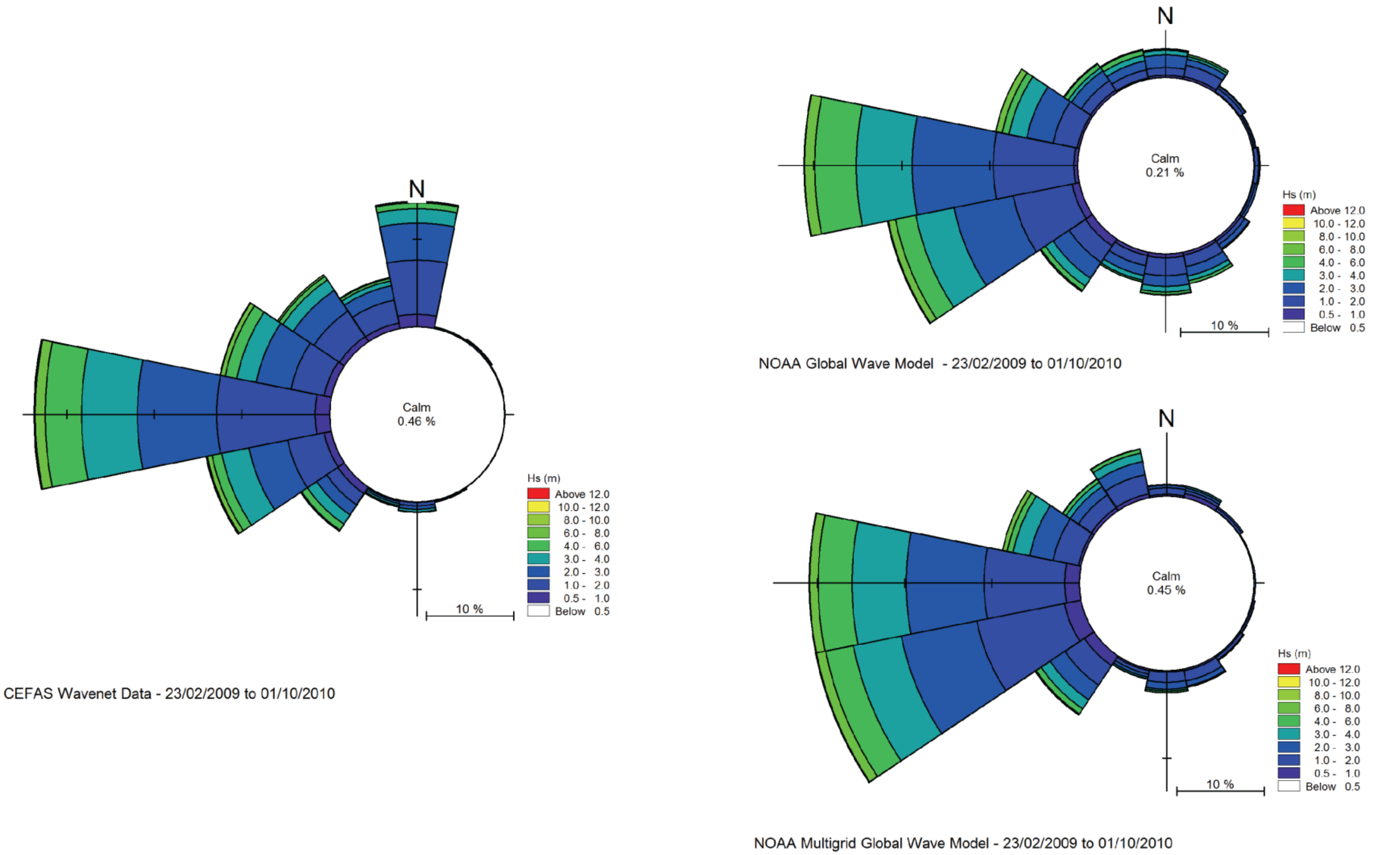
The UK Met Office data is commonly used in UK waters, and it is considered suitable for this study. This data was purchased at four points. The locations and the wave roses at the four points (which are located around the model boundaries) are presented in Figure 2-9b. The wind roses at these locations are also presented in Figure 2-9c.

2.3.6 Tide

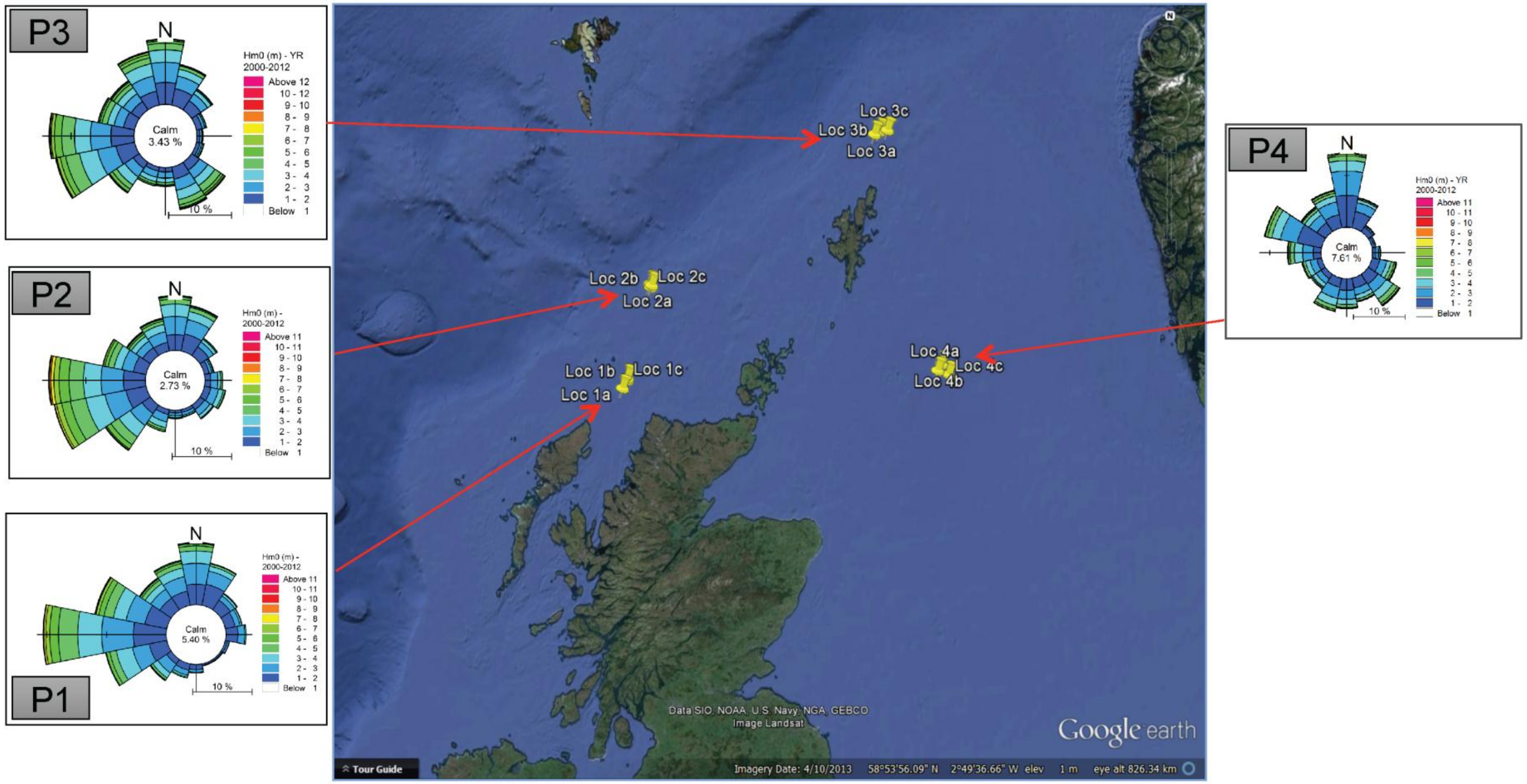
For the PFOW Model, the boundary data was derived from NOC-L's Atlantic Margin Model (AMM) with a 12km resolution. Water levels along with temperature and salinity time series data are extracted from the AMM model and applied at the boundaries of the PFOW model.



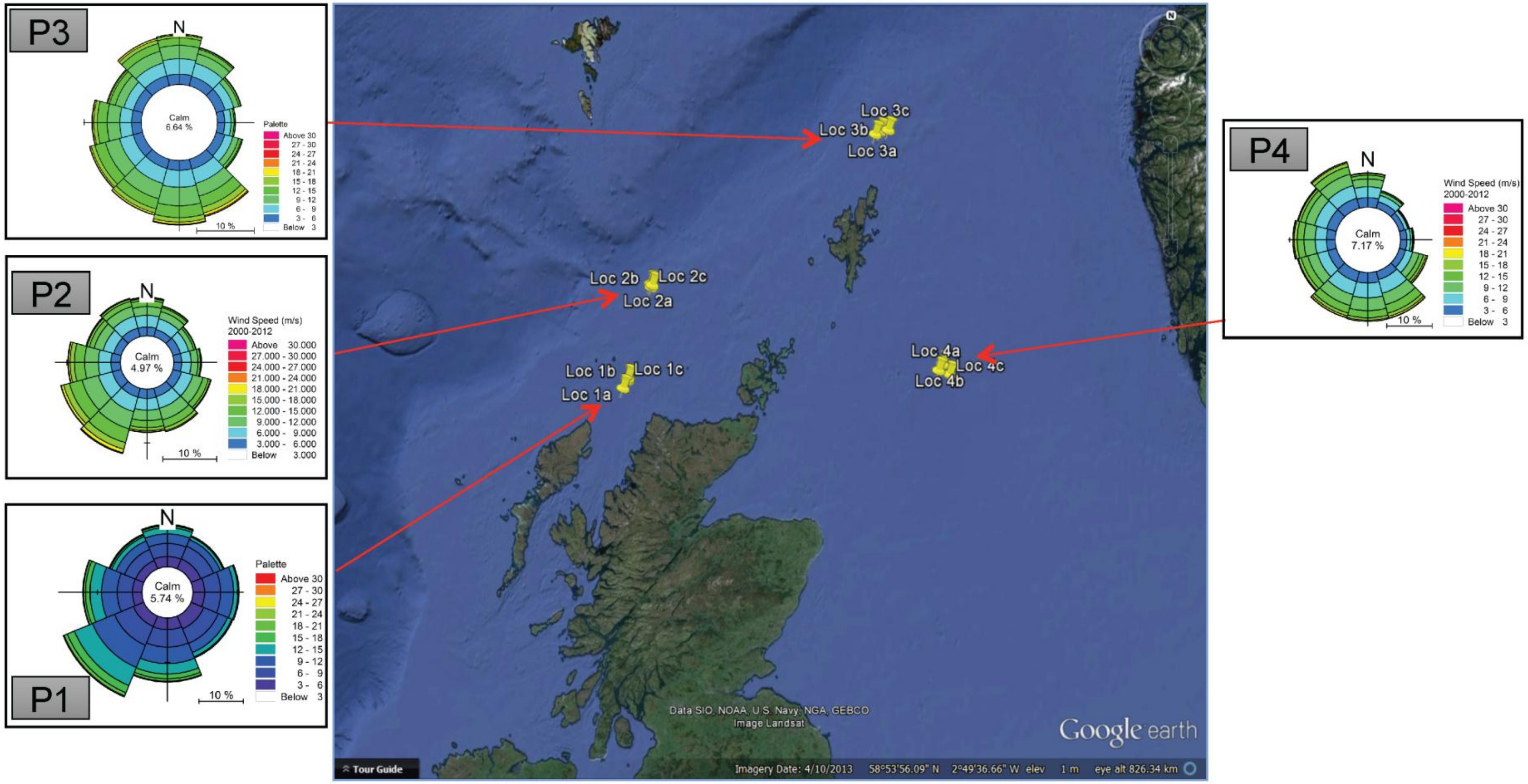
Client	Consulting Engineer	Project:	Figure Title:	Figure 2-8		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of wave heights from NOAA Wavewatch III and Multigrid global wave models, with wave buoy west of S. Uist, at 57.298°N, -7.926°W	Checked DMP	Scale Not to scale	Rev. 0
				Designed MMC	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-9a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Wave roses from NOAA Wavewatch III and Multigrid global wave models, with wave buoy west of S. Uist, at 57.298°N, -7.926°W	Checked DMP	Scale Not to scale	Rev. 0
				Designed MMC	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-9b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wave data obtained from UK Met Office at locations P1 to P4. Data from Jan 2000 – Dec 2012.	Checked DMP	Scale Not to scale	Rev. 0
				Designed HKJ	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-9c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Wind data obtained from UK Met Office at locations P1 to P4. Data from Jan 2000 – Dec 2012.	Checked DMP	Scale Not to scale	Rev. 0
				Designed HKJ	Drawn	Date 14/112012

2.4 Calibration Data

2.4.1 Introduction

Calibration is required for water level, currents, temperature, salinity and surface waves against observation datasets for periods of up to 1 month. In addition, the 1 year climatological runs are to be compared against accepted general flow characteristics including residual current speed and direction (seasonal variability) and seasonal temperature and salinity cycles. The available calibration data (observation datasets) are summarised in the sections below.

2.4.2 Water Level

Figure 2-10 shows all the locations of water level observations that are available in the PFOW region. These come from three main sources: tide gauge data from the BODC National Oceanographic Database (NODB); bottom pressure data from the NODB, analysed tidal data from NOC-L and tide gauge data from SEPA. All of the SEPA gauges (except Rothesay, which ends on 17th April 2007) have data between 2009 and 2012; most go back to 2001/2. Their locations are shown in Figure 2-11.

In addition, we have access to tidal data from TotalTide - a digital version of the UK Admiralty tide tables, from the UK Hydrographic Office. The locations of these datasets are shown in Figure 2-12a. As these data are based on harmonic analyses, water level estimates for any past or future date are obtainable, via the use of constituents from the Admiralty tide tables. All water level data available post year 2000 are shown in Figure 2-12b.

2.4.3 Currents

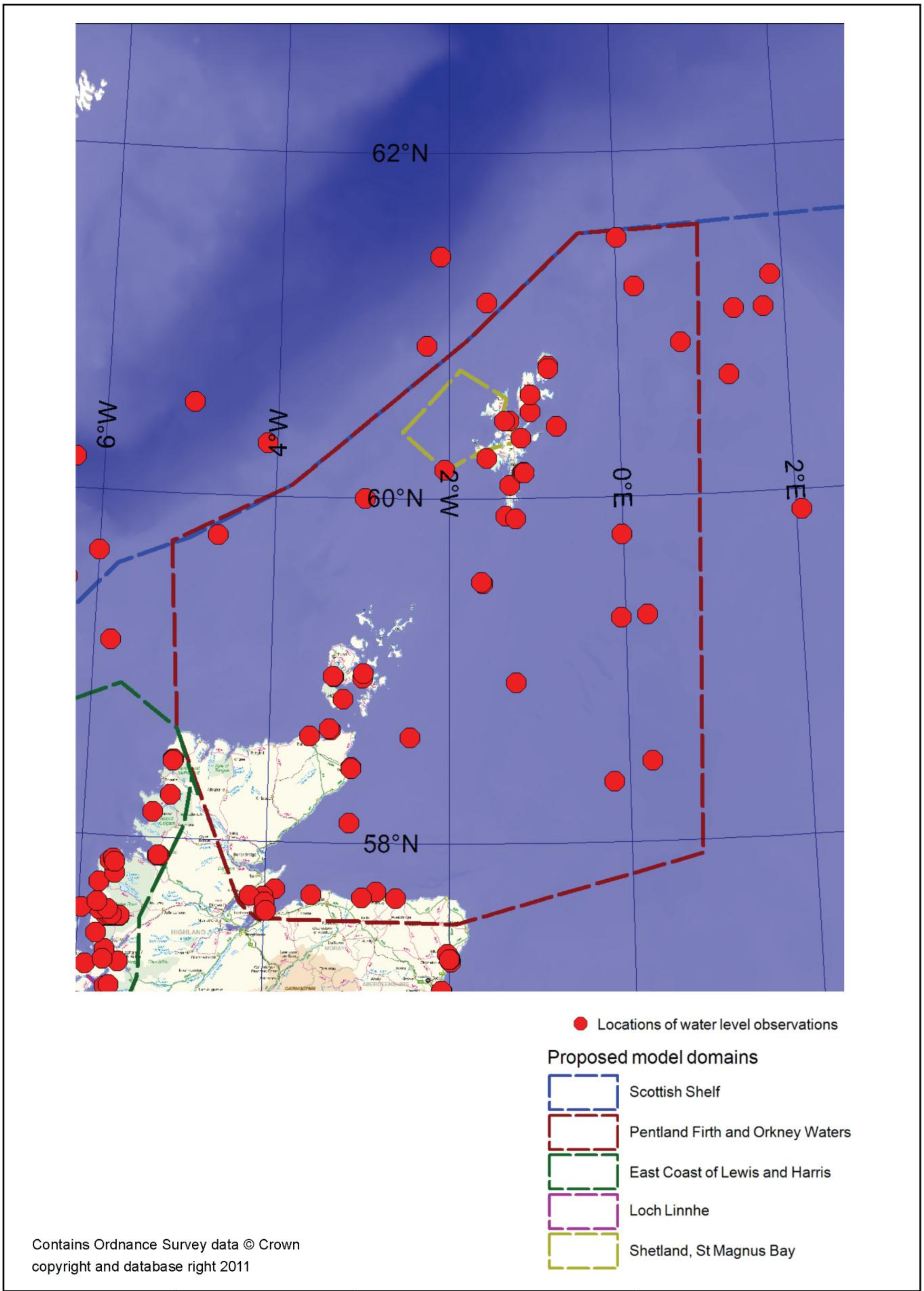
Datasets on currents have been found from a number of sources; all locations are shown in Figure 2-13. These come from the BODC National Oceanographic Database (NODB) and the TotalTide software from UK Hydrographic Office. As Figure 2-14 shows, there are only a few datasets from the BODC National Oceanographic Database since year 2000. In addition, some of these datasets (shown in red) may not be freely available. In some cases, vertical current profiles are available; these are shown in Figure 2-15a.

In the Pentland Firth, interest in tidal energy has led to the existence of other datasets. Baston and Harris (2011) presented results from Acoustic Doppler Current Profiler (ADCP) data collected in 2001. Also the Environmental Research Institute collected current data via ADCP in the Pentland Firth in 2009 (Figure 2-15a).

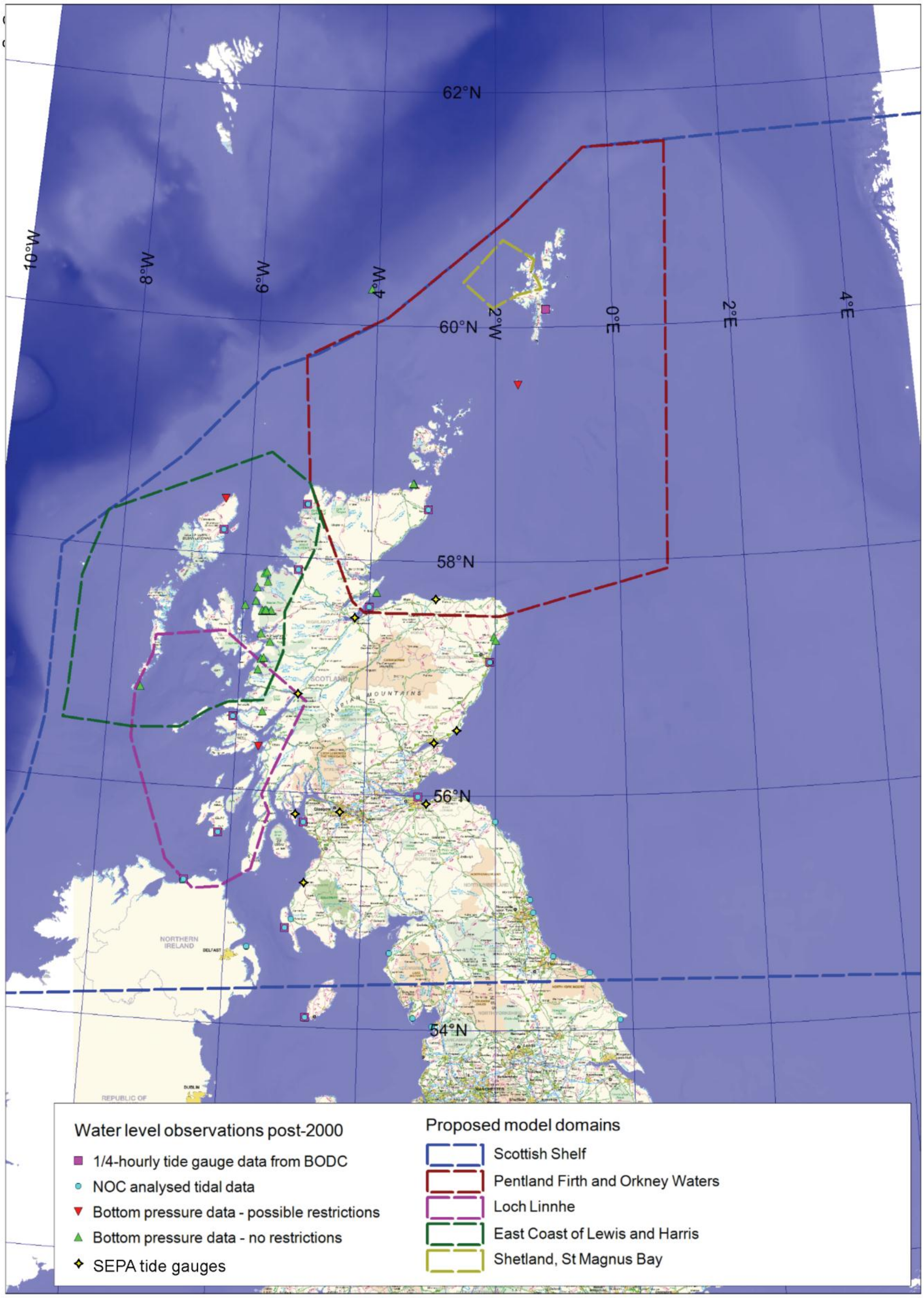
The methodology used by TotalTide for calculating currents is not known. In addition, these data have been estimated for the use of shipping; therefore, a greater weighting may be placed on surface currents than currents near the sea bed.

Additionally the MV Scotia collected current and CTD measurements in and around St Magnus Bay in Shetland in October 2012 and in Hoy Sound in Orkney in December 2012 (shown as ADCP Data from MV Scotia on Figure 2-15a with more detail shown on Figures 2-15b and 2-15c). This data is considered useful for the calibration of the PFOW model.

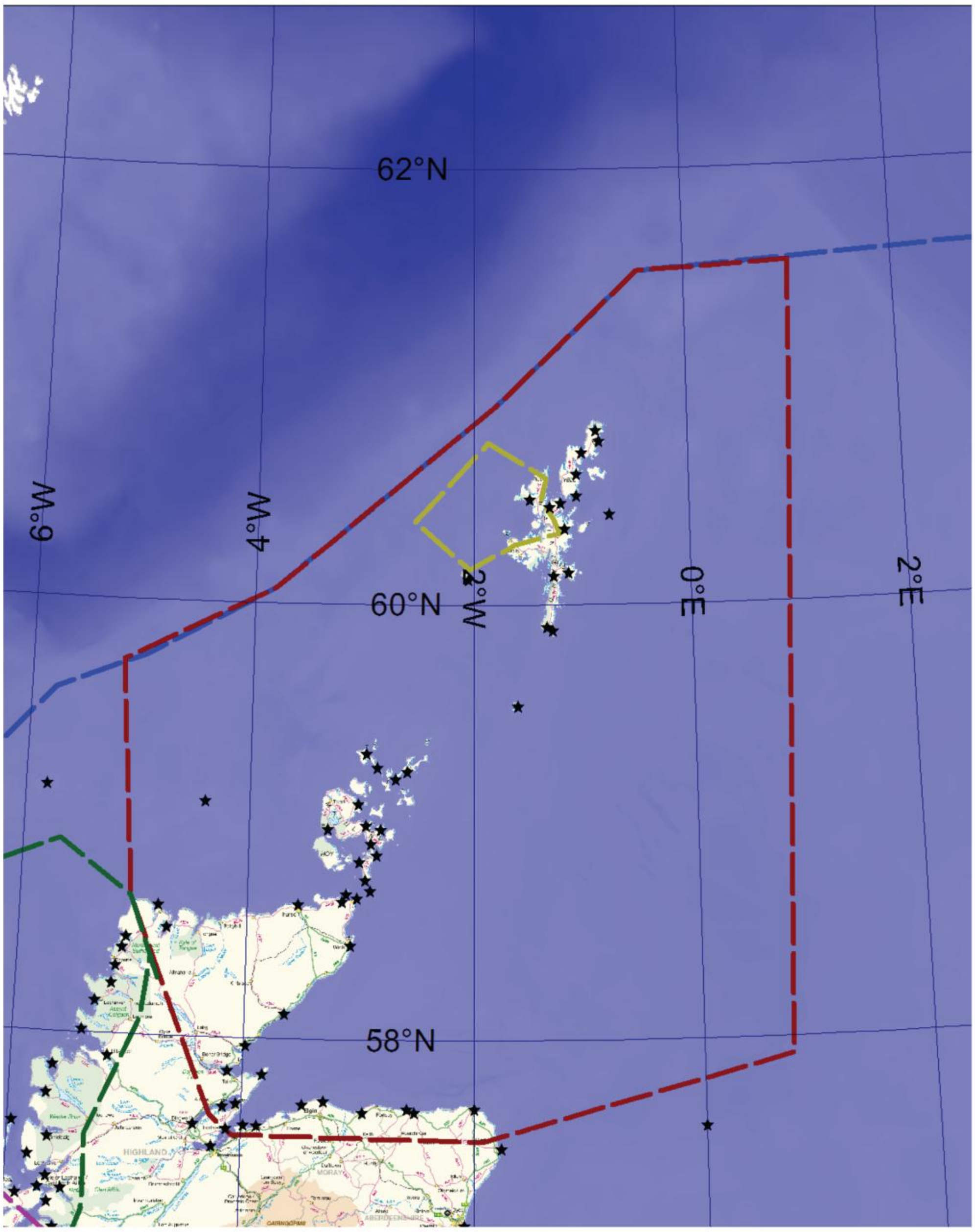
The Atlas of UK Marine Renewable Energy Resources (www.renewables-atlas.info) contains information on peak tidal current speeds over a mean spring and a mean neap tide. The dataset was derived from the POL HRCS Model, with peak spring and neap current speeds calculated from the major 2 or 4 tidal harmonics. Although this dataset is limited, it is freely available on a 0.0167° x 0.025° (latitude x longitude) grid throughout the region shown in Figure 2-16.



Client	Consulting Engineer	Project:	**Figure 2-10**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Water level observations within the PFOW model domain



Client	Consulting Engineer	Project:	Figure 2-11
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Post-2000 water level observations



Water level observations

★ TotalTide water levels

Proposed model domains

East Coast of Lewis and Harris

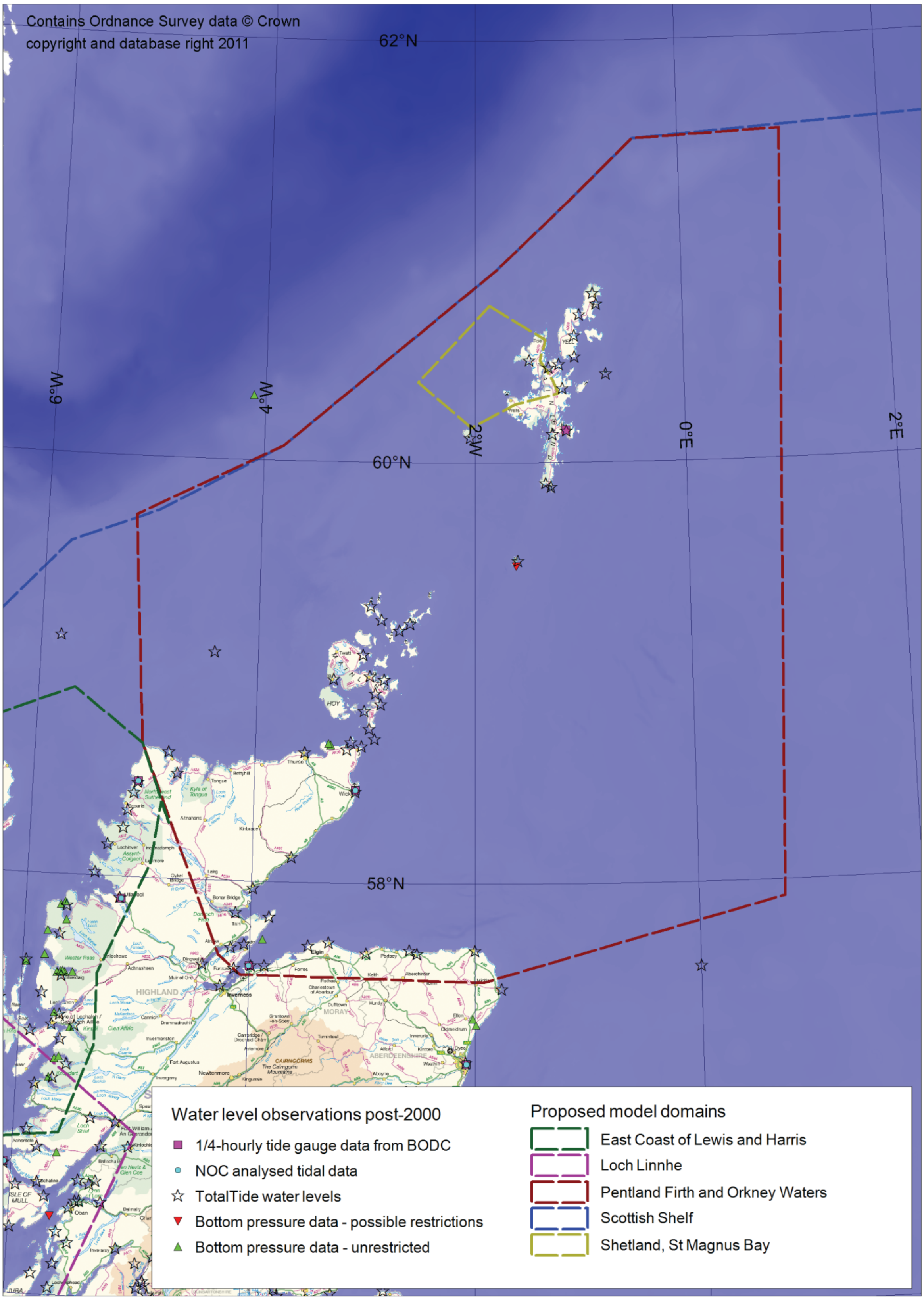
Loch Linnhe

Pentland Firth and Orkney Waters

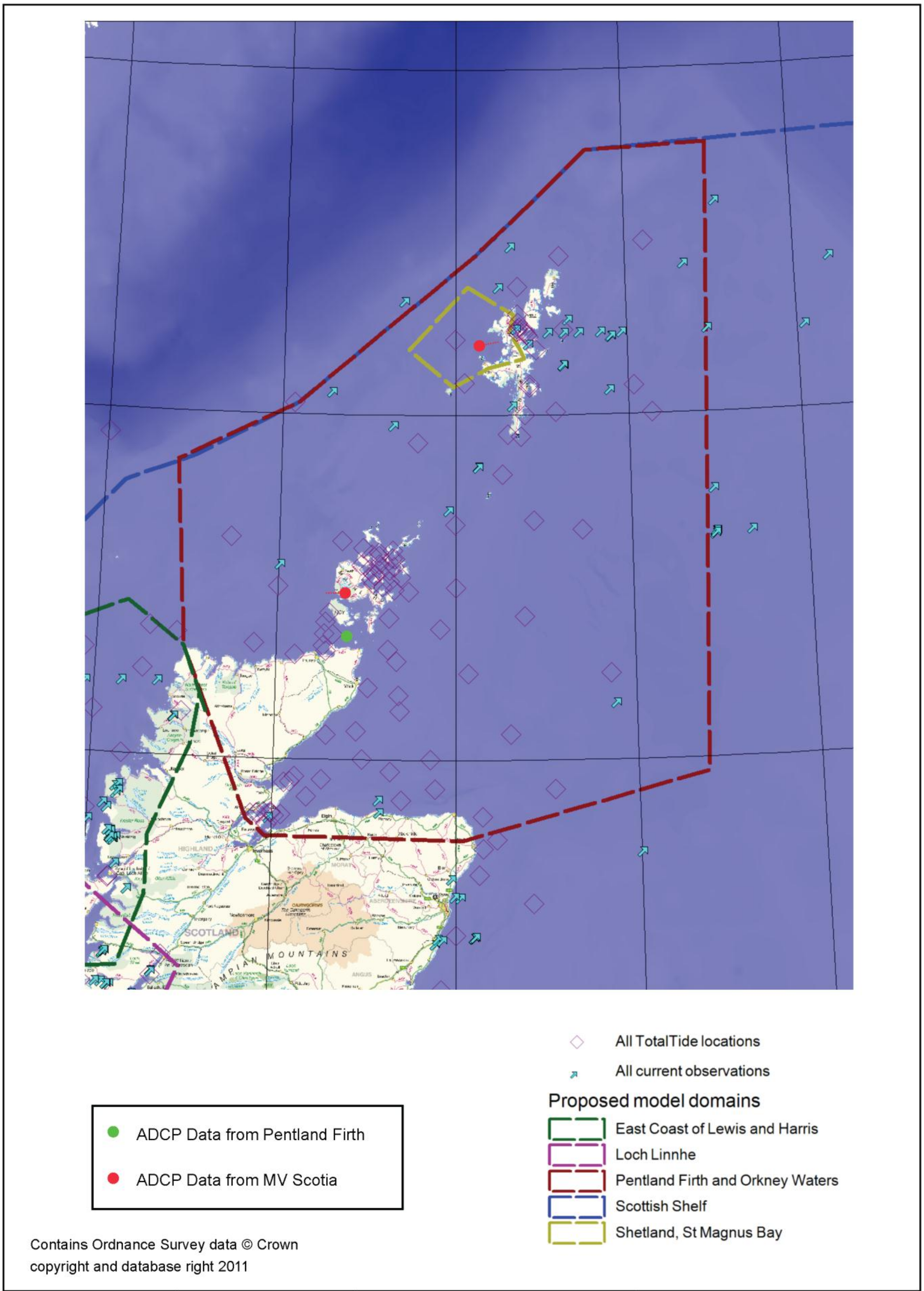
Scottish Shelf

Shetland, St Magnus Bay

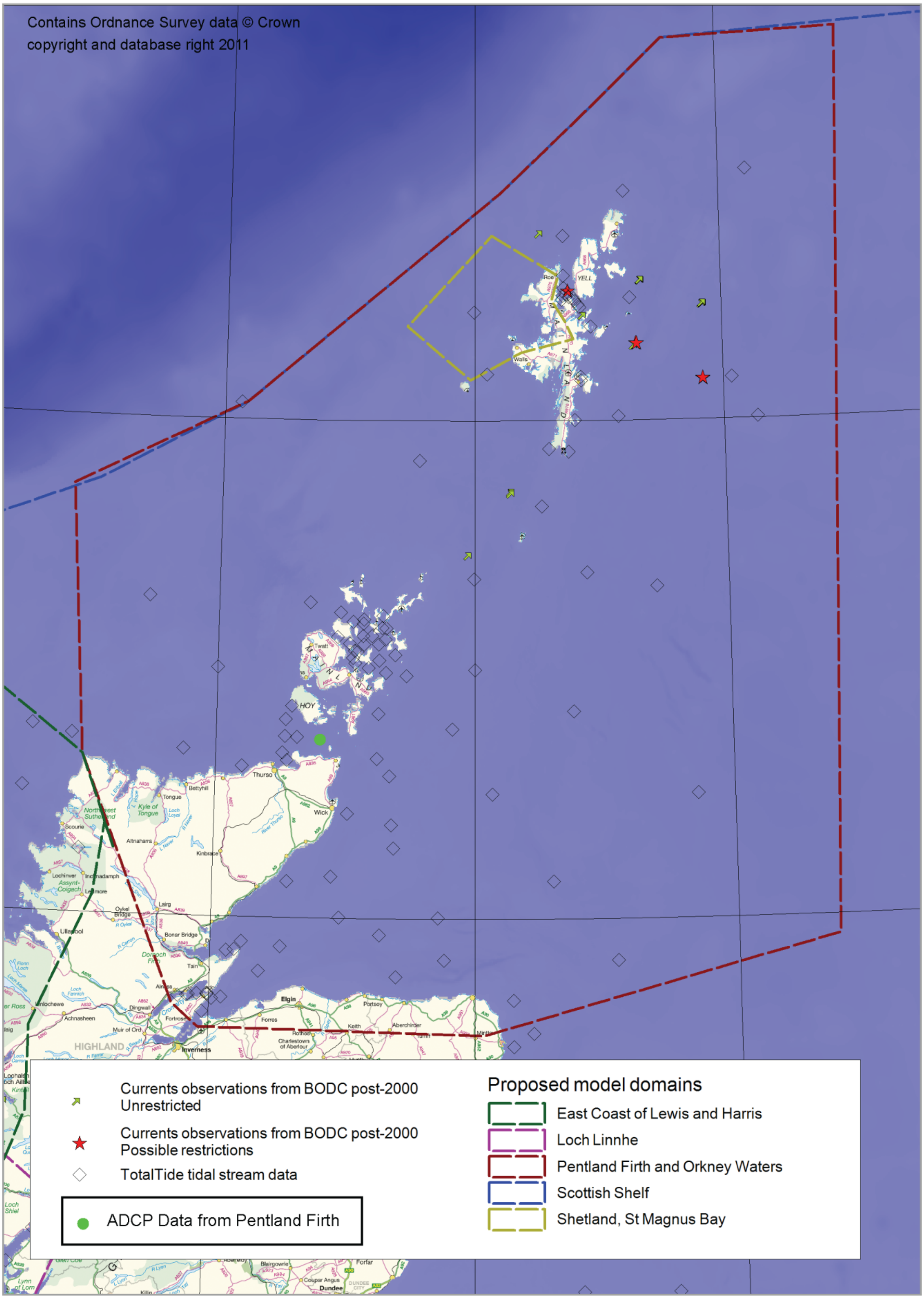
Client	Consulting Engineer	Project:	**Figure 2-12a**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Total-tide water level locations



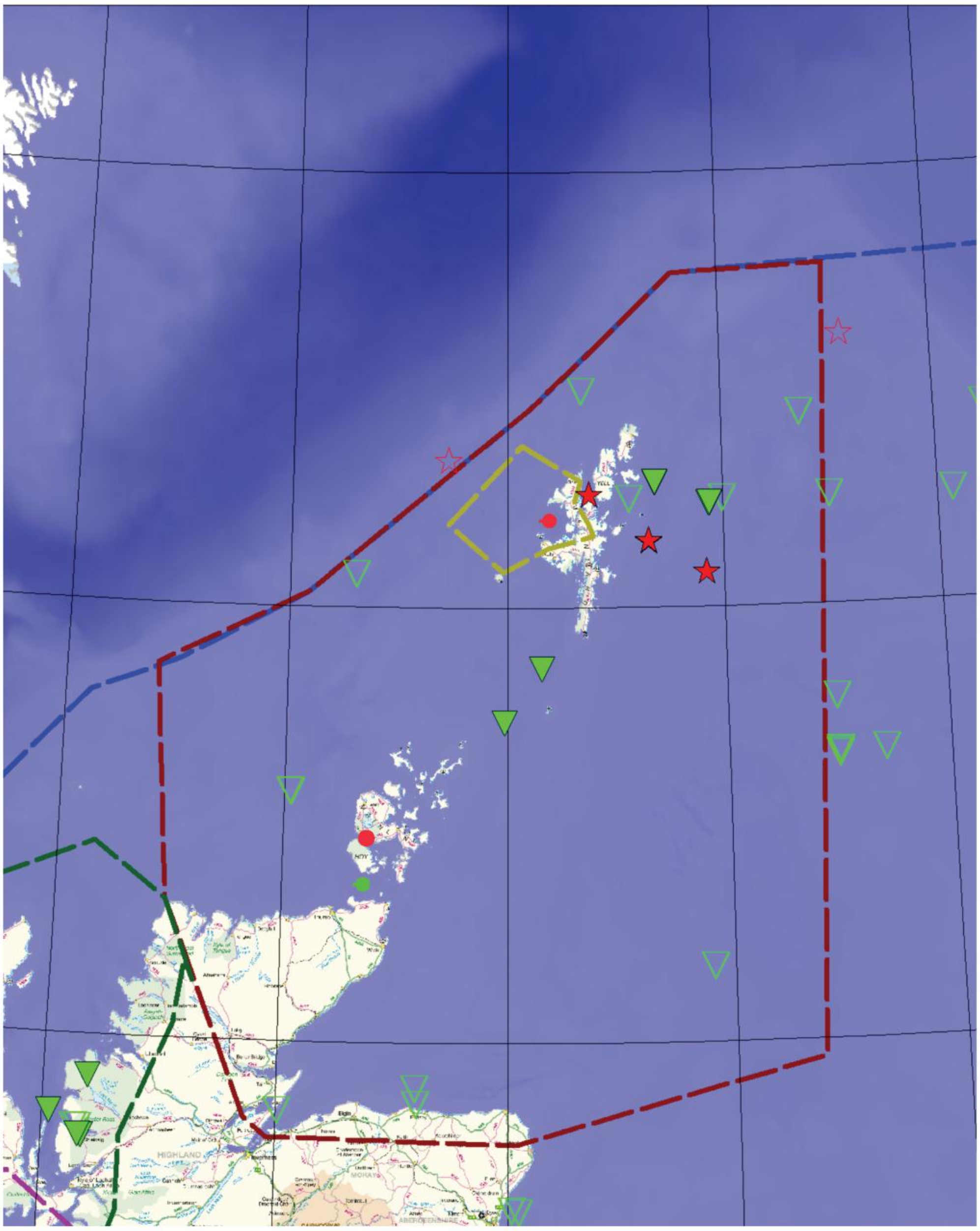
Client	Consulting Engineer	Project:	**Figure 2-12b**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Post-2000 water level observations in the Pentland Firth and Orkney Waters



Client	Consulting Engineer	Project:	**Figure 2-13**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	All current observations and TotalTide tidal stream locations



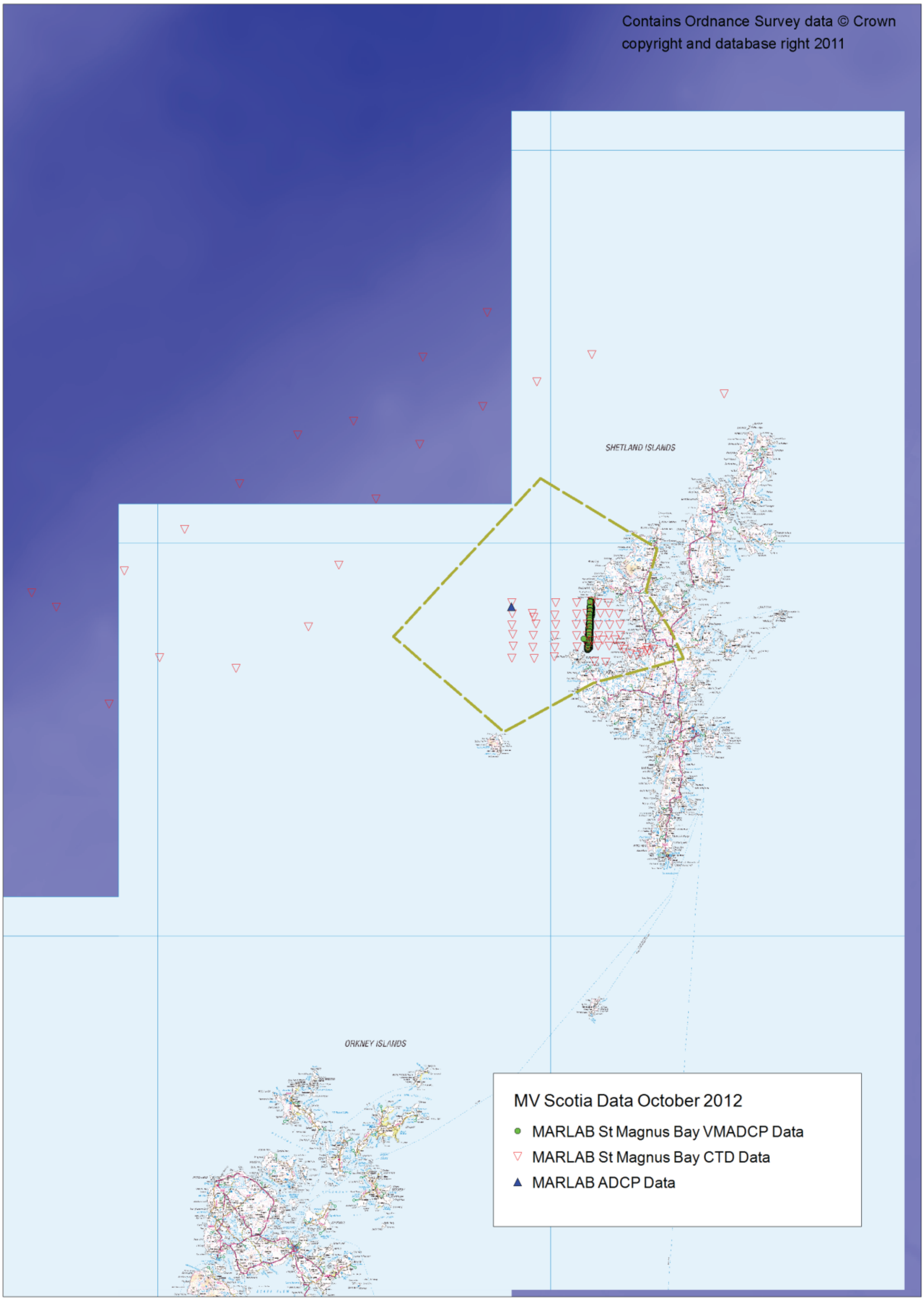
Client	Consulting Engineer	Project:	**Figure 2-14**
Marine Scotland		Pentland Firth and Orkney Waters Model	Post-2000 current observations in the Pentland Firth and Orkney Waters



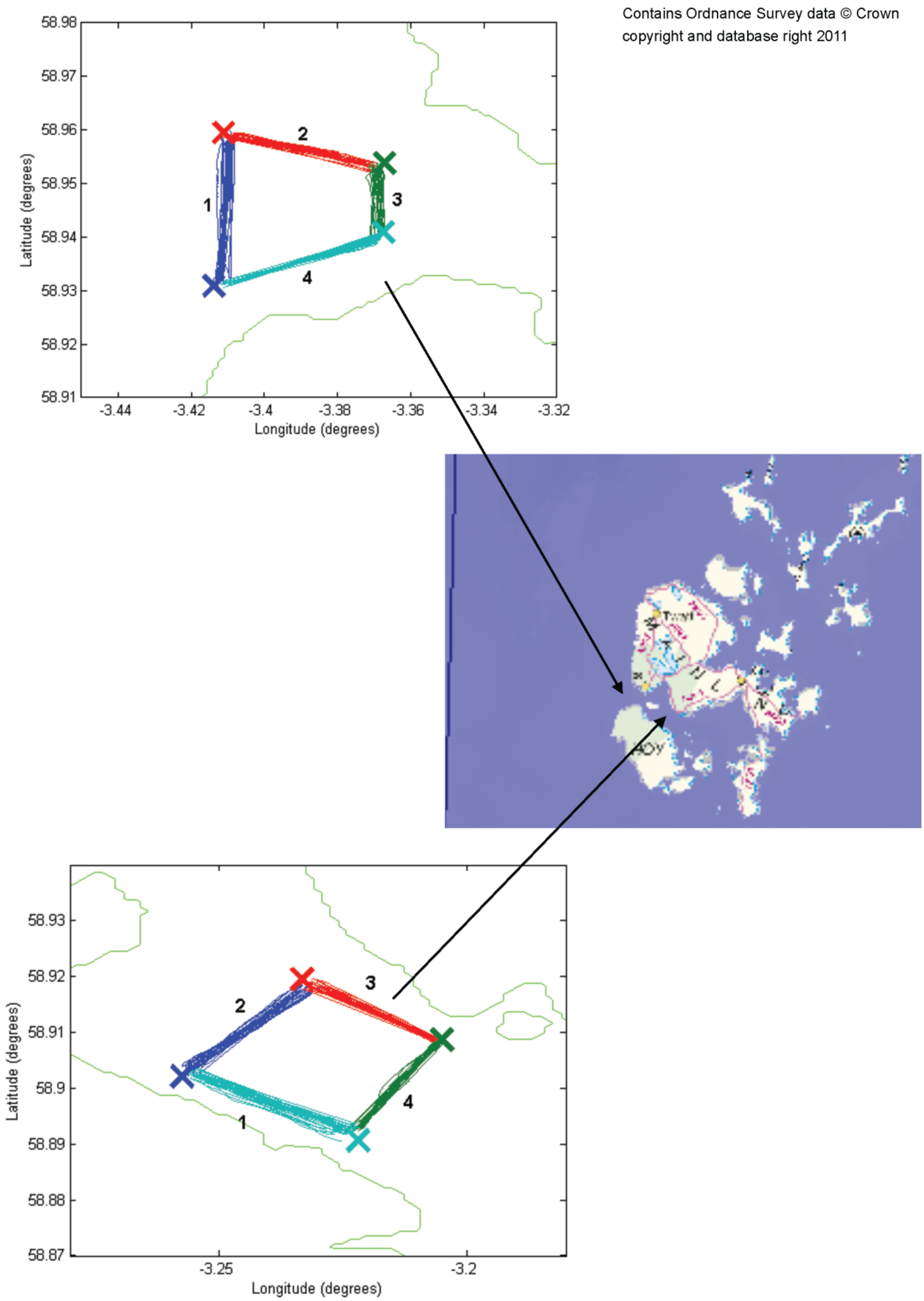
Current profiles, post-2000 - unrestricted
Current profiles, pre-2000 only - unrestricted
Current profiles, post-2000 - possible restrictions
Current profiles, pre-2000 only - possible restrictions
ADCP Data from Pentland Firth
ADCP Data from MV Scotia

Proposed model domains
East Coast of Lewis and Harris
Loch Linnhe
Pentland Firth and Orkney Waters
Scottish Shelf
Shetland, St Magnus Bay

Client	Consulting Engineer	Project:	**Figure 2-15a**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Pre and Post-2000 current profiles



Client	Consulting Engineer	Project:	Figure 2-15b
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Observations from MV Scotia in St Magnus Bay, Shetland in October 2012



Client	Consulting Engineer	Project:	Figure 2-15c
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	VMADCP track locations from MV Scotia in Hoy Sound, Orkney in December 2012

2.4.4 Waves

The Atlas of UK Marine Renewable Energy Resources (www.renewables-atlas.info) contains information on monthly, seasonal and annual mean significant wave heights. Waves were calculated from the Met Office 2nd generation wave model. Although this dataset is limited, it is freely available, largely presented on a 0.125° x 0.167° (latitude x longitude) grid throughout the region shown in Figure 2-16. This data is useful for comparison with the climatological wave data derived from this study.

Wave buoy data from CEFAS WaveNet programme is freely available for non-commercial purposes. In addition, some wave data is available from the BODC National Oceanographic Database, both from wave buoys and pressure gauges; however there are licensing restrictions on some of these datasets. Locations of available wave data from both sources, showing possible restrictions and data available since 2000, are shown in Figure 2-17.

Datasets from wave buoys exist within the proposed model domain (Figure 2-17). However, all but one of these datasets exists close to the shore. The Moray Firth WaveNet site is located over 20 km from the shore, and contains wave heights, periods and directions since August 2008. Other offshore datasets exist near the proposed model domain, but are not be freely available; in some cases these are from oil platforms. The wave data nearest the Pentland Firth are at Dounreay (water depth of approx. 20 m, from October 1997 to May 2001); however, there are no wave directions for this dataset. Nevertheless, these datasets are useful for calibration purposes.

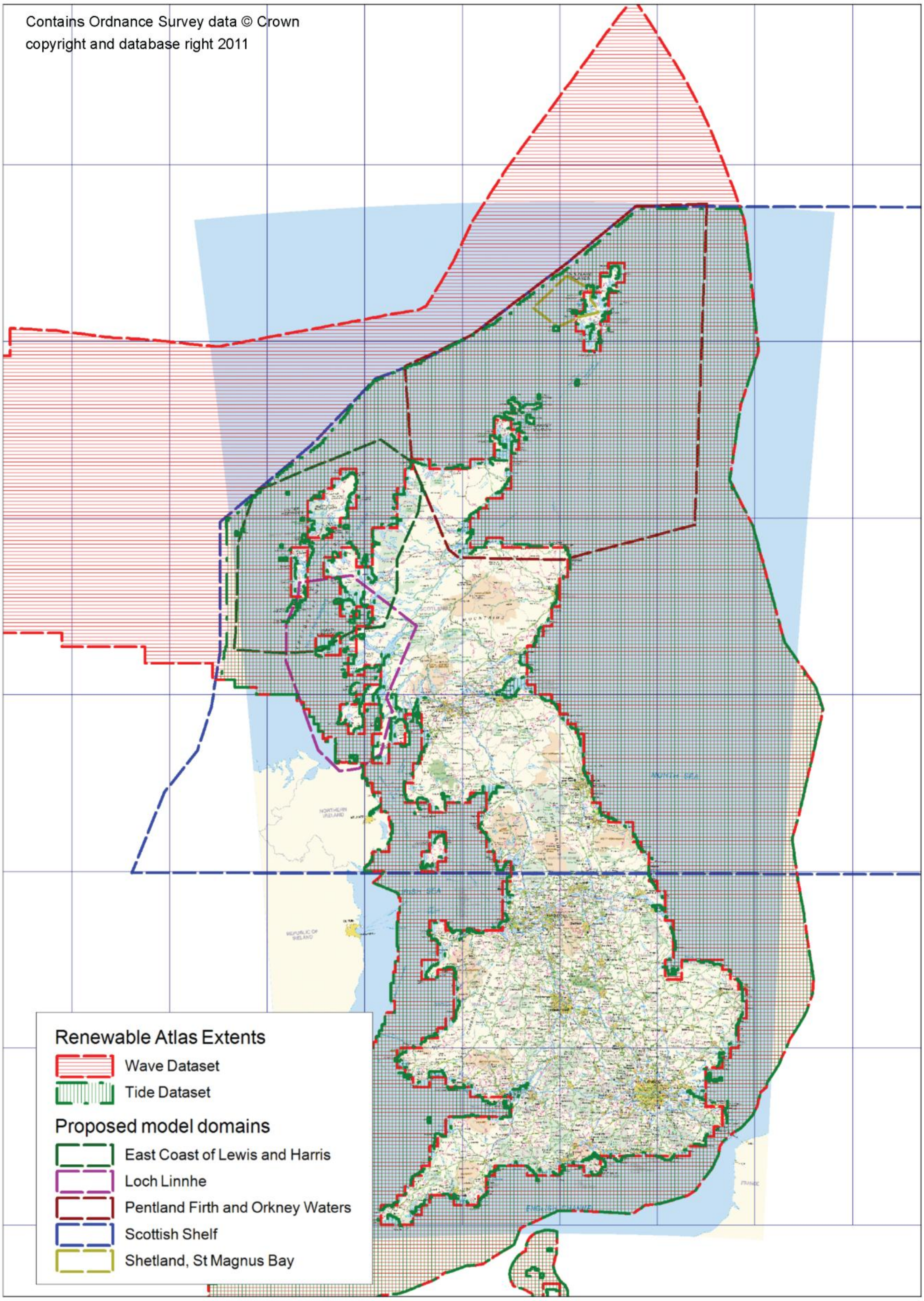
2.4.5 Temperature and Salinity

Temperature and salinity validation was carried out using selected hydrographic stations which are identified from the British Oceanographic Data Centre data holdings for UK. There are a very large number of datasets from CTD and bottle casts, both from the BODC National Oceanographic Database and the ICES database. Additionally, some of the CEFAS WaveNet buoys record sea surface temperature.

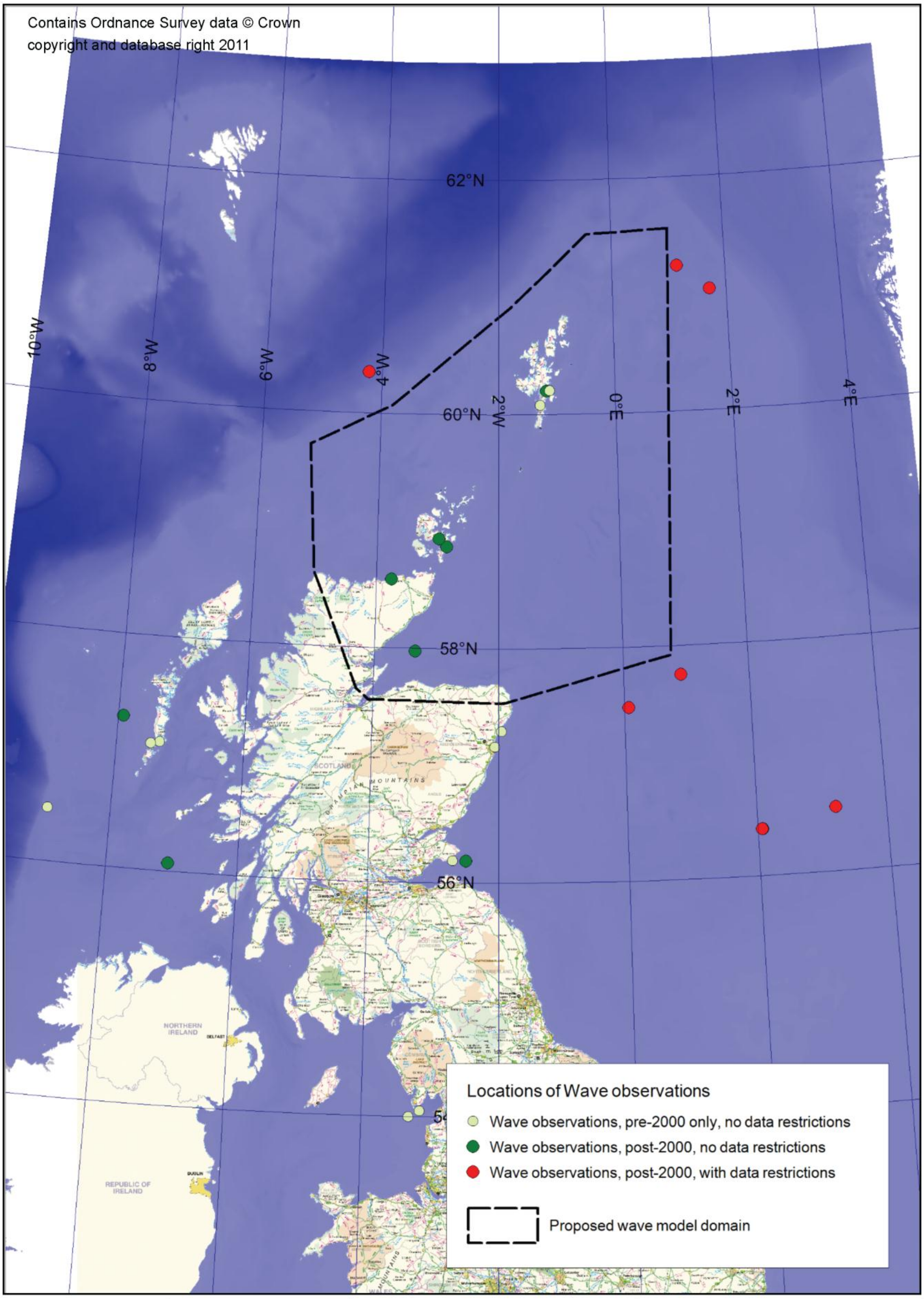
Figure 2-18 shows the locations of the temperature observations and Figure 2-19 shows the locations of the salinity observations. As Figure 2-20 shows, the temperature and salinity observations are available throughout the last two decades, with many observations throughout all model domains having occurred over the last two years. Figure 2-21 shows which of these observations include profiles over the entire water depth. Most temperature and salinity observations occurred at the same location and time. Figures 2-22a and 2-22b show there are sufficient temperature and salinity profiles within the model domain, both during the 2001 and 2009 ADCP observations

In addition, the Ocean Data analYsis System for SEA (ODYSSEA) dataset is a re-analysis of satellite observations of sea surface temperature. Daily mean average sea surface temperatures since 01/10/2007 have been obtained, on a 0.1° x 0.1° grid.

The results from the climatic run are compared with climatological atlas information for sea surface temperature and salinity, from the World Ocean Atlas (WOA) and International Council for Exploration of the Seas (ICES) climatological datasets.



Client	Consulting Engineer	Project:	Figure 2-16
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Wave and tidal domains from the Renewables Atlas



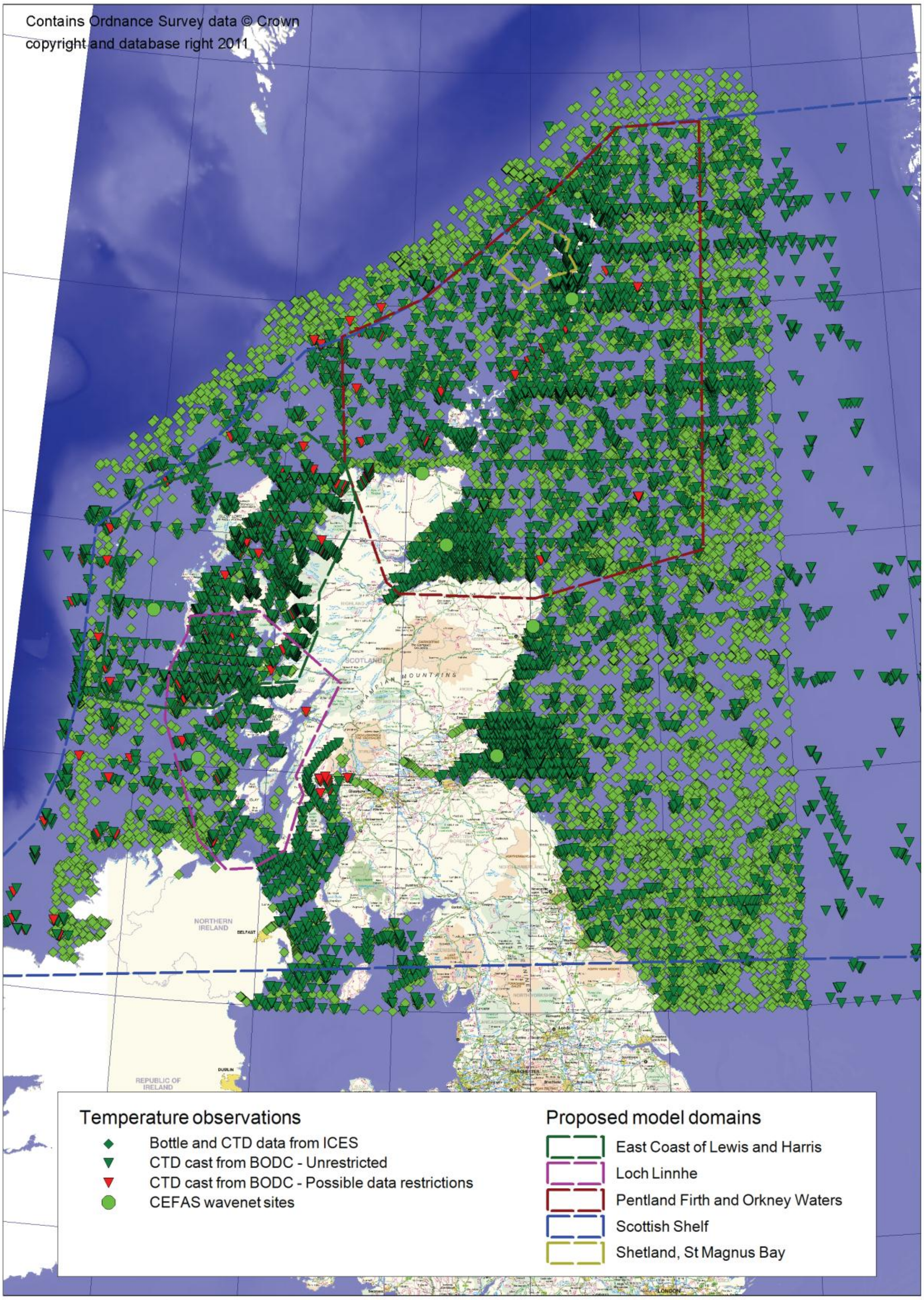
Client	Consulting Engineer	Project:	Figure 2-17
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	All wave observations

2.4.6 Summary of data availability for the PFOW model

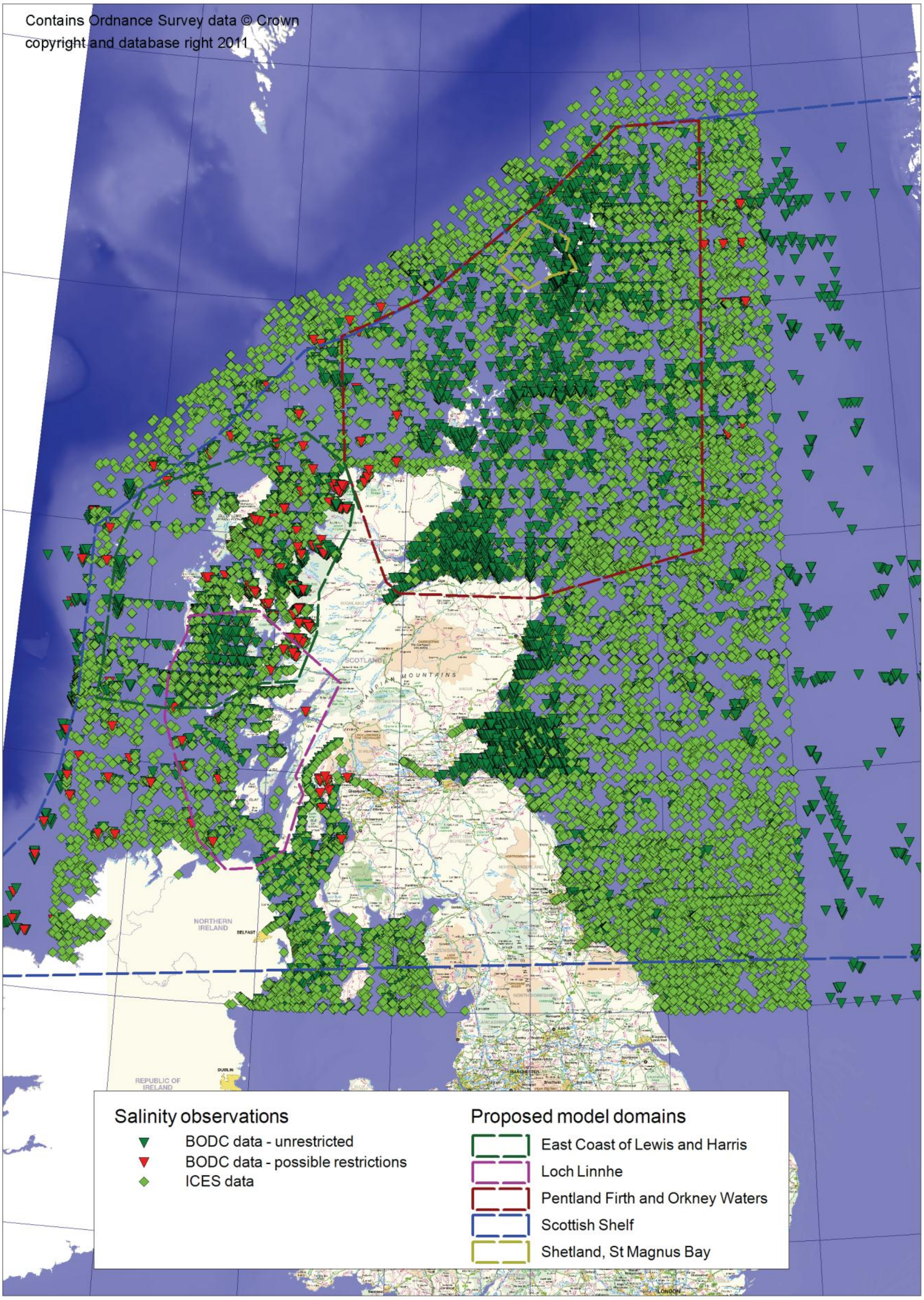
A summary of the data available for calibration of the PFOW hydrodynamic model is presented in Table 2-1. It can be seen that the year 2009 is the period where a complete set of the required data is available. 2001 will be used for model calibration, validation will be carried out for hydrodynamic in 2012 and for temperature and salinity in 2009.

TABLE 2-1 CASE STUDY MODELS AND AVAILABLE DATA

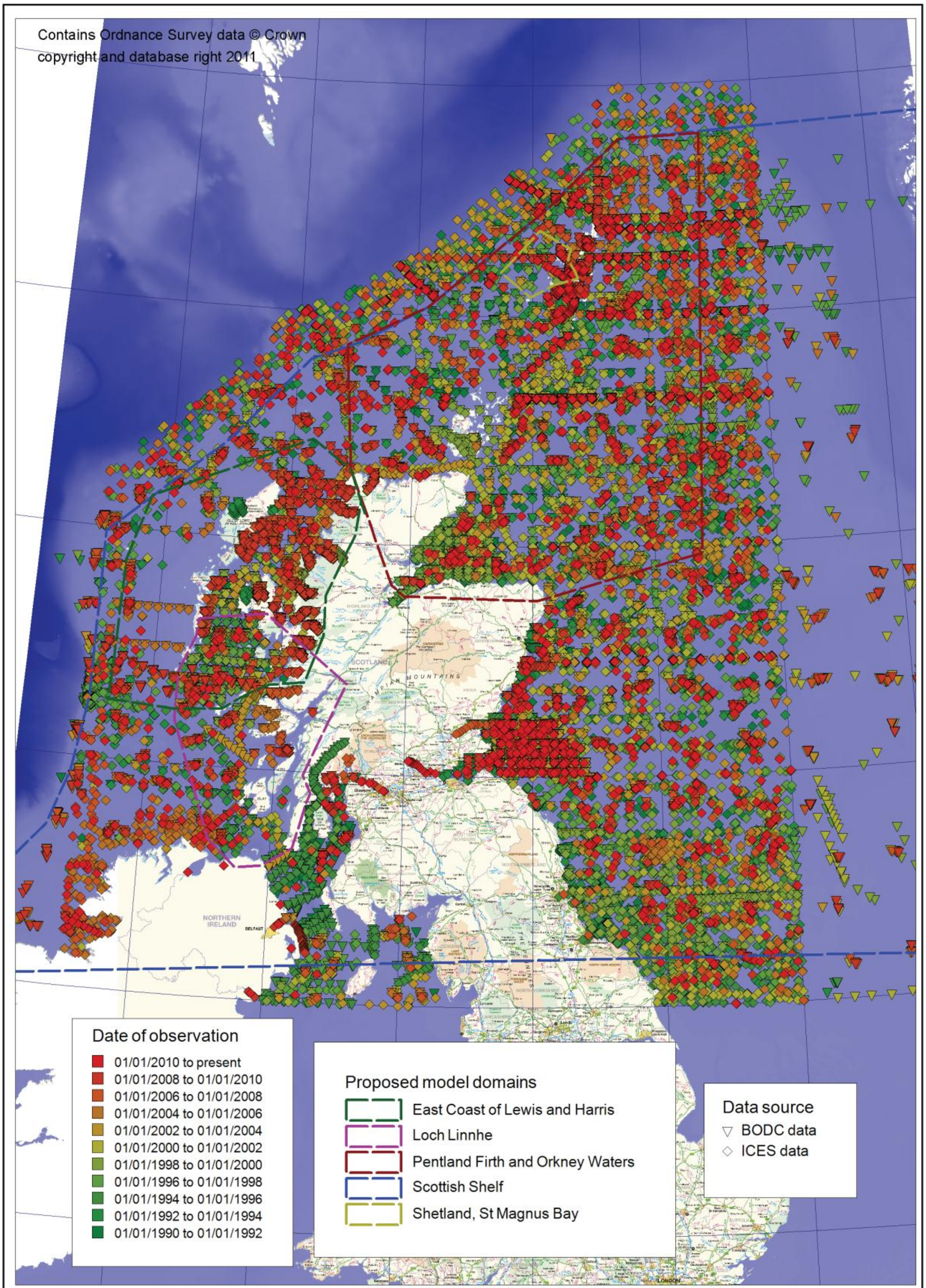
Sub model	Year	Water level	Currents	Temperature /salinity	Meteorological	Wind	River
Pentland Firth and Orkney Waters	2001	✓	✓	✓	X	✓	X
	2009	✓	✓	✓	✓	✓	✓
	2012	✓	✓	✓	X	✓	X



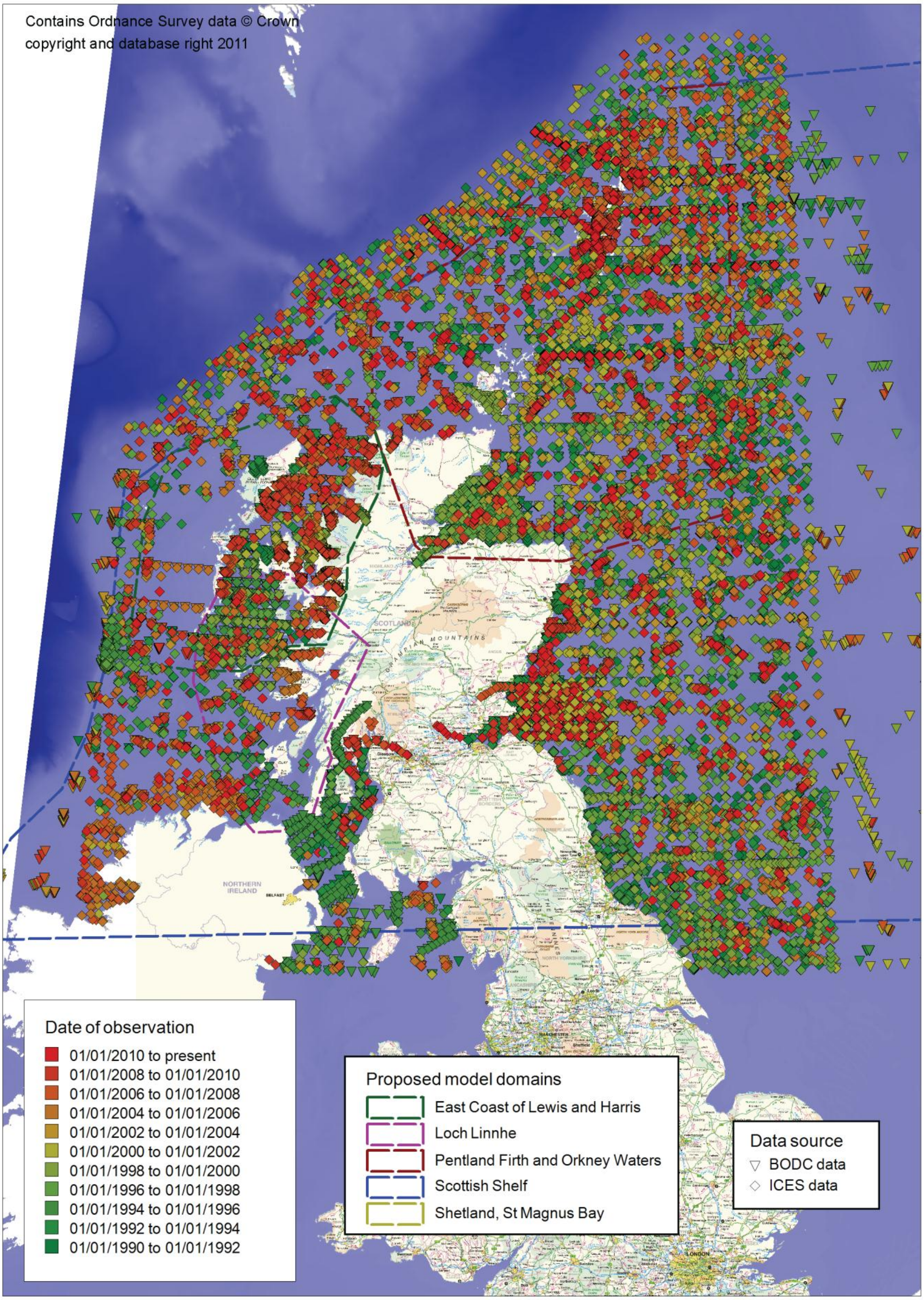
Client	Consulting Engineer	Project:	Figure 2-18
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	All temperature observations



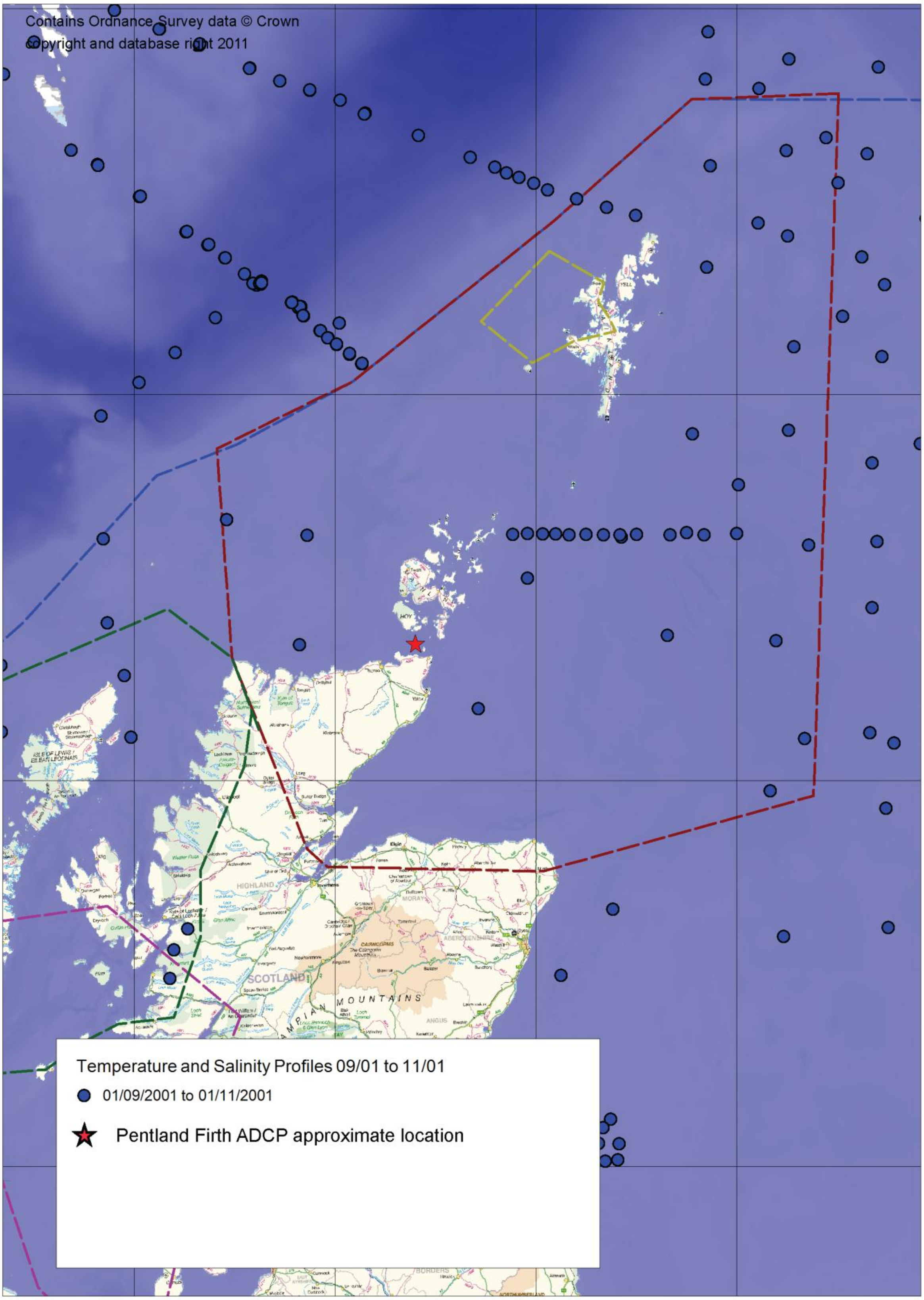
Client	Consulting Engineer	Project:	Figure 2-19
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	All salinity observations



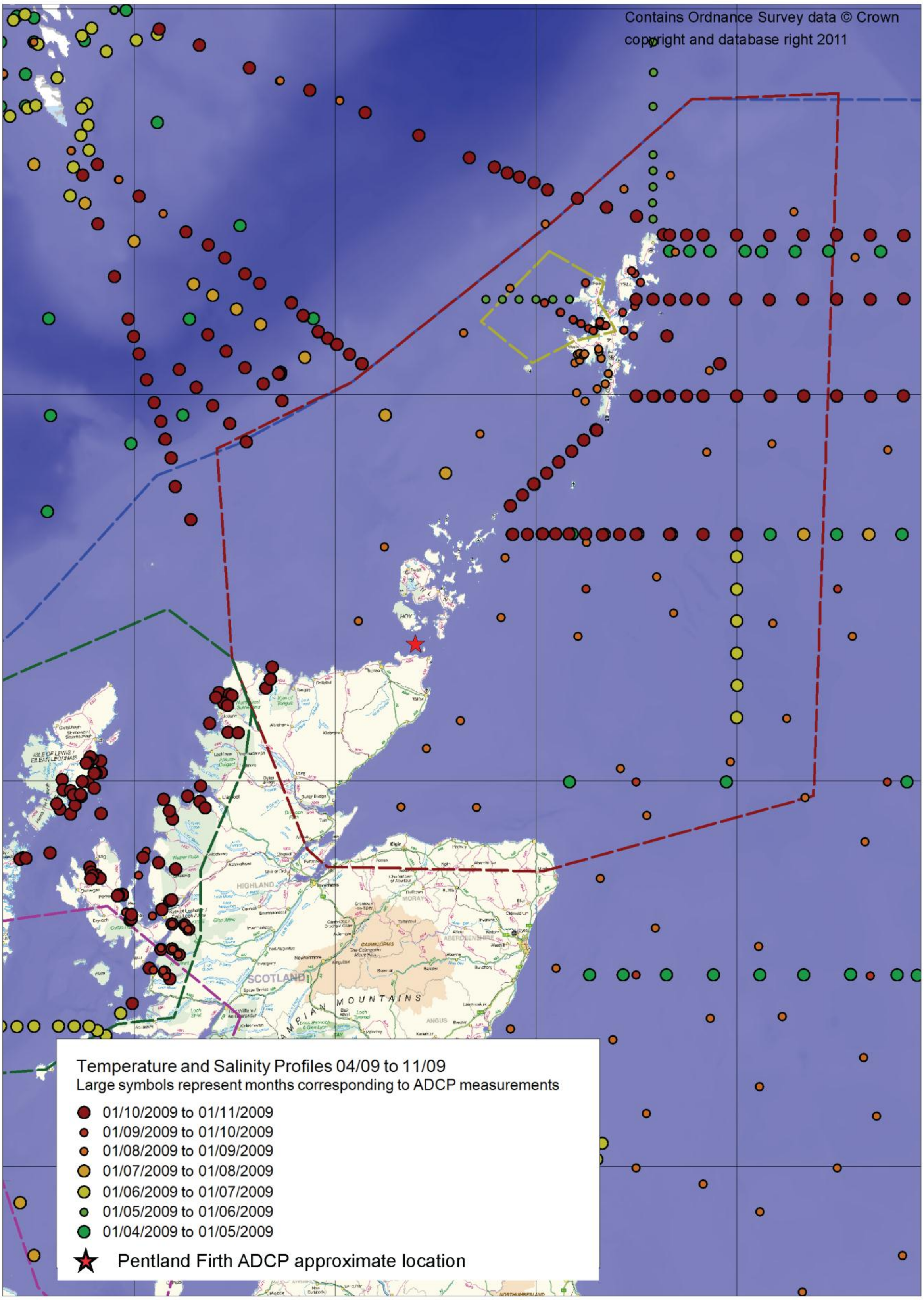
Client	Consulting Engineer	Project:	Figure 2-20
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity observations by date, including surface observations and profiles



Client	Consulting Engineer	Project:	**Figure 2-21**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity profile observations by date



Client	Consulting Engineer	Project:	Figure 2-22a
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity profiles corresponding to 2001 Pentland Firth ADCP deployments



Client	Consulting Engineer	Project:	**Figure 2-22b**
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity profiles corresponding to 2009 Pentland Firth ADCP deployments

2.5 Summary

A review has been undertaken to identify and collate data that are relevant to the setting up, forcing and calibration of the PFOW models. It has been found that there are many datasets available providing coverage over a wide spatial and temporal field.

2.5.1 Bathymetry

The EMODnet data is considered appropriate for use as the base bathymetry for model construction. This data is used as our base bathymetry data (coarse resolution), but is replaced with higher resolution data where available. UKHO data and other higher resolution datasets from ICES and Marine Scotland have been used to replace the coarser resolution data in areas that they overlap, with appropriate checks for consistency. However even with these data there are areas which have been identified in the data review report (Halcrow, 2012) as not having sufficient bathymetry data at a fine enough resolution. In this case data from digitised Admiralty Charts have been used.

2.5.2 Forcing data

For this case study, **tidal forcing, temperature and salinity data** have been obtained from the NOC-L AMM model to provide boundary conditions to the PFOW model.

Meteorological forcing for the PFOW model are derived from the Met Office model data that NOC-L holds. The Met Office data provides wind data from 1991 to present day, however other parameters such as sea level pressure, low, medium and high level cloud coverage, specific humidity at 1.5m, air temperature at 1.5m, total accumulated precipitation and sensible heat flux are only available from 2007 to 2011. This therefore limits the periods where calibration data are available coincident with full meteorological forcing. For the 2009 validation period (used for this study), the full meteorological forcing is available.

Fluvial inputs are derived from G2G river flow data obtained from CEH for the PFOW area. This data includes additional G2G runs undertaken by CEH to provide river flow data in Shetland.

Wave data for use as boundary data in the PFOW wave model has been obtained from the UK Met Office.

2.5.3 Calibration Data

Section 2.4.6 presents information about which data are available for the PFOW model. In general there is sufficient data with which to undertake calibration for waves, water level, currents, temperature and salinity for the year 2009. Thus, the calibration of the model is carried out for the year 2001 and validation is carried out for the year 2012 and 2009.

3 Hydrodynamic Model Development

3.1 Introduction

This section of the report describes the setting up of the PFOW model mesh, bathymetry and the calibration of the flow model. The version of FVCOM used was 3.6.1, with the code being compiled using the Intel Fortran and C compiler for LINUX.

3.2 PFOW flow model setup

3.2.1 Model mesh

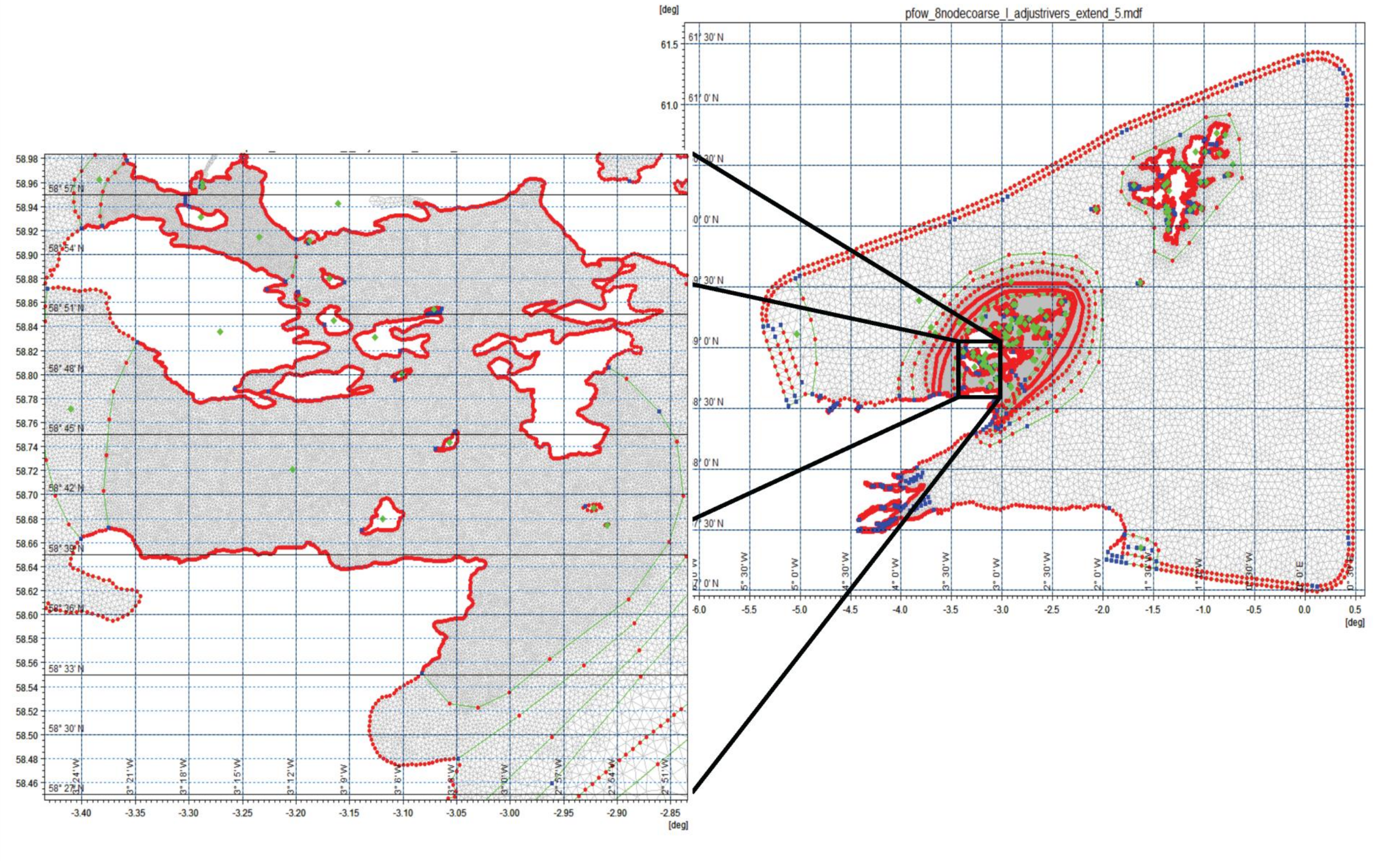
The model mesh developed for the PFOW model has been created using the DHI MIKE 21 mesh generator. The horizontal coordinate system used has been latitude and longitude with a vertical datum of mean sea level.

A number of tools exist for generation of the mesh, including SMS and BlueKenue, however our preferred choice was the MIKE 21 Mesh generator because of its ease of use and flexibility. However later on in the study, the FVCOM grid was converted into an SMS format so that the quality checking built into the SMS mesh generator could be used. This enabled a final smoothing/editing of the mesh to be done so that it met all of the FVCOM mesh criteria.

The MIKE 21 Mesh generator requires coastline and boundary data to define the extent of the active and inactive mesh. Additional information is provided regarding the resolution required in user-specified domains. The resolution is based upon modelling experience, bathymetry gradient/resolution, geographical features and requirements for the study. Although the mesh generator is able to create meshes with triangular or quadrilateral elements, FVCOM requires only triangular elements. Mesh generation is an iterative process in order to derive a mesh that varies smoothly, with triangles that do not have angles that are too acute (less than 30^{o}), and resolution that does not require an overly small model timestep. The mesh file produced in the MIKE 21 mesh generator is in ASCII format that is easily converted into a format that can be used by FVCOM. This has been done using a FORTRAN code to read and write the data into the necessary format.

The whole PFOW model mesh is shown on the right hand side of Figure 3-1. This shows the variable resolution employed in the mesh. The resolution is much higher within the Pentland Firth and the waters in and around the Orkney Isles than further afield away from these areas of interest. The left hand image in Figure 3-1 shows a closer view of the model mesh within the Pentland Firth and Scapa Flow. Resolution in the coarser parts of the model domain away from the area of interest is approximately 2.5 to 3km, whereas within the Pentland Firth and Orkney waters the resolution is in the order of 250m, reducing to 150m in places.

Two coastline data sets have been obtained for use in this study, the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) distributed by National Geophysical Data Centre (NGDC) in the US, and Ordnance Survey Mapping. These are discussed and attributed in Section 2.2. The coastline was resolved to between 120m-200m around the Orkney Isles and Pentland Firth (depending upon orientation with latitude/longitude. The coastline and the polylines used to define areas with different resolutions can be seen in Figure 3-1. The offshore boundaries of the model can also be seen in this Figure, it was defined to be along the continental shelf edge in the northwest and generally perpendicular to the tidal flow to the east and south. It can be seen that there is a polyline inside the outer boundary. The nodes along this line were defined so that one edge of each open boundary elements is normal to the open boundary. Although FVCOM will run without this restriction, it helps to reduce numerical noise due to high frequency wave reflection from the open boundary.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-1		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW coastline and polylines used to create the mesh	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

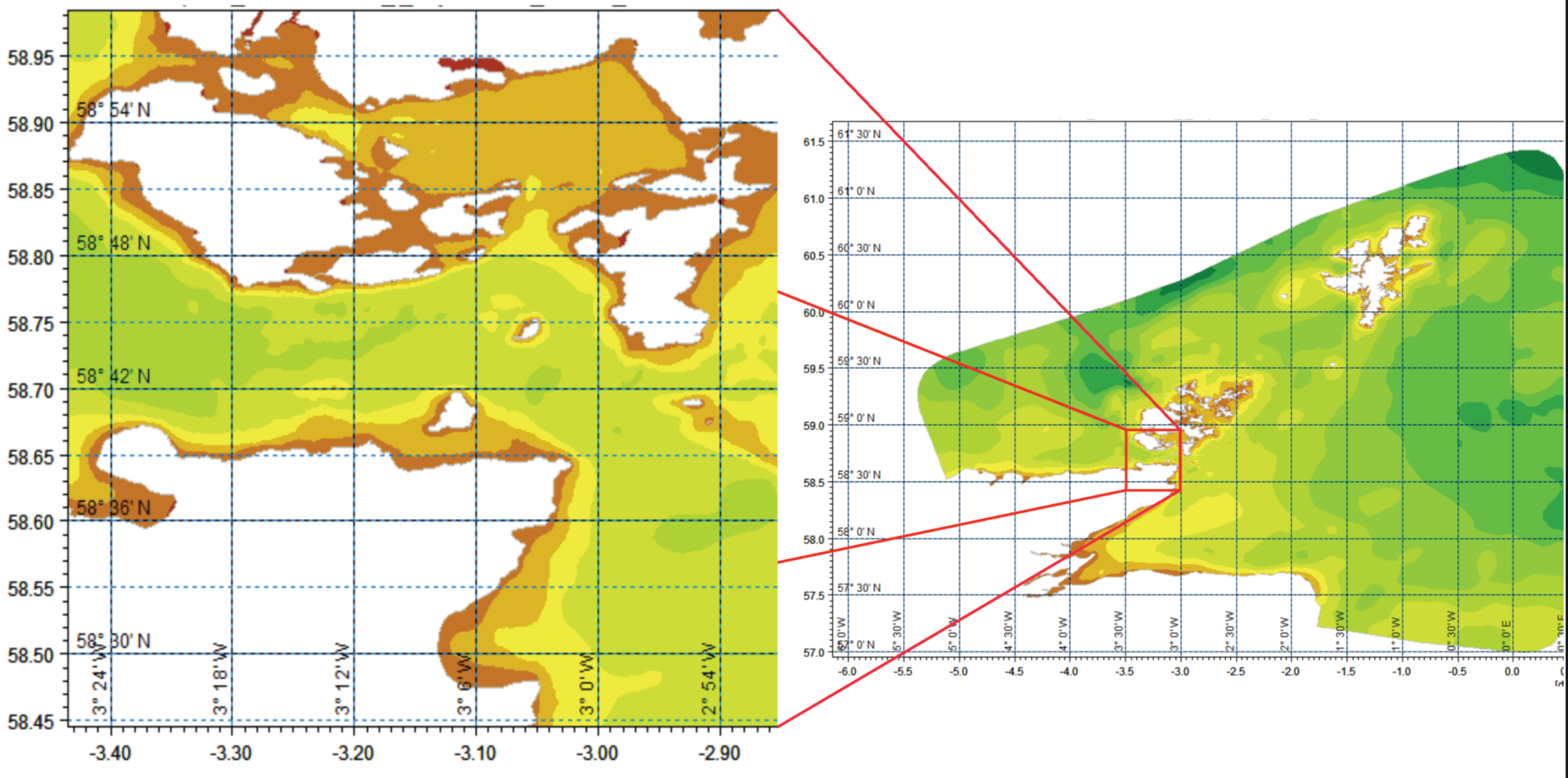
3.2.2 Model bathymetry

The model bathymetry was interpolated onto the model mesh presented in the preceding Section. This provides FVCOM with details about resolution and bathymetry upon which to perform its simulations. Figure 3-2 presents an overview of the bathymetry over the whole model area as well as within the Pentland Firth. This section describes the data used and the final model bathymetry taken forward for the model simulations.

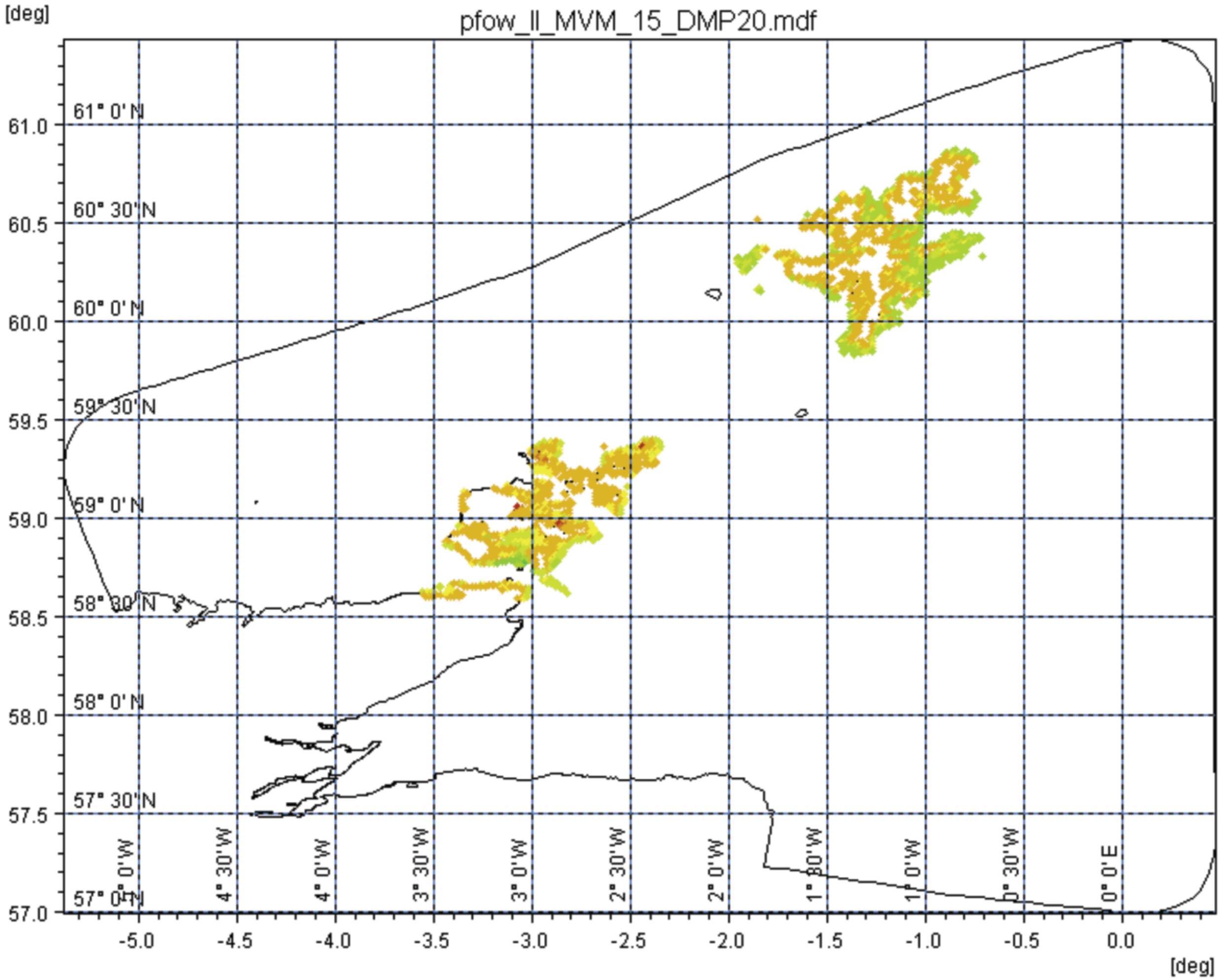
As discussed in Section 2.2, different datasets were available at different resolutions and coverage. Where possible the highest resolution data was used, this was in general from the UKHO (United Kingdom Hydrographic Office) and Marine Scotland datasets. The EMODnet/NOOS datasets covered a wider area but had a lower resolution. There were some areas however that did not have sufficient resolution to resolve narrow waterways in sufficient detail, in these instances Admiralty Charts were digitised (under licence with the UKHO). The different datasets were converted to a common datum of Mean Sea Level (MSL) by using conversions provided in Admiralty Tide tables that had been interpolated onto a surface. The separate datasets can be seen in Figures 3-3 a-d, and the combined dataset interpolated upon the mesh elements in Figure 3-3e.

The mesh information and the interpolated bathymetry values at the mesh nodes are saved in and an ASCII formatted Mike21 .mesh file. Fortran code was written which read in this file and produced the necessary grid, depth and open boundary files required by FVCOM. When setting up the MIKE 21 mesh, it is possible to add a code to the open boundary. The FORTRAN code uses this to identify boundary nodes, which enables it to produce the open boundary files required by FVCOM.

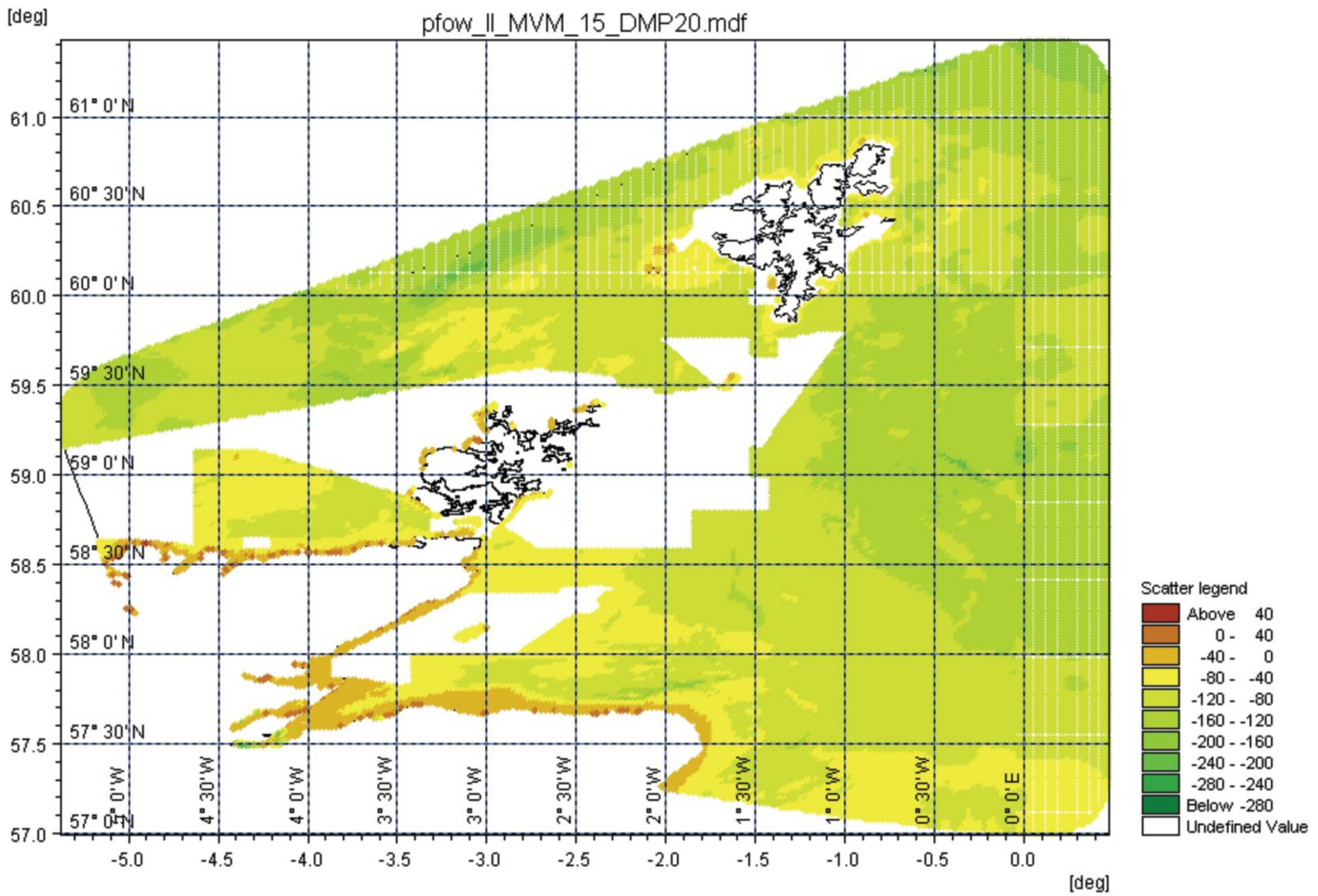
The final mesh used for the simulations presented in this report had been converted from the FVCOM grid file into an SMS format. This allowed the mesh to be adjusted to fit within the recommended FVCOM quality indices (Please see the FVCOM manual (Chen et al, 2013) for details). Additionally after carrying out some simulations it was found that the model was more stable if the bathymetry was smoothed which helped reduce steep gradients in the mesh bathymetry. The mesh bathymetry was smoothed four times using the FVCOM toolbox smoother. Figure 3-3f shows the originally interpolated bathymetry in the left frame, and the smoothed bathymetry on the right. In general all of the main features remain although some finer variations in the Pentland Firth have been smoothed out.



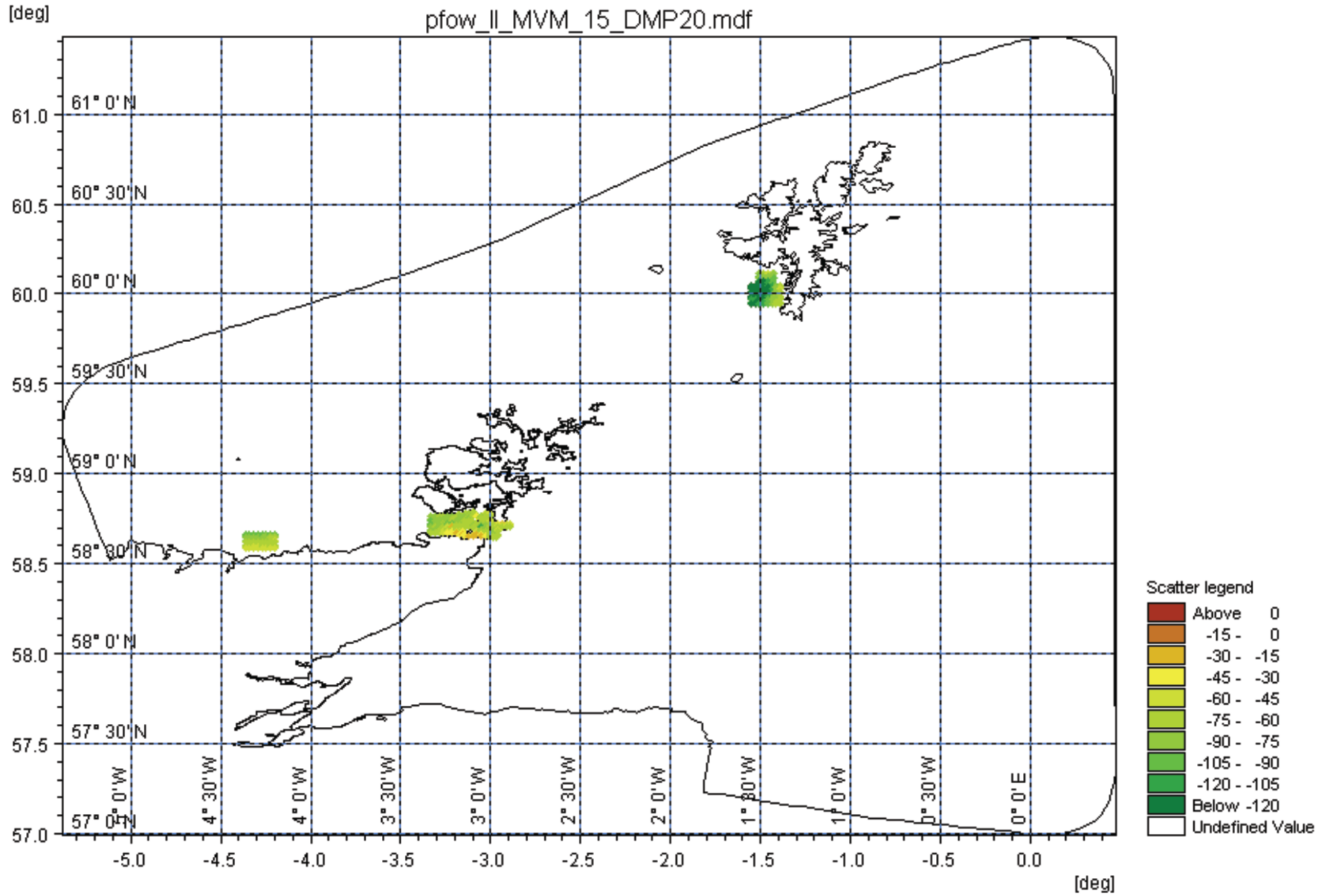
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-2		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	PFOW model mesh (right) and focus on Pentland Firth (left)	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 14/112012



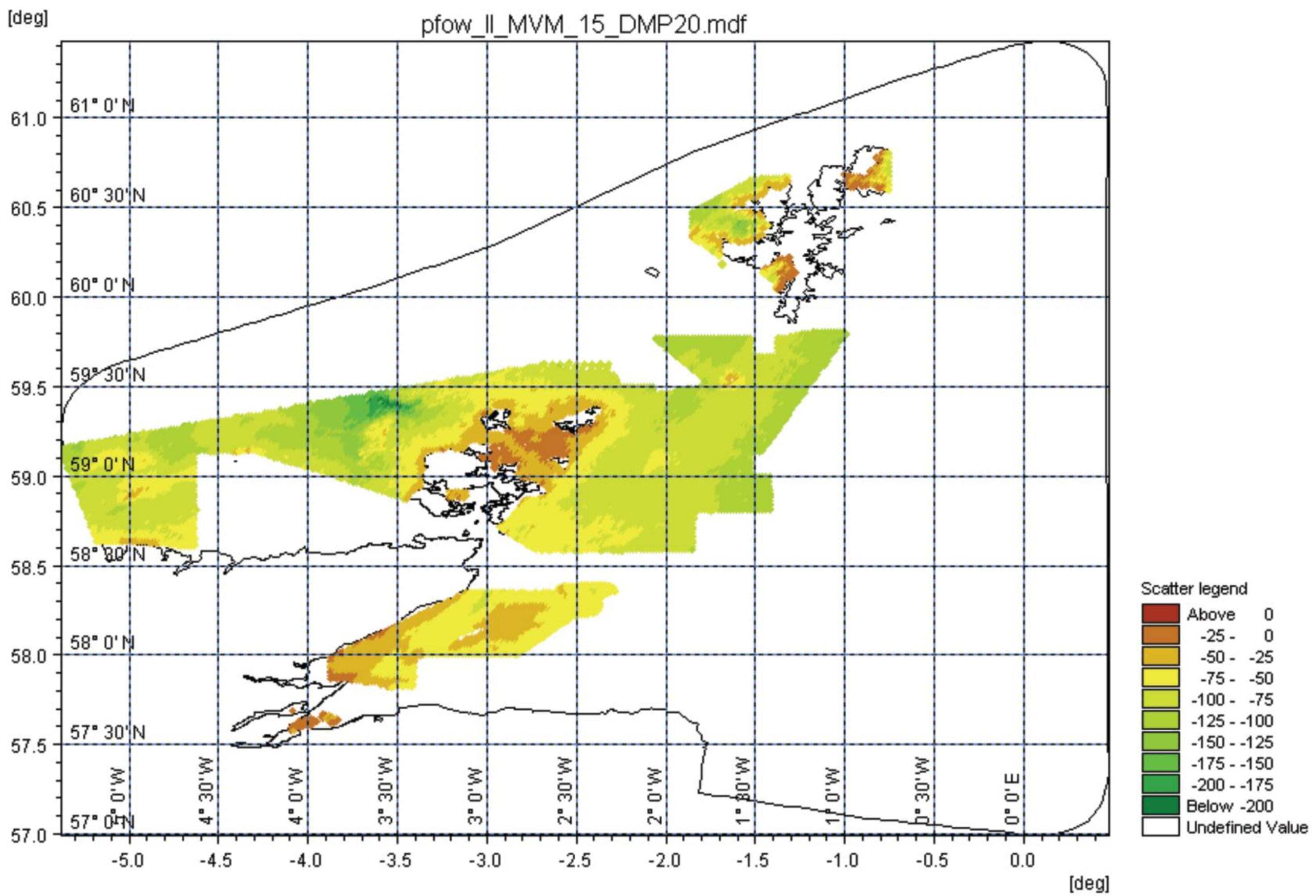
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3a		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	PFOW bathymetry subset – Admiralty Chart data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



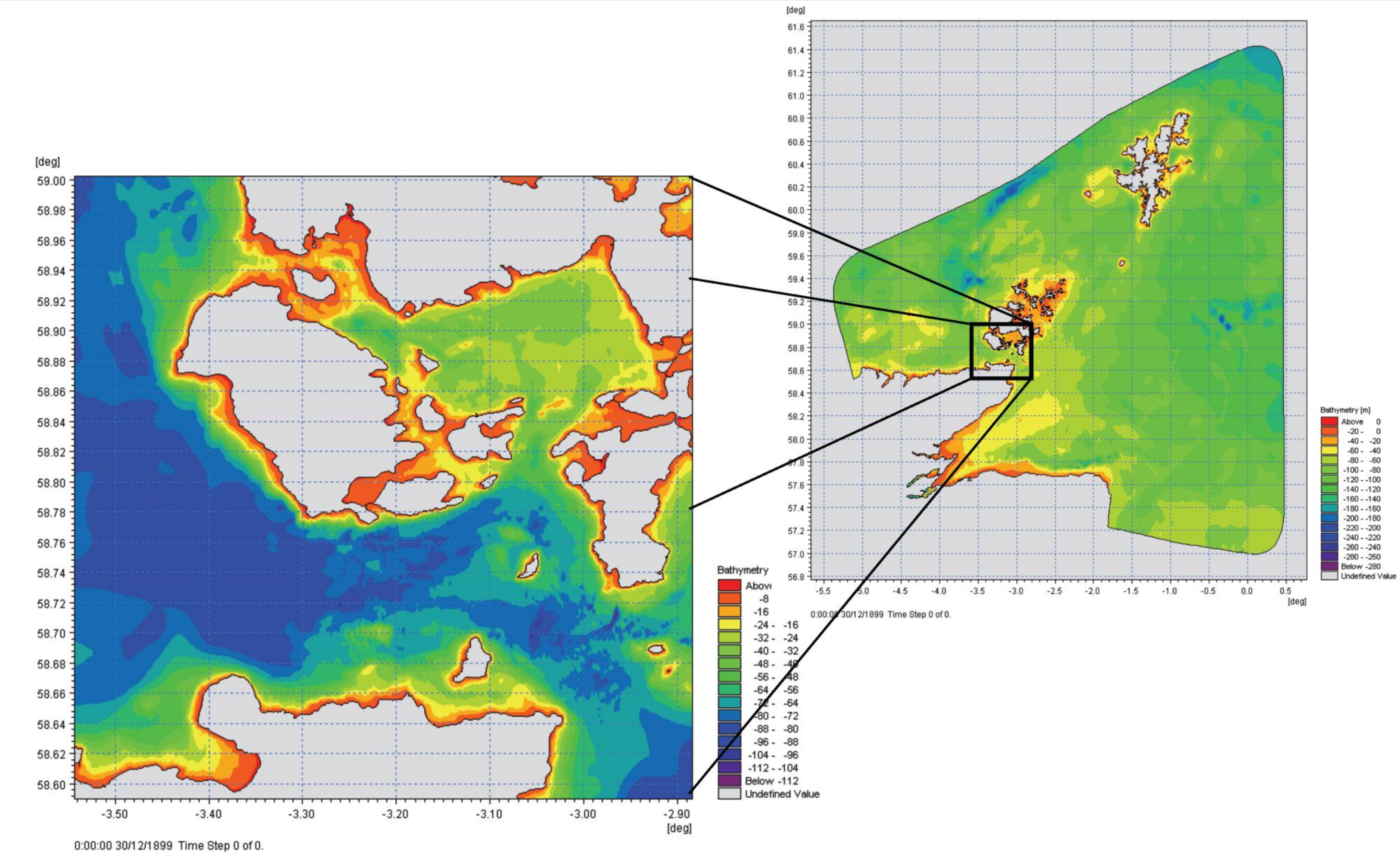
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW bathymetry subset – EMODNET/NOOS data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



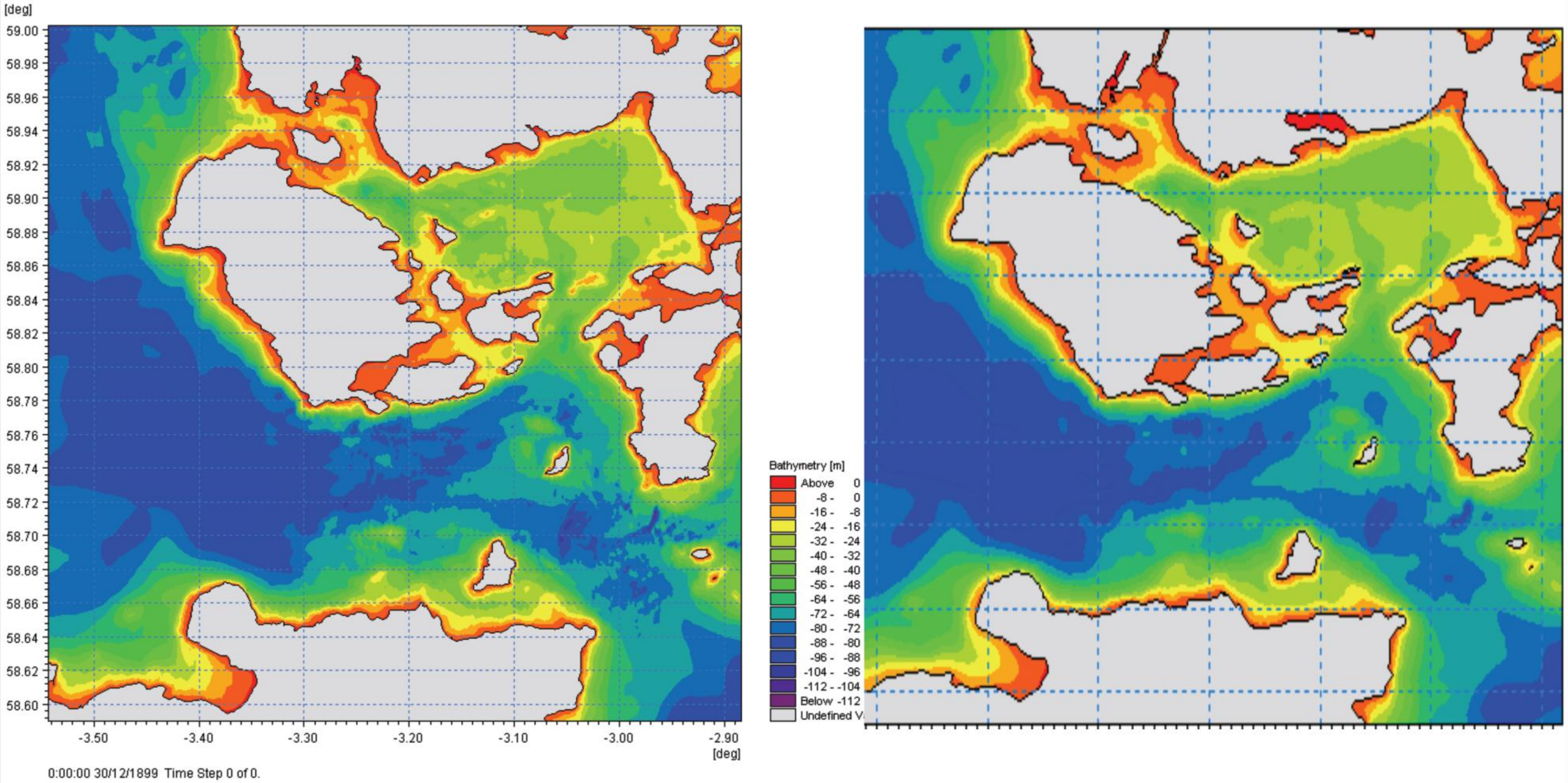
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW bathymetry subset – Marine Scotland data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3d		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW bathymetry subset – UKHO data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3e		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model Combined bathymetry data (relative to mean sea level) for whole area (right) and Pentland Firth area (left)	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3f		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Initial interpolated bathymetry (right) smoothed bathymetry (left) in the Pentland Firth Area	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 14/112012

3.2.3 Boundary data

Boundary data for the model calibration and validation simulations have been derived from the NOC-L Atlantic Margin Model (AMM). This model provides hourly water level, depth-averaged velocities, and daily temperature and salinity throughout the models vertical layers. Matlab routines were provided by NOC-L to read in the water level and temperature/salinity files. These routines were extended, so that the model boundary nodes were used to extract and interpolate the AMM model data onto the PFOW model boundaries. Water levels were produced around the PFOW model boundary at 0.25 hourly intervals from the AMM model.

In the earlier stages of the modelling, the PFOW model was run with 3 vertical layers using water levels only at the model boundaries. Although problematic initially a near 30 day simulation was achieved and the model was calibrated against data. However, with 10 vertical layers, it was not possible to get a model that would run stably (with water level boundary data only) no matter what was tried. In the end nesting boundaries were investigated in which velocities, temperature and salinity are prescribed at all the nodes associated with the elements along the open boundaries. The prescription of the velocities, rather than letting the model calculate them itself proved to be important to run the model successfully. Water levels were still prescribed as before, therefore choosing the type 2 nesting approach, rather than the type 1 where water levels are also prescribed in the nesting file. Further details on type 1 and type 2 nesting approaches can be seen in the FVCOM manual (Chen et al, 2013).

Temperature and salinity data have been extracted from the daily AMM model data and also included in the nesting file.

3.3 Flow model calibration and Validation

3.3.1 Introduction

The calibration and validation of the PFOW flow model has been undertaken in a number of stages; the first being the running of the FVCOM model (version 3.1.6) and making sure that it is stable; secondly, comparison against tides and current speeds for a period in 2001 using tidal forcing (constant temperature and salinity) and validation against currents in December 2012.

The PFOW model was originally run on a 64-core computer running Windows Server 2012 operating system. FVCOM was installed using CYGWIN, a linux emulator that runs under Windows. However there were many problems with using this approach along with using the GNU Fortran and C compilers. Therefore a virtual LINUX machine was created on the computer with 60 available cores. This was used for many of the early simulations, however we have since used a larger cluster (called EnCORE, www.stfc.ac.uk/hartree/) which has allowed us to run simulations with up to 500 cores.

The next sections describe what was required to get the model running stably, and the sensitivity tests and calibration against observed data.

3.3.2 Initial model runs

Initial runs of the PFOW model were undertaken with FVCOM version 2.7, however as soon as version 3.1.6 was obtained all effort was switched to this version. Boundary conditions were obtained for a period in 2009 from the AMM model and were used to get the PFOW model running.

Initially problems were encountered with the model crashing; these issues were tracked down to problems at the model boundary as well as internally with small elements. The model at this stage was run using 3 vertical layers. The following adjustments to the model setup were found necessary in order to obtain a stable 3-layer model.

- Some iterations were made with the model mesh to remove small elements as well as smooth bathymetry in a deep area (>200m) west of Shetland (on the offshore boundary adjacent to the continental shelf) where instabilities were observed.
- Further adjustments to the mesh bathymetry were made at the points where the open boundary met with the mainland coast. At these locations the depths were adjusted so that they did not dry out and are uniform so that any gradients did not produce instabilities.
- Bed roughness maps and horizontal mixing maps were applied to the model with increased values at the open boundary (a few elements wide) in order to damp any oscillations or instabilities. This had the desired effect without any significant impact upon the model calibration.

The vertical resolution in the model was subsequently increased to 10 vertical layers and many stability problems were encountered. As discussed in Section 3.2.3 a nesting boundary approach was adopted, making the model behave much more stably. This meant that the adjustments to the model roughness and horizontal mixing at the boundaries (using the maps) were no longer required. Likewise sponge nodes were also not required.

A period in 2009 was initially selected for the calibration period. This period was chosen as the most complete set of data for calibration and forcing the model was available (full met forcing, river flows, tides and current transects). However it soon became apparent that although there was ADCP data available in the Pentland Firth, this was only transect vessel mounted ADCP data (VMADCP) in a small area between Stroma and the Scottish mainland on the south of the Pentland Firth. Some preliminary results were presented at a Steering Group meeting. However it became apparent that this data was not representative over the entire Pentland Firth and only provided data over a relatively short time period.

Therefore, the focus was shifted to the 2001 ADCP and VMADCP data mentioned in Section 2. This data was received from the Environmental Research Institute and Heriot Watt University, but originally collected by Gardline Surveys for the Maritime and Coastguard Agency. Figure 3-4 presents the locations of the three fixed stations and the VMADCP transects. Whereas this data provides good spatial and temporal coverage within the Pentland Firth there are some other limitations in using this data. Only wind speed and direction is available for the met forcing and there is no river flow data available from the Grid2Grid model during this period. However for the purposes of calibrating the model for tide and currents it was felt that the 2001 data was superior to the 2009 data.

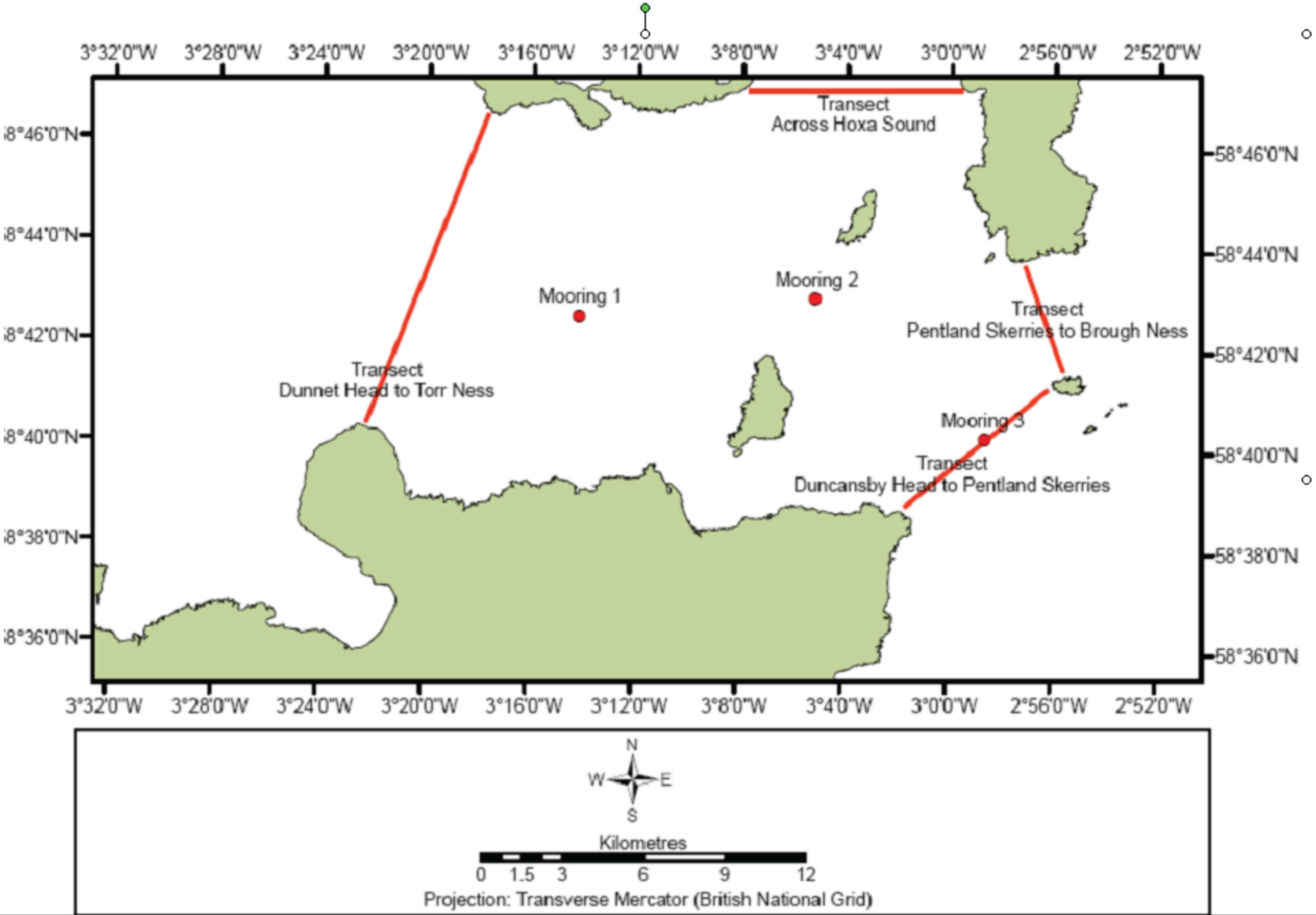
EMPHASIS WAS PLACED UPON THE THREE FIXED STATIONS INITIALLY AS THESE CONTAINED APPROXIMATELY 30 DAYS OF CURRENT MEASUREMENTS THROUGH THE WATER COLUMN. THESE HAVE BEEN DEPTH-AVERAGED FOR INITIAL CALIBRATION PRIOR TO INCLUDING TEMPERATURE AND SALINITY VARIATIONS AT THE MODEL BOUNDARY.

Table 3-1 presents the details of the ADCP campaign, this table was taken from Table 1 in Baston and Harris (2011). It shows that the ADCP data did not provide information in the top 10m of the water column which may mean that the ‗observed' depth-averaged peak speeds (calculated by depth-averaging below the 10m level in the water column) may be slightly lower than would otherwise be observed.

TABLE 3-1 2001 ADCP CHARACTERISTICS IN THE PENTLAND FIRTH

Location	Number of 4m bins	Deepest Bin depth(m)	Shallowest Bin depth(m)	Duration (days)	Deployment date
1	17	77	13	32.5	14/9/2001
2	17	75	11	31.25	19/9/2001
3	15	67	11	30	15/9/2001

The calibration effort at this stage has been focussed on reproducing correctly the tidal levels and flows in the model area, while keeping the temperature/salinity variation constant. Early versions of the model with 3 vertical layers were used for model calibration so as to speed up the simulations. However the final results presented in this report are for the 10 layer model unless otherwise stated.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location of ADCP/VMADCP surveys and analyses performed by Gardline surveys for Maritime Coastguard Agency in 2001(provided by the Environmental Research Institute and Heriot Watt University)	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.3.3 Model calibration against 2001 data

The calibration described in this section has been performed with constant temperature and salinity boundaries, ten vertical layers and without the effect of meteorology or river inputs. Water levels were applied to the boundary nodes at 10 minute intervals whilst the depth-averaged velocity from the AMM model was prescribed using a nesting boundary file equally through the vertical layers. The main purpose of this calibration is to make sure current speeds and water levels are reasonably reproduced within the Pentland Firth model given the forcing from the AMM model. The Pentland Firth is highly energetic and tidally dominated and therefore it is felt that this is a valid approach prior to including other forcing terms which may be of secondary importance. In Stage 3 of this project, the regional shelf model (developed in Stage 1) is used to supply boundary conditions to the four individual case study areas developed in Stage 2. However, as the development of the Stage 1 and Stage 2 models is carried out in parallel, the boundary conditions used for the stage 2 models is derived from an external source; in this case the AMM model.

The level of calibration of the PFOW model has been determined by visual inspection of time-series comparison (speeds and water levels) as well as statistical analysis for a more quantitative comparison. A description of the statistical measures is presented later in this section. Additionally comparison against calibration guidance provided in Bartlett (1998) has also been made.

3.3.3.1 Sensitivity to bed roughness

Initial model runs (using the 3 layer model) undertaken for comparison against the 2001 timeseries data used the default bed roughness of 0.1m and a horizontal mixing Smagorinsky coefficient of 0.2. Current speeds from the model tended to under-predict the peak speeds on the flood tides at Moorings (locations) 1 and 2 - see Figure 3-4 for locations. Sensitivity to bed roughness was therefore undertaken with the aim to improve the comparison with the data. Each model was run for a period of 16 days, with subsequent analysis undertaken for the last 15 days. The model is driven by boundary conditions (water levels and depth-averaged currents) from the AMM model although no meteorological forcing has been included. This sensitivity analysis is presented in Appendix A.

The sensitivity tests to roughness presented in this current section are for the ten layer model but have made use of the earlier findings from the three layer model tests presented in Appendix A.

During the development of the 10 layer model it was found that using the original roughness of 0.025 produced speeds that were too high. Therefore building upon the 3 layer model results two bed roughness values were tested - a roughness length of 0.1m, and a roughness length of 0.04m. The results of the comparison of observed and modelled speeds can be seen in Figures 3-5a-c for the roughness =0.1m and Figures 3-6a-c for a roughness length of 0.04m. On each of these plots, in common with other figures in this report, the observed data is represented with a black line and the model results with a red line.

Figure 3-5a shows that at location 1 there is a significant asymmetry in the depth-averaged tidal currents (Figure 3-6d has a closer view). With a roughness length 0.1m the model tends to under predict current speeds, especially for the smaller of the two peaks in each tide. Figure 3-6a shows the same location but for a roughness of 0.04m. This shows a slight over-prediction of the highest peak currents in some instances but the lower peak is reproduced well.

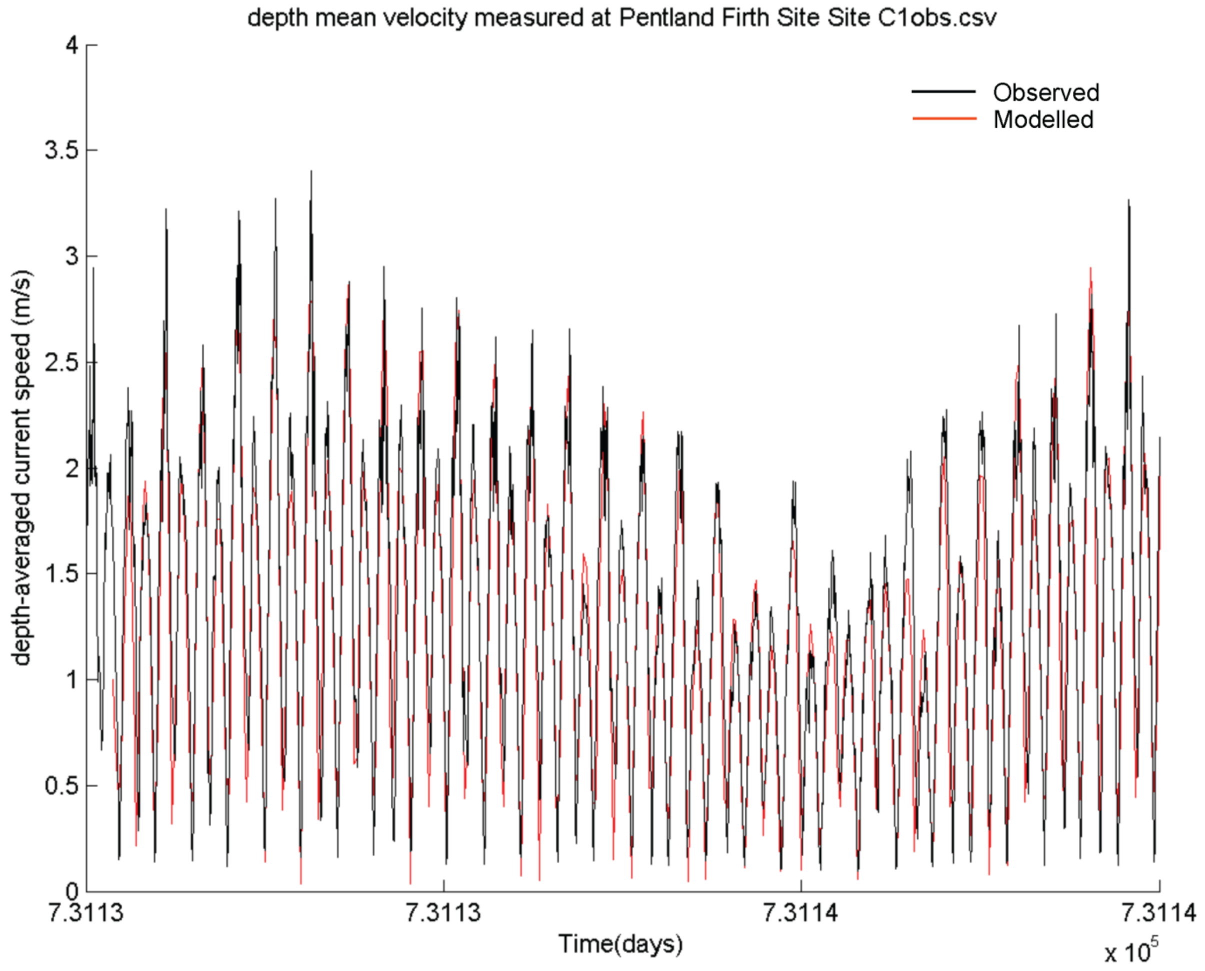
Figure 3-5b shows that at location 2 there is no obvious asymmetry in the depth-averaged tidal currents. With a roughness length 0.1m the model tends to under-predict current speeds. Figure 3-6b shows the same location (Figure 3-6e has a closer view) but for a roughness of 0.04m, the match with the current speed is improved over that shown in Figure 3-5b.

Figure 3-5c shows that at location 3 there is a strong asymmetry in the depth-averaged tidal currents. With a roughness length 0.1m the model tends to under-predict current speeds for the smaller of the peaks, but over-predict the larger one on each tide. Figure 3-6c shows the same location but for a roughness of 0.04m (Figure 3-6f has a closer view), the match with the current speed is improved for the smaller of the peaks although the higher of the peaks is over predicted. It should be noted however that the ADCP data misses out the top 10m of the water column, and therefore the depth average value may in fact under-estimate the actual value.

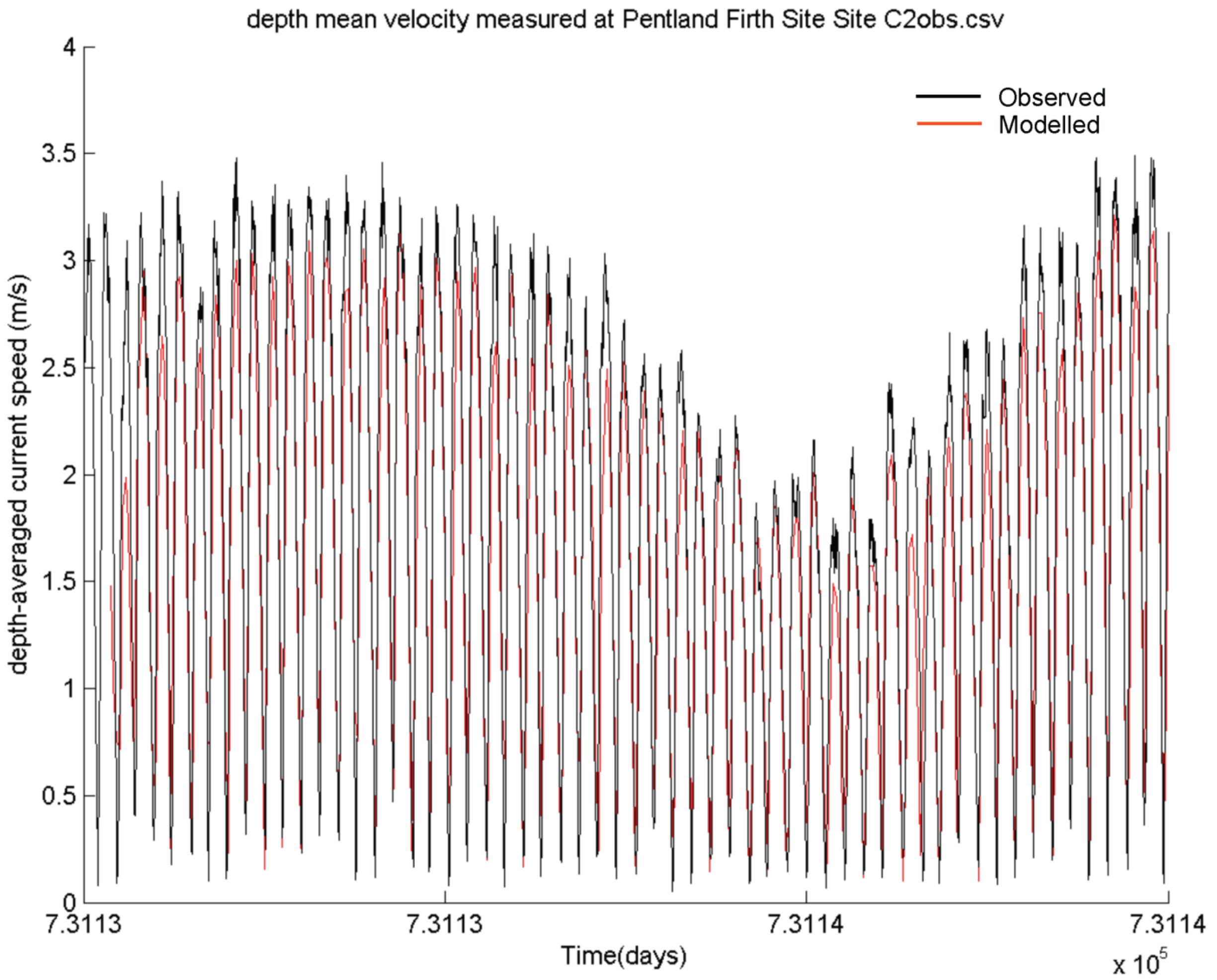
Figures 3-6g-k present comparisons of the same ADCP data at location 2 against model results but at instantaneous times through the vertical.

The model results compared are for the 10 layer model and the 3 layer model. There are some differences between the model setups (10 layer model had a slightly higher roughness, and the boundary condition approach was different) and so an exact match between the two model results should not be expected. However these have been included so that the differences between the 3 and 10 layer can be seen. It should be noted that on each of these figures the axis scales differ.

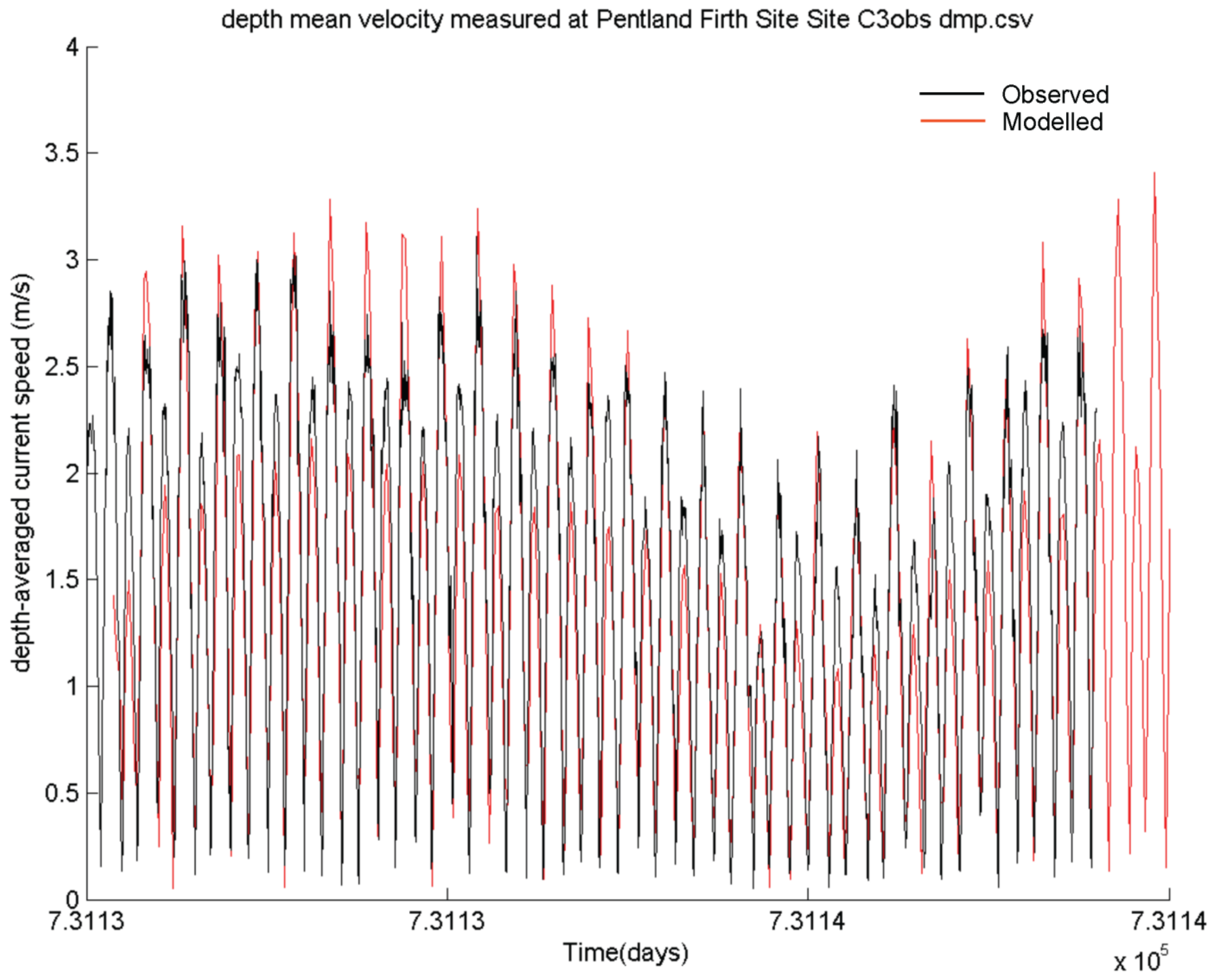
What is evident from these figures is that the 10 layer model represents the lower velocities towards the bed in more detail as might be expected, and similarly for near surface speeds. The 10 layer model is able to represent the vertical variation in velocity much better than the 3 layer model. Figure 3-6i shows a time when there is a reversal in the flow, with the peak velocities in the ADCP data appearing approximately at mid depth. The 10 layer model is also able to reproduce this feature (although with lower magnitude – difficult to get phasing exactly the same) whereas the 3 layer model barely shows this feature. Although such a flow structure appears for only a short period of time during a tidal cycle, it adds confidence to the 10 layer model that it is able to reproduce this structure.



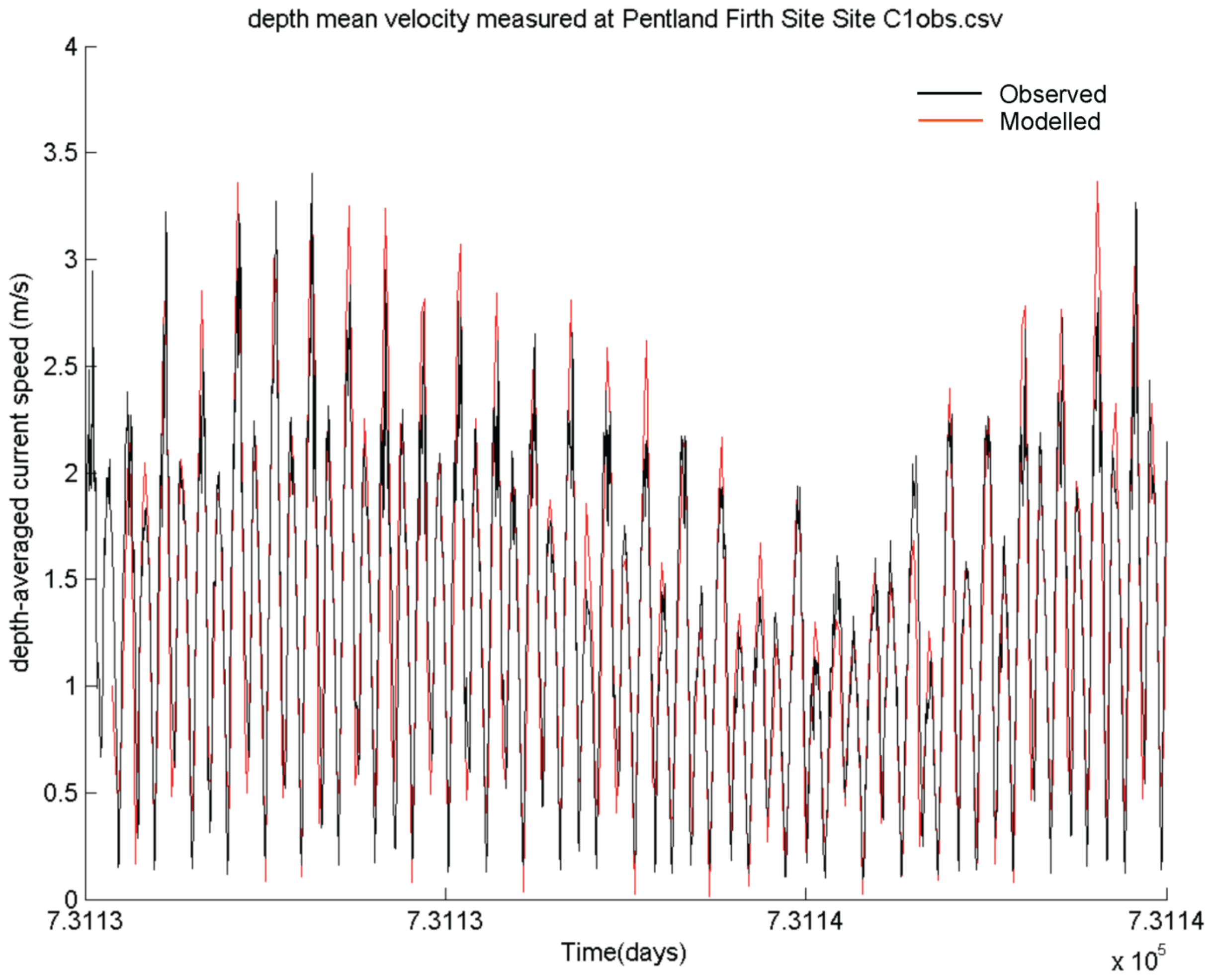
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location 1 comparison between data and model with roughness = 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



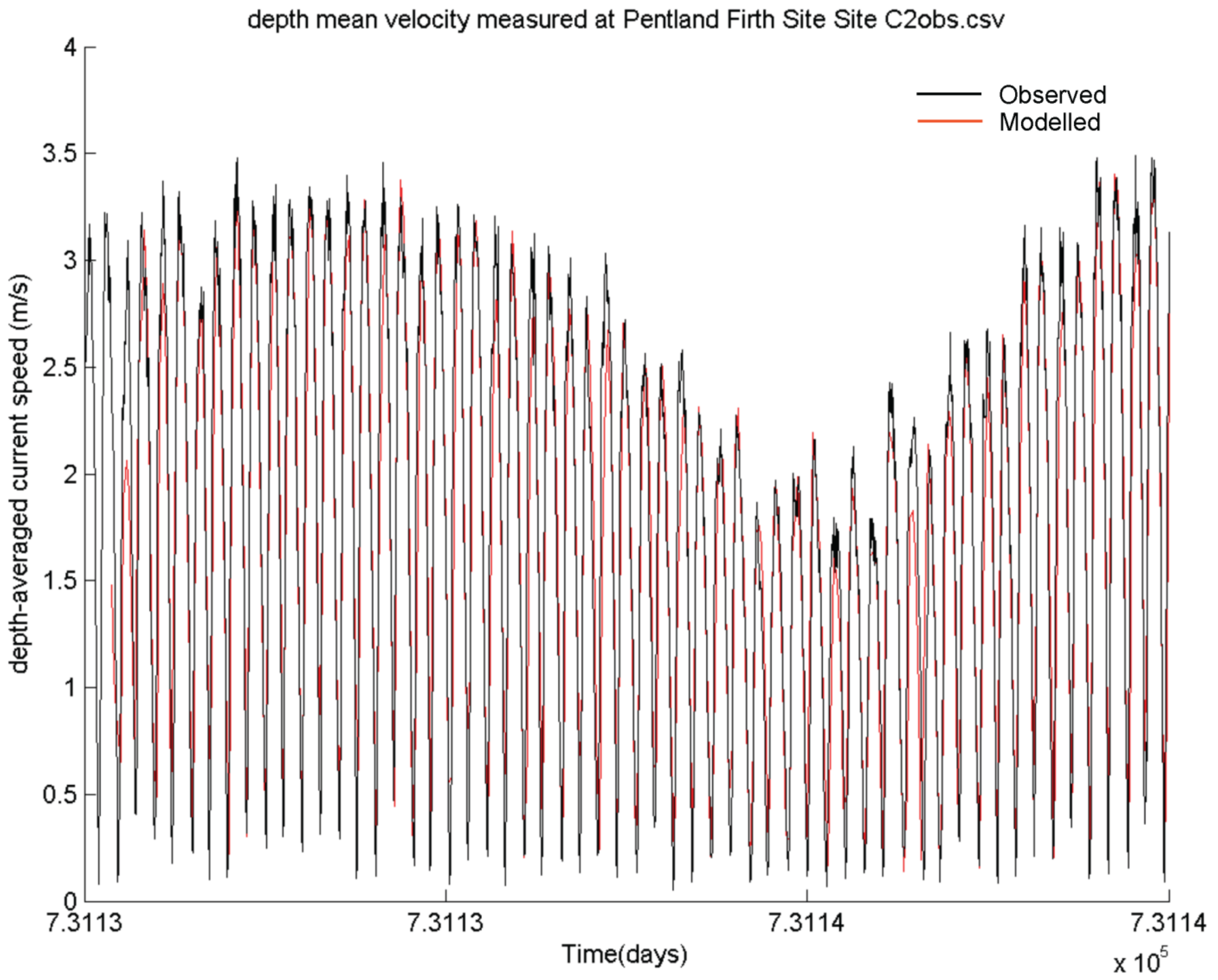
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location 2 comparison between data and model with roughness = 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5c		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Location 3 comparison between data and model with roughness = 0.1m	Checked DMP	Scale Not to scale	Rev. 0
			.	Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location 1 comparison between data and model with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location 2 comparison between data and model with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
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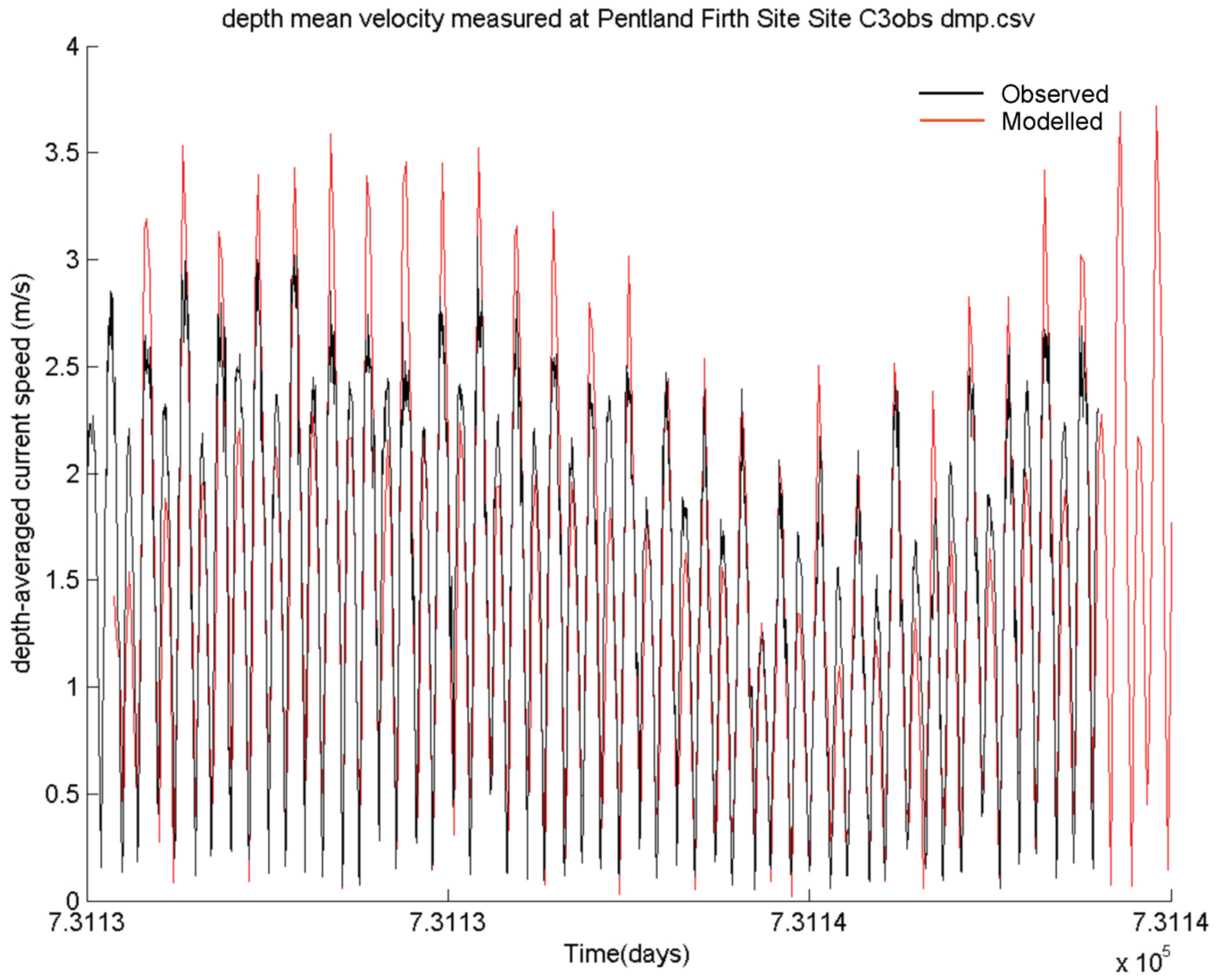
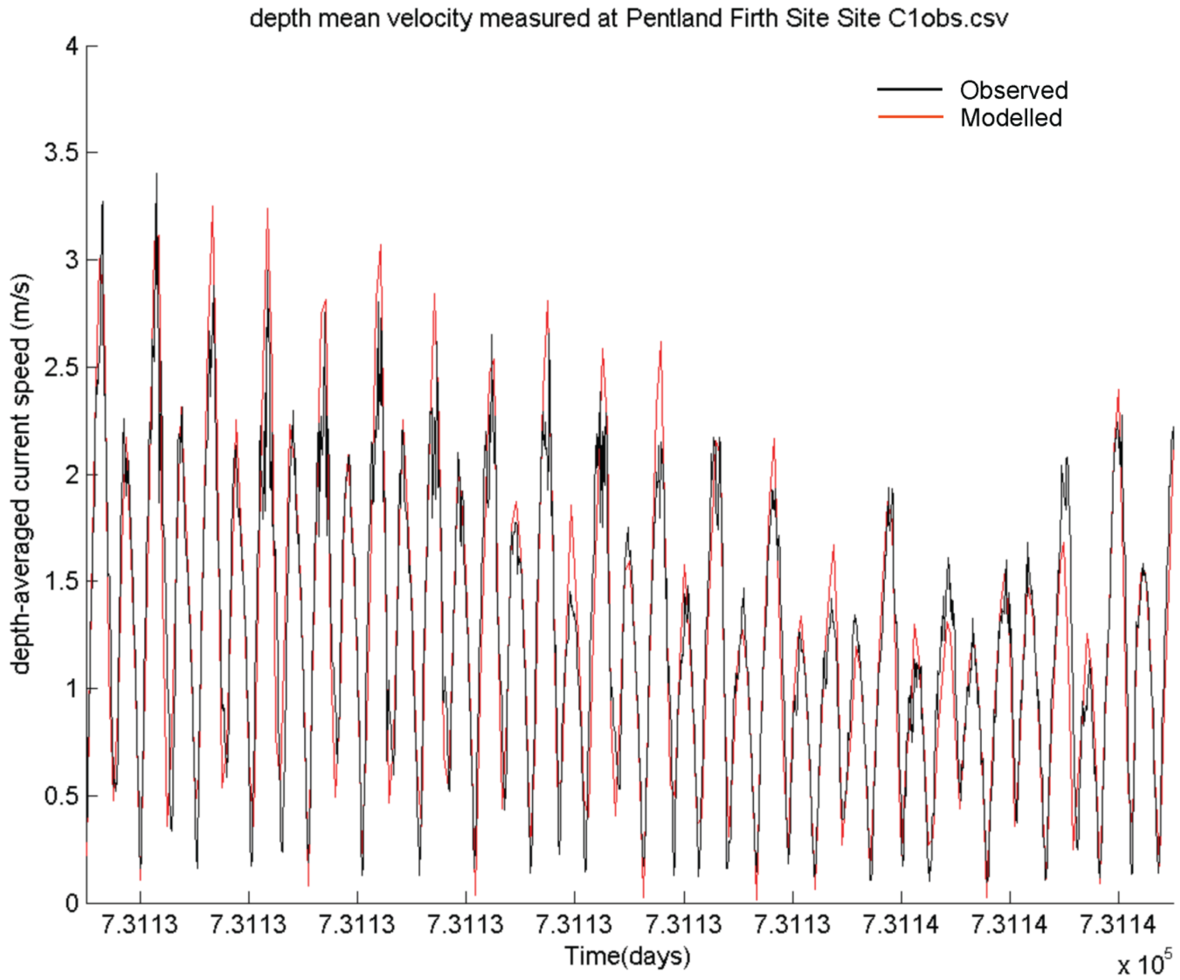
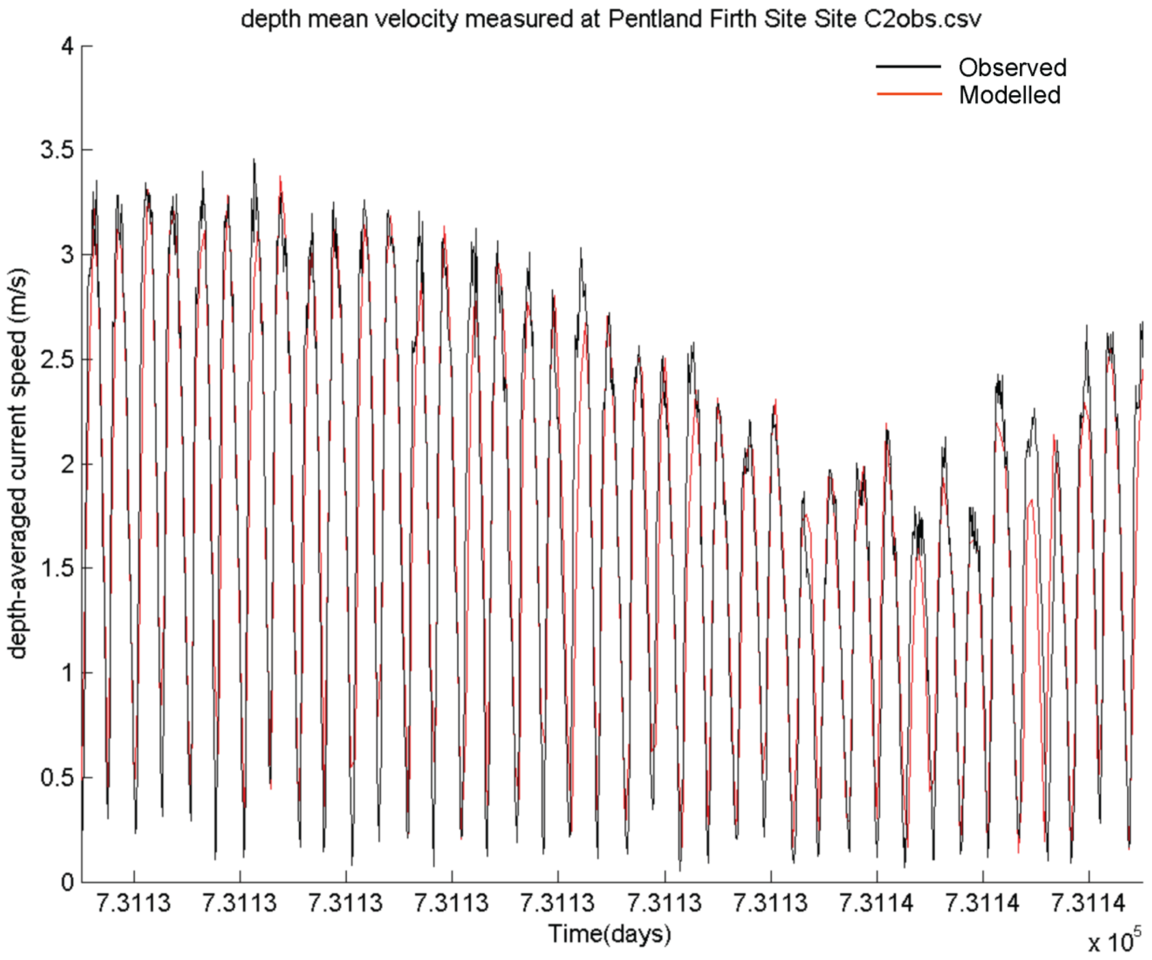


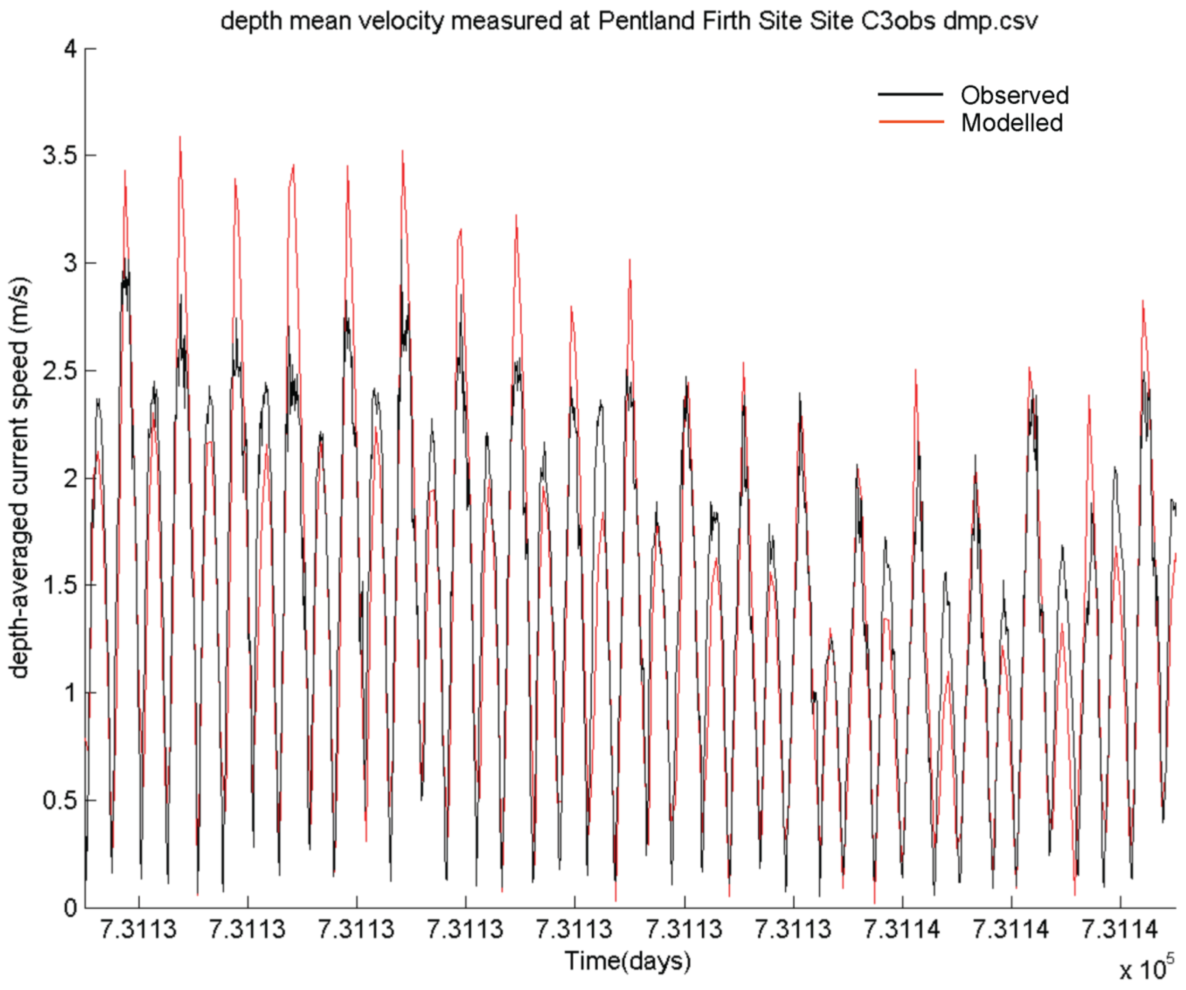
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Location 3 comparison between data and model with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



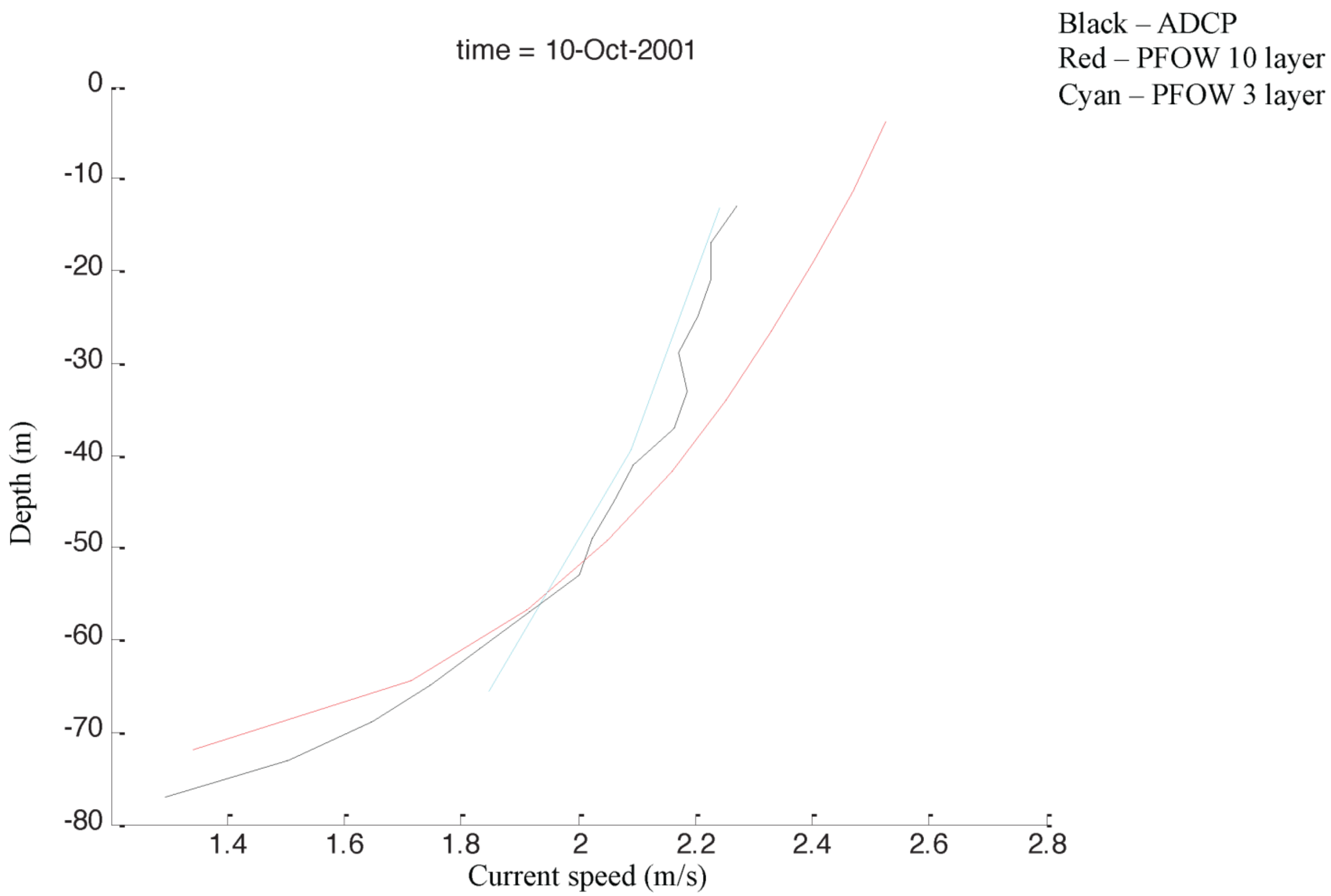
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6d		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of current speeds at location 1. Closer view with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



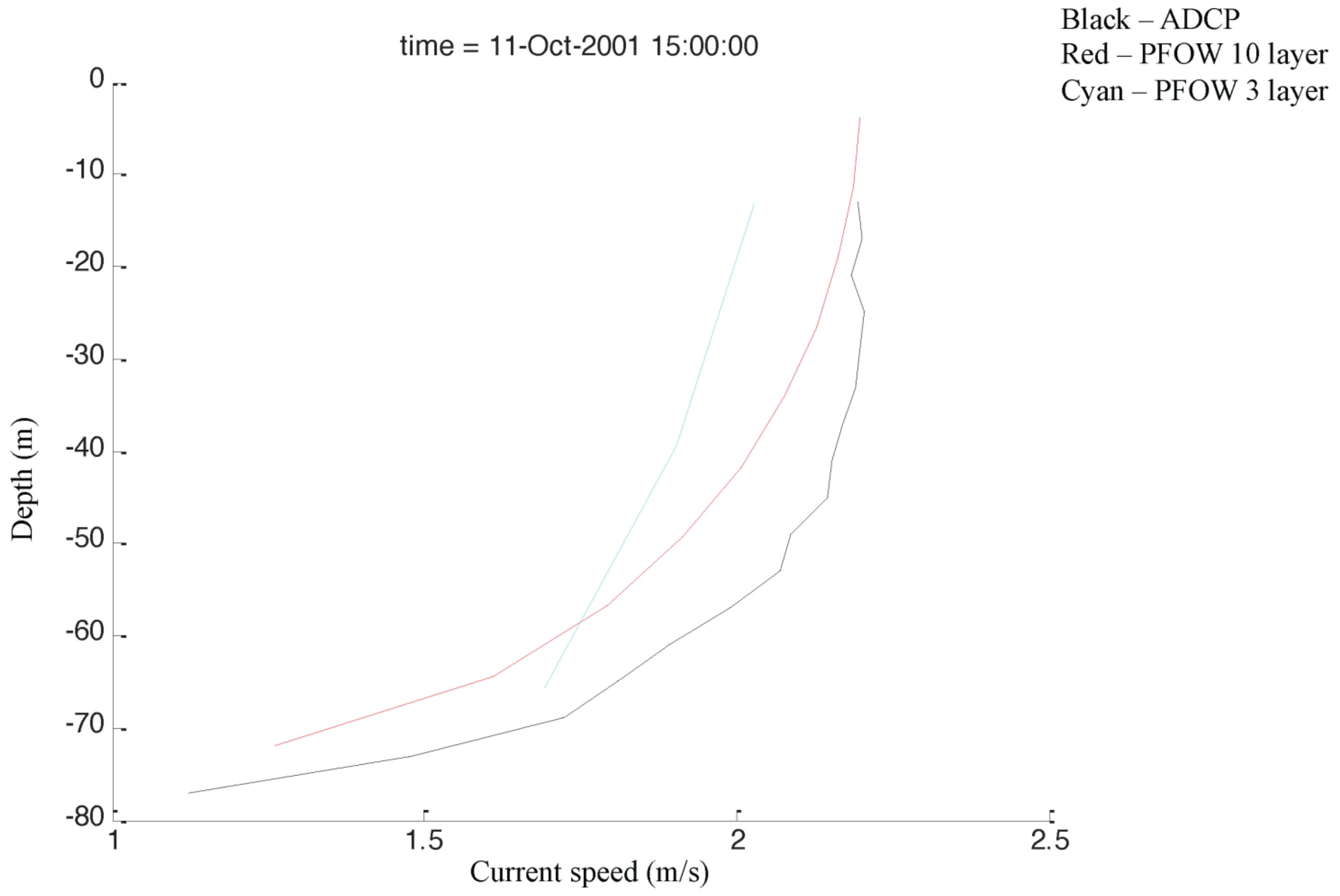
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6e		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Comparison of current speeds at location 2. Closer view with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



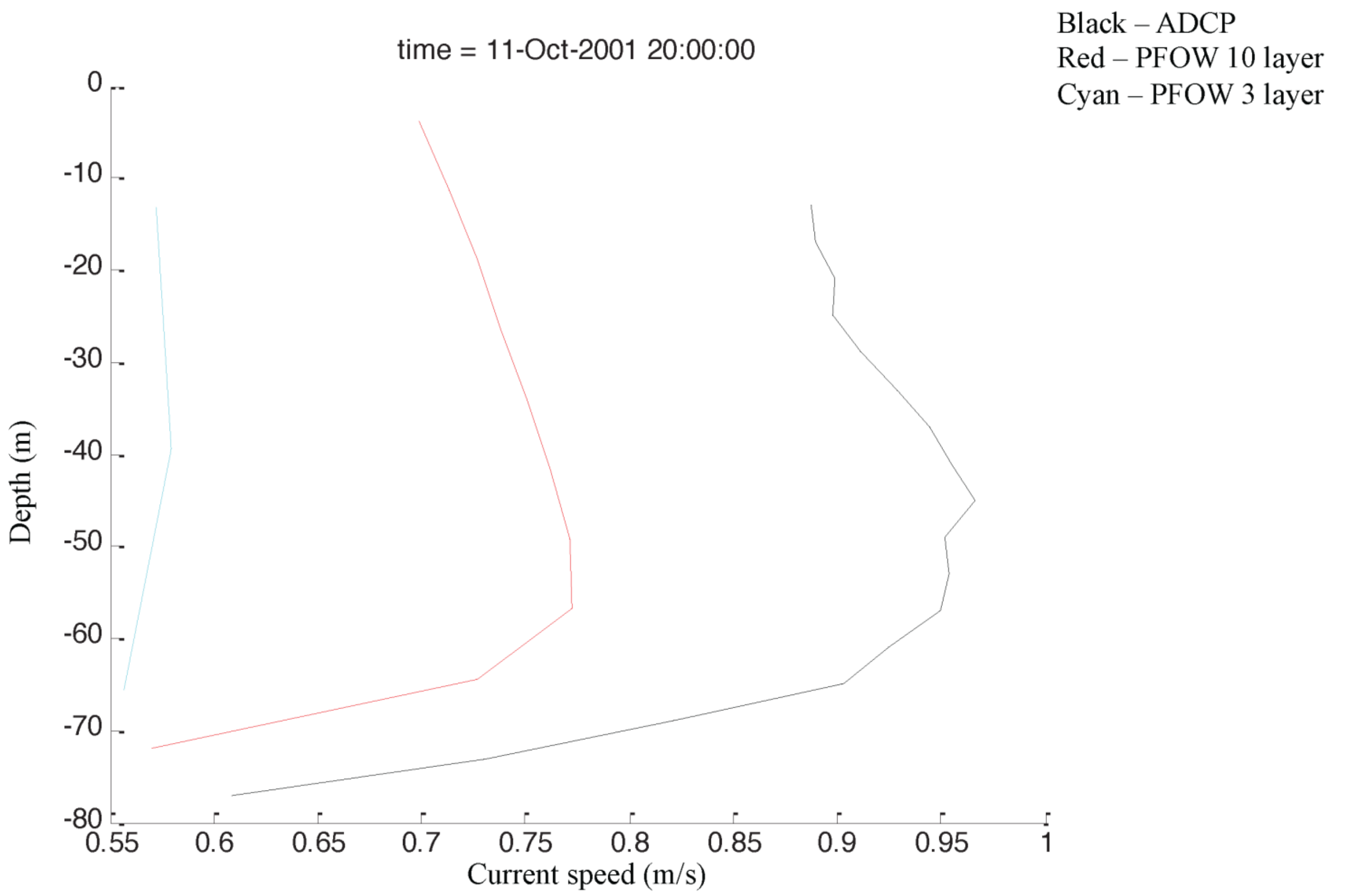
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6f		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Comparison of current speeds at location 3. Closer view with roughness = 0.04m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



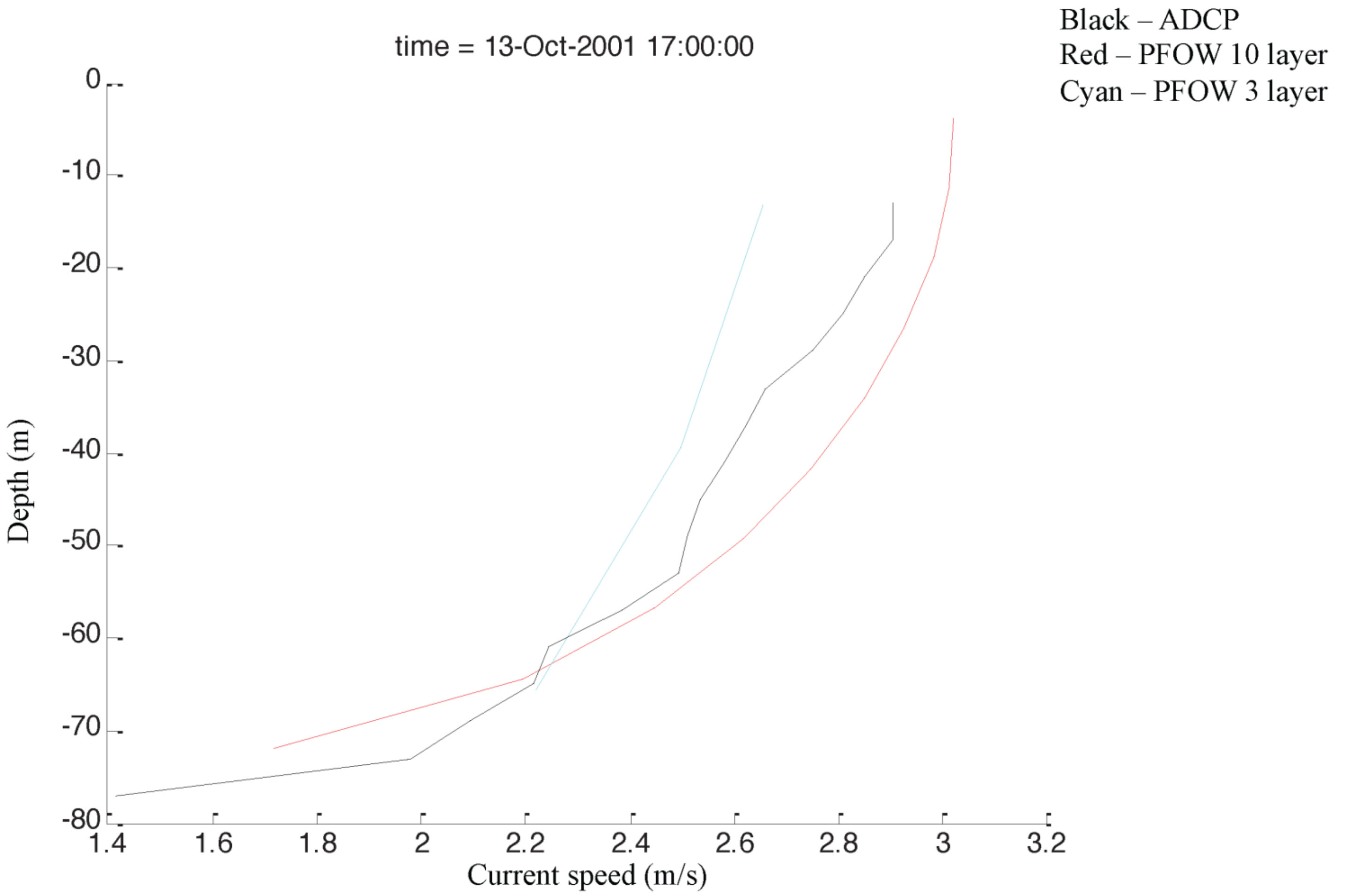
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6g		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Vertical profile comparison of current speeds at location 2.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



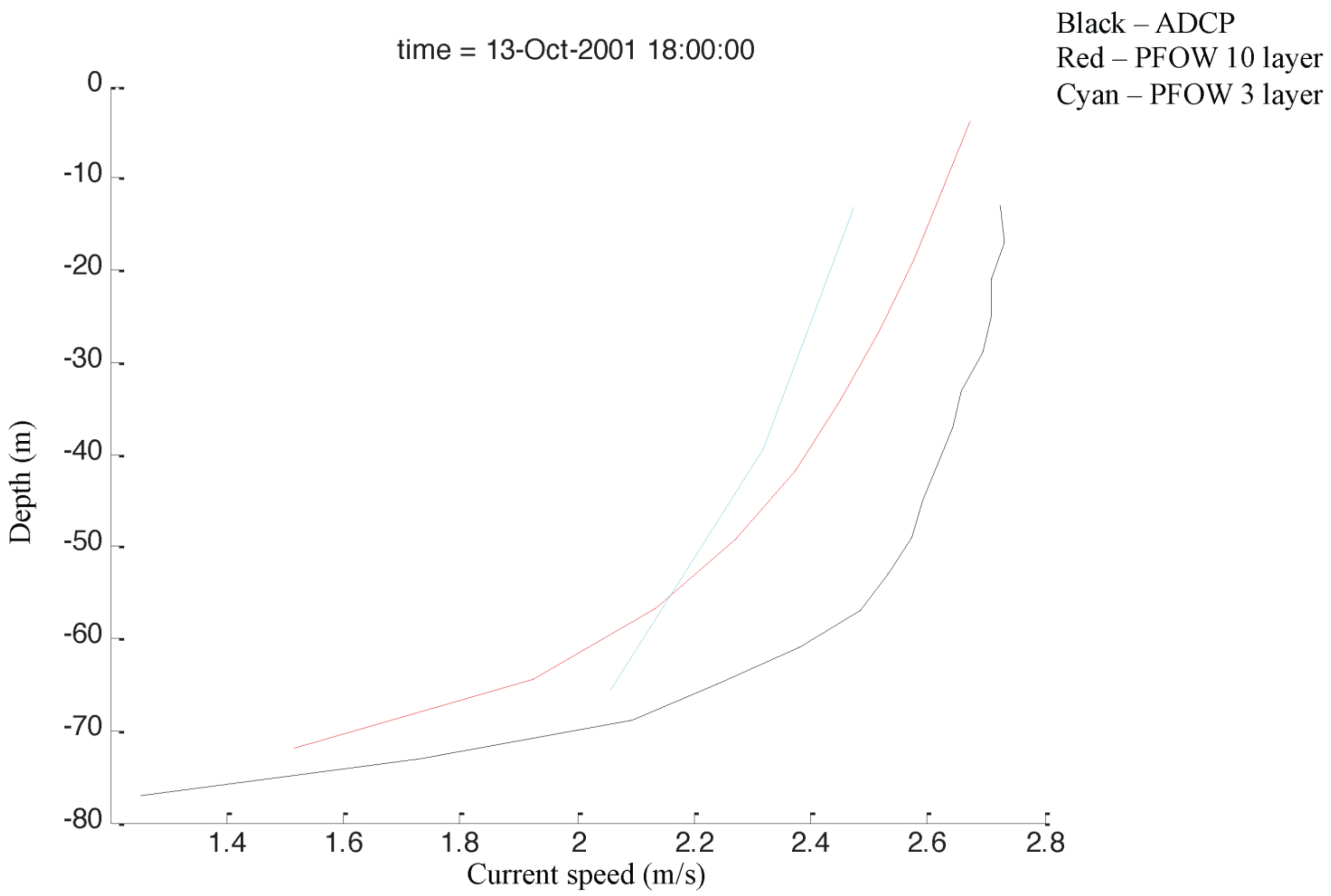
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6h		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Vertical profile comparison of current speeds at location 2.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6i		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Vertical profile comparison of current speeds at location 2.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6j		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Vertical profile comparison of current speeds at location 2.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6k		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Vertical profile comparison of current speeds at location 2.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

Error statistics have been calculated for depth-averaged current speeds for each of the two roughness sensitivity runs (0.1 and 0.04m); these are presented in Table 3-2. For the error analysis, the time series of the measured data were interpolated to obtain data at the same time intervals as the output from the model simulations..

The statistics presented in Table 3-2 are as follows:-

- meanMeas = mean of the measurement data
- meanModel = mean of the model data
- rmsError = root mean square of the difference between measured and modelled values
- bias = mean of the difference between model result and measured data
- correlationCoef = correlation coefficient
- bias/meanMeas = mean error/mean measurement

Visual inspection of the peak speeds was also considered.

TABLE 3-2 ERROR STATISTICS OF DEPTH-AVERAGED CURRENT SPEEDS (M/S) FOR ROUGHNESS SENSITIVITY

Run\location	1	2	3
Roughness length= 0.1m	maxMeas: 3.22 maxModel: 3.25 meanMeas =1.32 meanModel =1.26 rmsError=0.25 bias=-0.0629 CorrelationCoef =0.94 bias/mean Meas =-0.05	maxMeas: 3.88 maxModel: 3.54 meanMeas =1.96 meanModel =1.79 rmsError =0.31 bias =-0.17 CorrelationCoef =0.97 bias/mean Meas = -0.09	maxMeas: 3.02 maxModel: 3.28 meanMeas =1.5 meanModel =1.3738 rmsError =0.27 bias =-0.11 CorrelationCoef =0.95 bias/mean Meas =-0.07
Roughness length= 0.04	maxMeas: 3.22 maxModel: 3.64 meanMeas =1.32 meanModel=1.34 rmsError=0.29 bias =0.02 CorrelationCoef=0.94 bias/mean Meas =0.01	maxMeas: 3.88 maxModel: 3.79 meanMeas=1.96 meanModel =1.90 rmsError =0.30 bias =-0.06 CorrelationCoef =0.96 bias/mean Meas =-0.03	maxMeas: 3.02 maxModel: 3.59 meanMeas =1.48 meanModel =1.46 rmsError =0.32 bias =-0.03 CorrelationCoef =0.94 bias/mean Meas =-0.02

Table 3-2 is useful in providing quantitative measures of how well the model reproduces the measured data; which in this case is the depth-averaged current speeds at three locations.

Guidance provided in Bartlett (1998) for calibration of water levels and currents speeds is reproduced below:-

- *Water levels to within +/- 0.1m*
- *Speeds to within +/- 0.1m/s*
- *Direction to within +/- 10 degrees*
- *Timing of high water to within +/- 15 minutes*
- *Alternatively some of these could be expressed in percentage terms:-*
- *Speeds to within +/-10-20% of observed speed*
- *Levels to within 10% of Spring tidal range or 15% of Neap tidal range*

It is accepted that these criteria might be too testing for all regions of the modelled area. A less stringent expectation might thus be that these conditions should be satisfied for 90% of the position/time combinations evaluated.

Given the high peak speeds observed (difficult to obtain within +/- 0.1m/s) our target has been to attain predicted current speeds within 10-20% of observed speeds, and likewise for water levels, to attain prediction within 10% of the Spring tidal range.

The statistics presented in Table 3-2 are useful in determining the relative change between simulations and whether an improvement in the level of fit has been achieved between simulations. The metric ―bias/mean" is useful as this gives an overall measure of the proportion of the difference between the predicted and simulated current speeds in relation to the observed values. For the run with a roughness of 0.04m in Table 3-2, it can be seen that in terms of a percentage these are at or below 3% at all three locations, which lies within the ±10%-20% target given above. The bias shows whether the model is over (positive) or under (negative) predicting the observed data. The run with 0.04m has biases (mean of the differences between the model and observed values) for the three locations which are closer to zero, i.e. closer to the observed values, in this case 0.06m/s or less.

Some of the statistics (rms error and correlation coefficient) initially suggest a slightly better match for the simulation with a roughness of

0.1m, however the bias is also a good indication, as is the visual match of the data which suggested the roughness of 0.04m was more appropriate. Similarly the mean model results are closer to the mean observed data with the lower roughness.

Peak speeds are important for in-situ renewable energy current devices and therefore the observed and measured maximum speed is also presented in Table 3-2. The peak speeds were also used as a target; the 0.04m roughness produced peak speeds higher than those observed, however given the fact that the top 11-17m was not measured then the depth-averaged observed values are likely to be under-stated

It was felt that the roughness length of 0.04m provided the best overall fit to the measured depth-averaged current speeds.

3.3.3.2 Comparison of water levels

Following the comparison of the model against measured current speeds, a comparison against measured water levels was made. This had previously been checked for an initial simulation in 2009 and was found to be good using the AMM model for boundary conditions. Observed tide gauge water levels were available at Lerwick (Shetland), Wick (north of Aberdeen) and Buckie on the Moray Firth. Wick and Lerwick tide gauge level data was obtained from the class A tide gauge data held by the National Tide and Sea Level facility. The gauge data at Buckie was obtained from SEPA. Whilst the water level comparisons for 2009 were good, the comparison with the 2001 period showed a defined difference in mean sea level.

This observed difference in mean sea level appears to be due to the boundary conditions derived from the AMM model, an earlier version than the 2009 results. In discussing the concerns with NOC-L, it was made known that mean sea level in this early version of the AMM model was not checked. Therefore in order to proceed with the 2001 boundary conditions a sensitivity test was undertaken by adding a vertical shift to all of the water level boundary nodes. It was found that the current speed through the Pentland Firth was insensitive to the small vertical shifts made due to the large water depths (>50m in general).

Therefore based upon initial statistical analysis of the model results compared with the measured data at Wick (the closest and most complete tide gauge to the Pentland Firth) a number of vertical shifts were considered before concluding that a vertical shift of 0.62m was required to be added to the mean water levels.

The comparison of water levels predicted by the model compared to the observed tide gauge data can be seen in Figures 3-7a-c as well as a closer view of the same locations in Figures 3-8a-c. The model appears to generally provide a good match especially at Wick. The comparison at Buckie was not quite so good especially towards low water but there was some uncertainty with the datum at this location as well as what appeared to be a two hour timeshift. Comparisons at Lerwick are more difficult in all but a few tides as the tide gauge data quality is not so good which is shown by the erratic nature of the tidal signature.

The statistics for the Wick location have been calculated in the same way as for the current speeds. These can be seen in Table 3-3. The middle column provides the statistics for the model, whilst the right hand column provides the statistics for a +0.5 hour phase shift added to the model results. Such an analysis was undertaken to examine if there was a phase shift between the model and observed data. The phase shift analysis is described in the next section 3.3.3.3. The rms error is reduced from 0.23 to 0.11m with the 0.5 hour phase shift. These are all within the guidelines of Bartlett (1998) when considering the magnitude of the rms error compared with the tidal range, then you get a percentage error of 15% (0.23m/1.5m) for the smallest neap tide and 6% (0.23m/3.5m) for the largest spring tide. With the phase shift of 0.5 hours added to the model water level results, these percentage errors drop to 7% and 3% respectively. These are all within the Bartlett (1998) criteria given above.

TABLE 3-3 SUMMARY STATISTICS FOR WATER LEVELS (M MSL) AT WICK

Run\location	WICK	WICK with 0.5 hour shift to model results
Roughness length= 0.04m Vertical boundary datum shift 0.62m (for 2001 only)	maxMeas = 1.98 maxModel = 1.90 minMeas= -1.71 minModel= -1.55 meanMeas = 0.27 meanModel = 0.21 rmsError = **0.23** bias = -0.05 CorrelationCoef = **0.96**	maxMeas = 1.98 maxModel = 1.90 minMeas= -1.71 minModel= -1.55 meanMeas = 0.27 meanModel = 0.21 rmsError = **0.11** bias = -0.05 CorrelationCoef = **0.99**

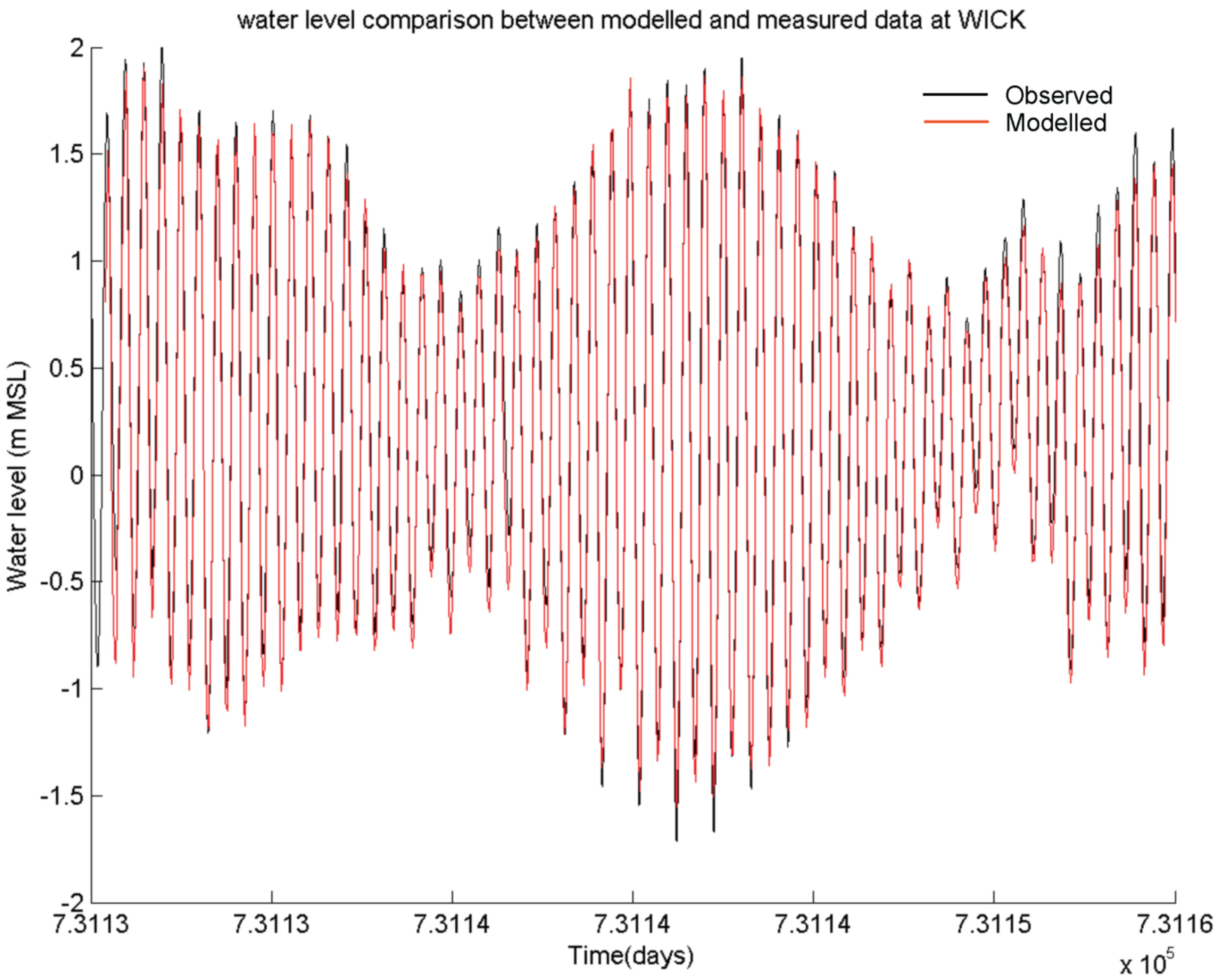
3.3.3.3 P

3.3.3.3 Phase error analysis

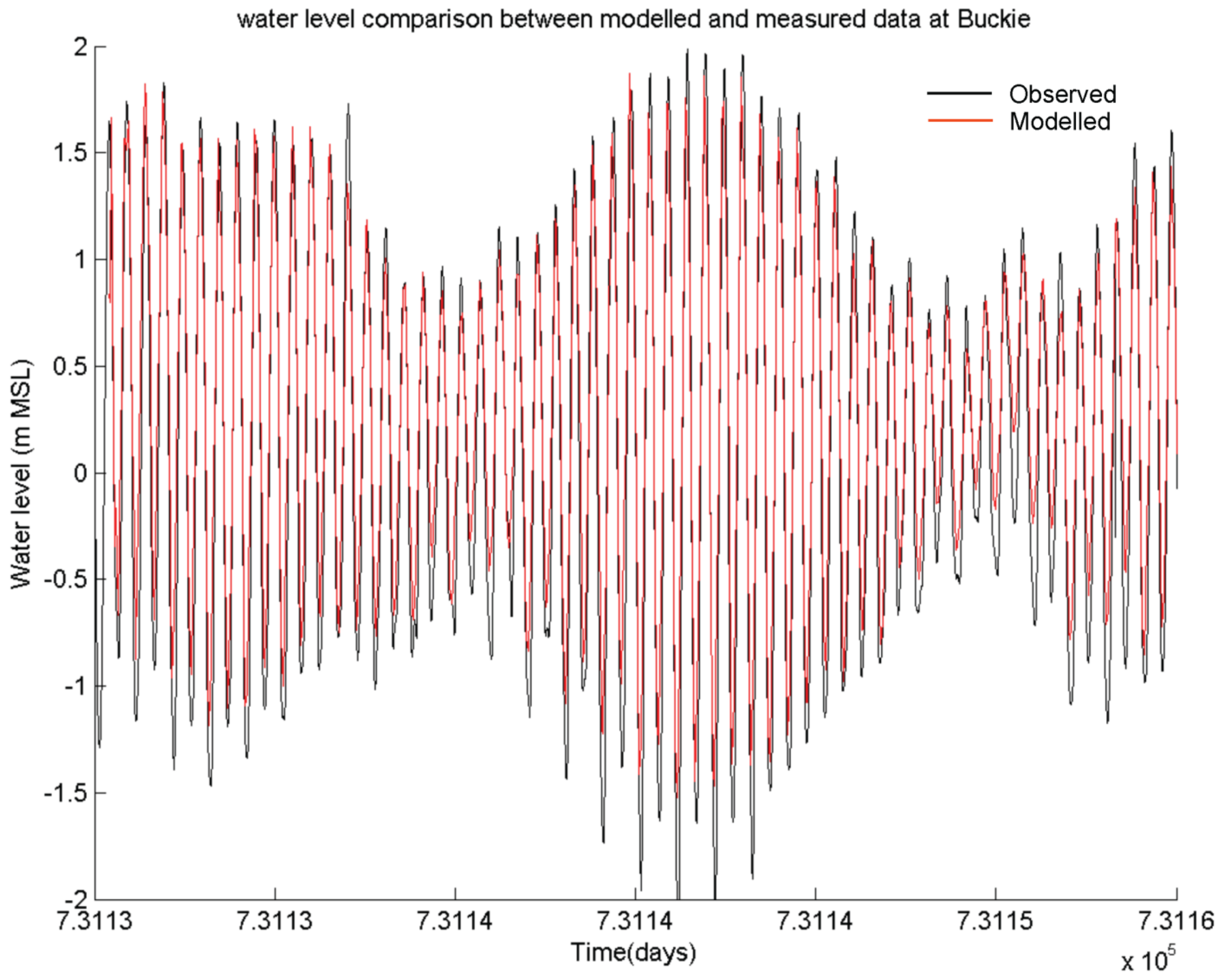
There did appear to be a small phase shift between the model water levels and the observed water levels. The magnitude of the phase shift was investigated by calculating the rms error at Wick for a range of time shifts applied to the model results. The aim was to determine where the minimum rms error occurred and for what time-shift. Figure 3-9 presents the results of this exercise. It can be seen that for the existing phasing the rms error is about 0.23m (for a time-shift of zero). The minimum rms error occurs with a time-shift of +0.5 hours (0.11m).

The rms was calculated for a range of phase shifts for the 3 ADCP locations in the Pentland Firth, there was no phase shift found between the model and the data.

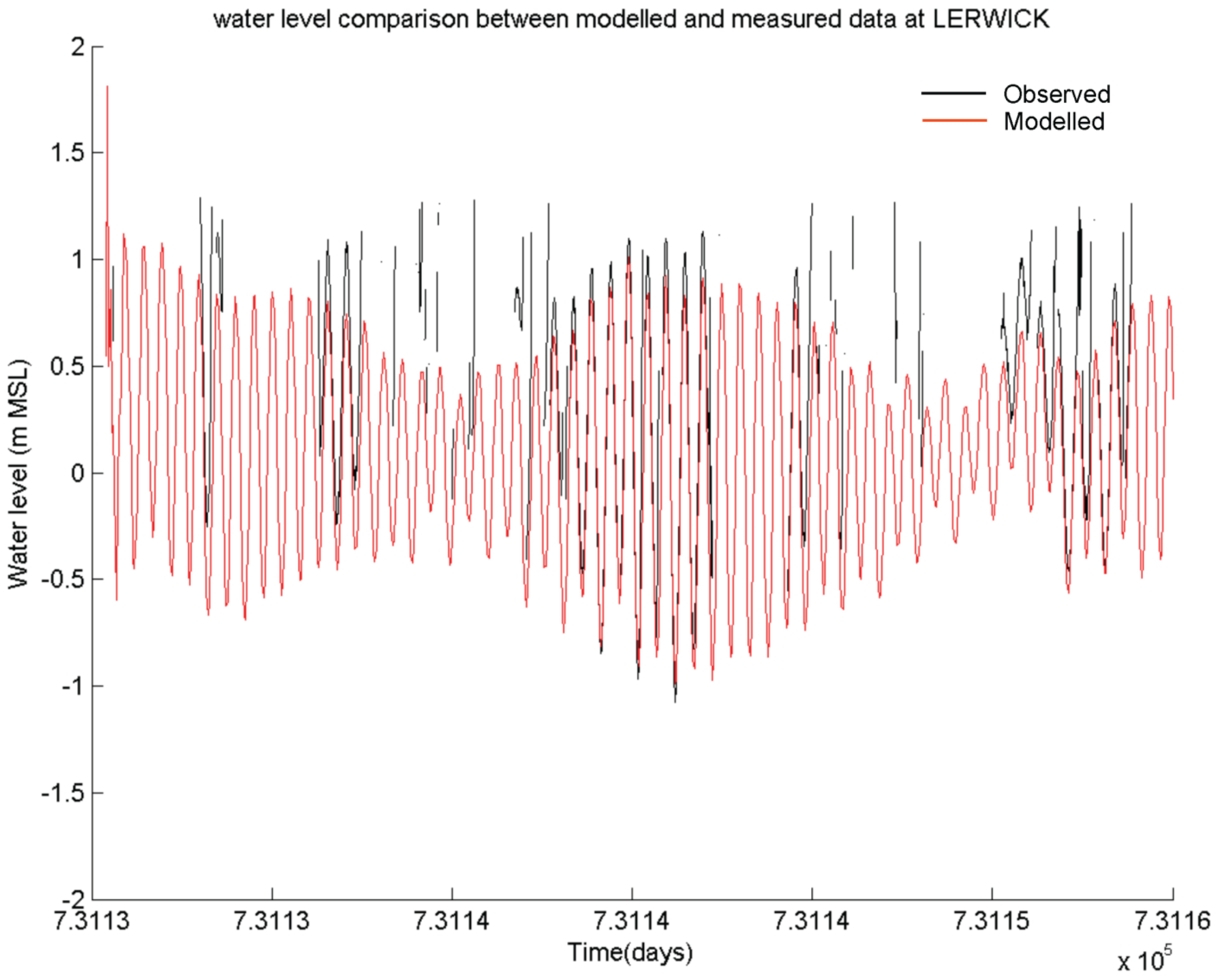
Therefore it appears that the water levels have a phase shift of 0.5 hours whereas the currents do not.



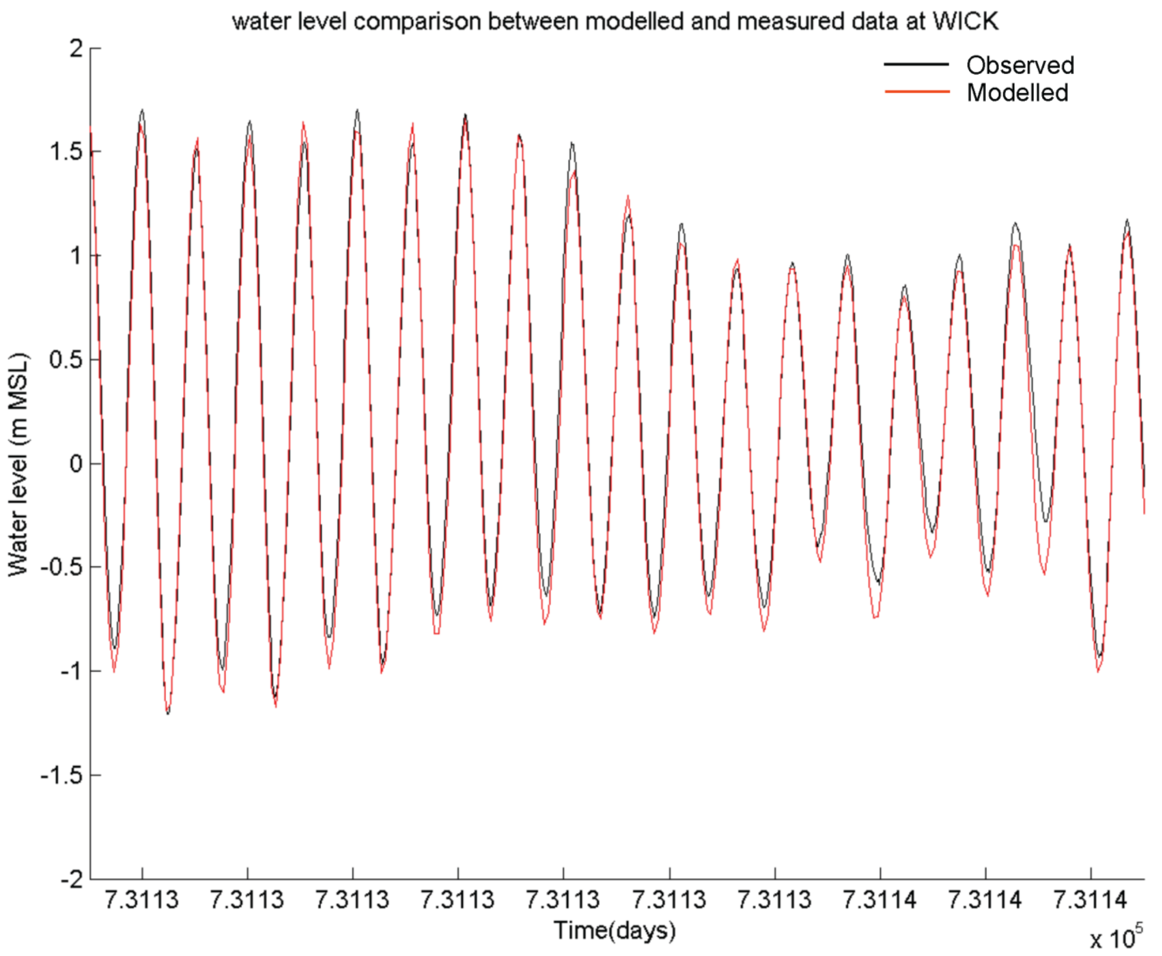
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Wick	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



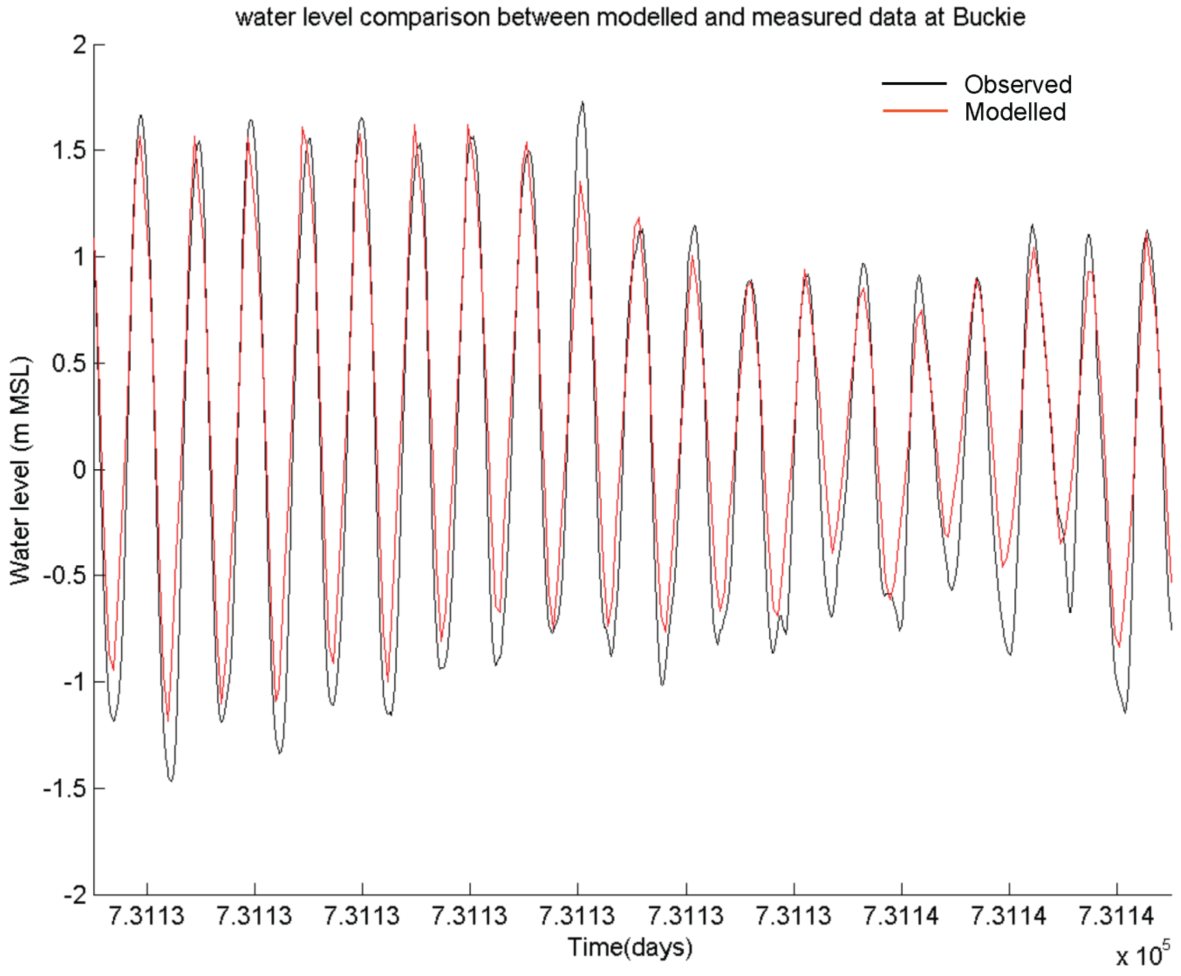
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Buckie.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



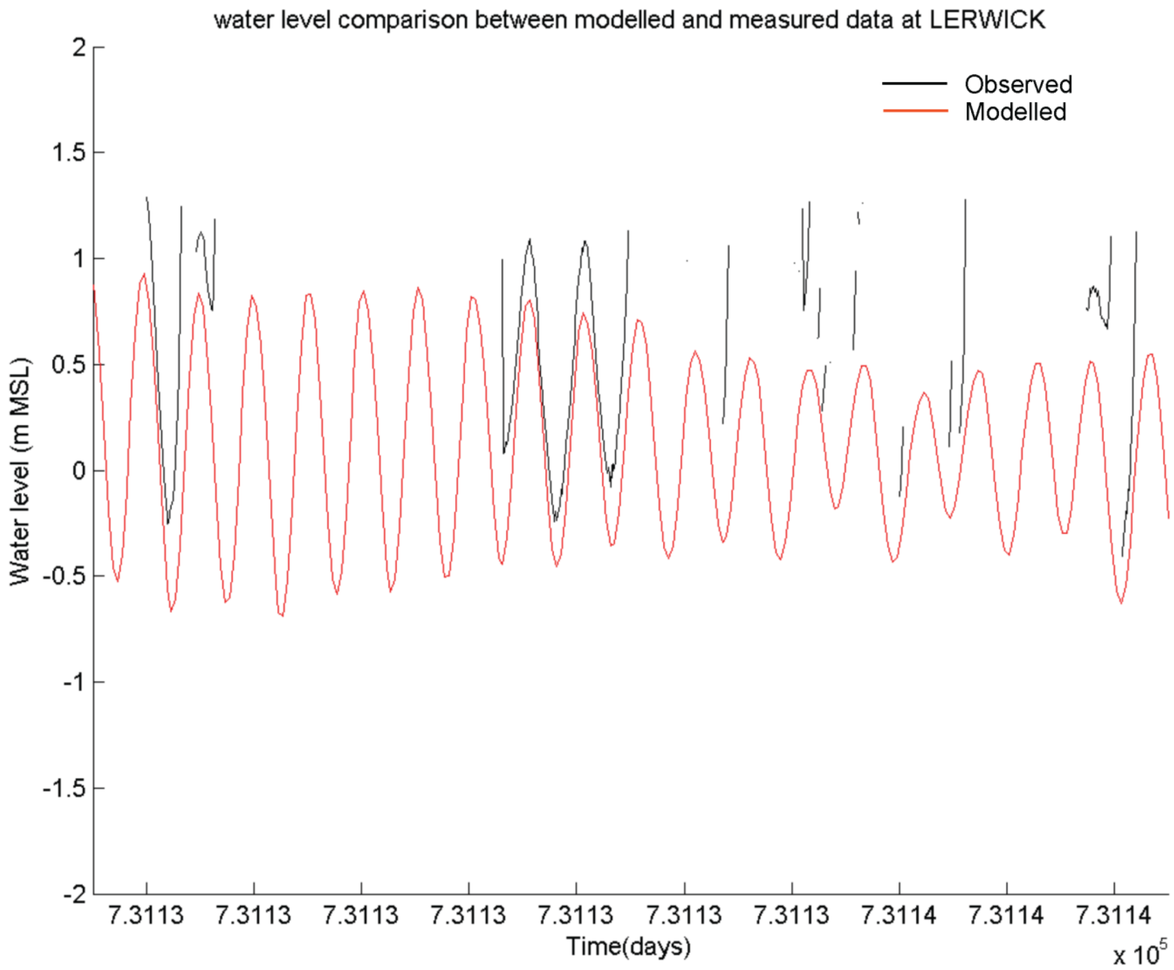
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Lerwick	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



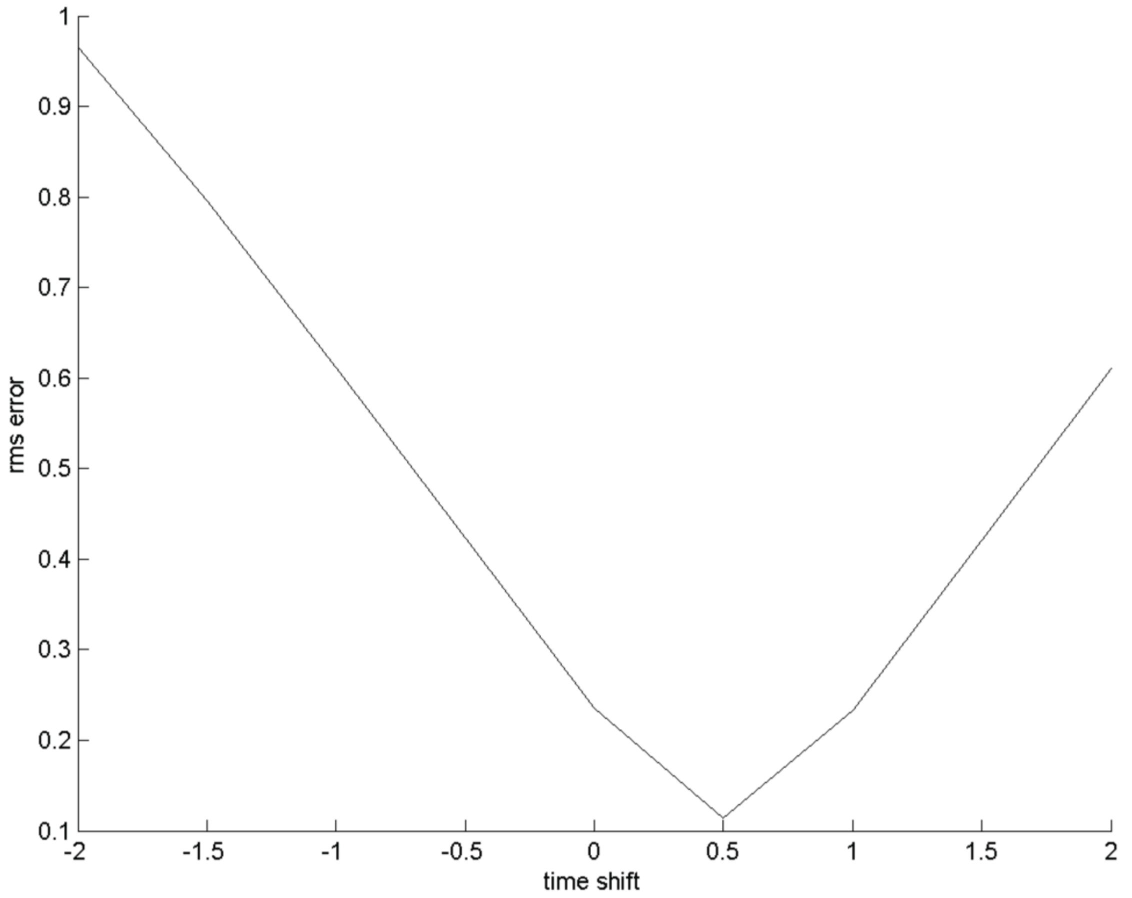
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-8a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Wick – closer view	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-8b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Buckie – closer view	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-8c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Lerwick – closer view	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Rms error (m) for water levels at Wick with varying timeshift (hours).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.3.4 Comparison against transect data

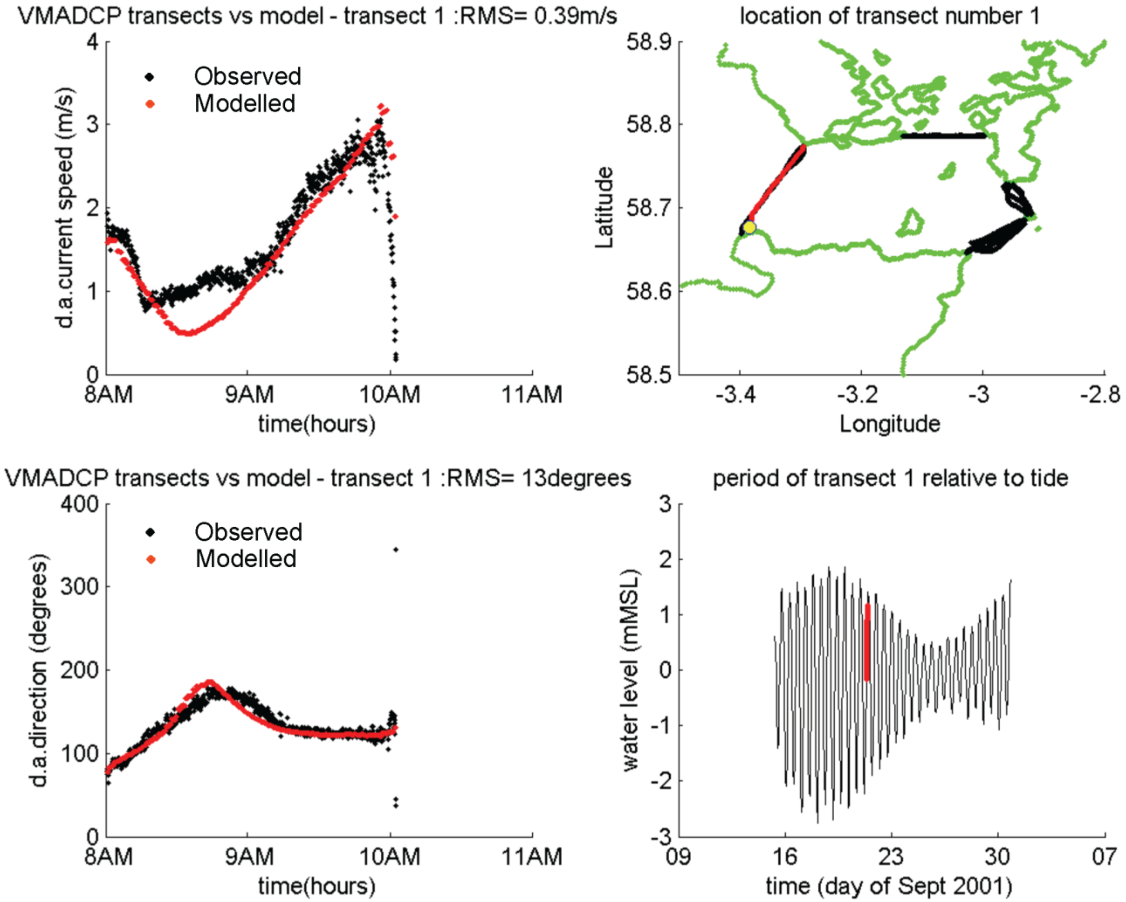
In addition to the timeseries data (at selected locations) that has been used for calibration, a number of transect data sets is also available. These data are available in 2001, 2012 and 2013. The simulations used for comparison are based upon the run with a bed roughness of 0.04m presented above.

3.3.4.1 2001 transect data – Pentland Firth

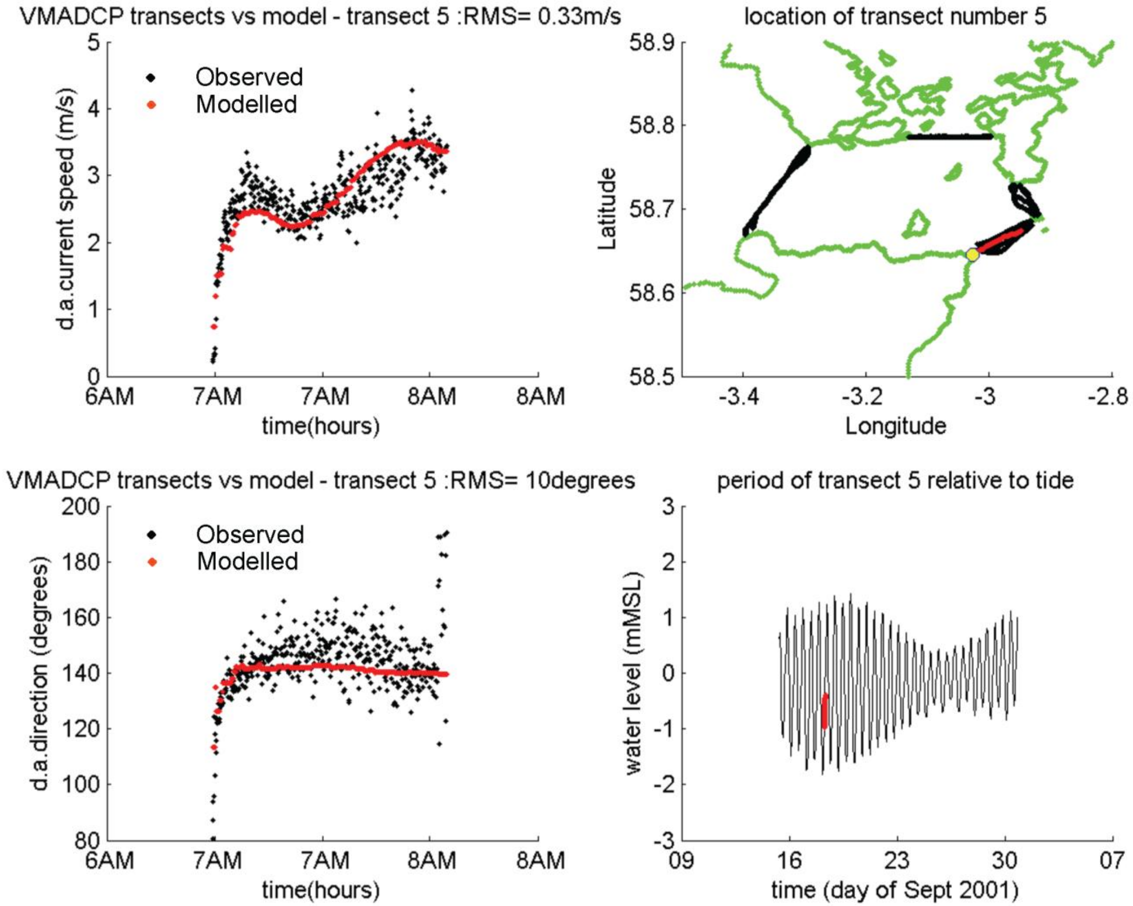
Transect data was observed during the 2001 survey as presented in Figure 3-4. Figure 3-4 shows the locations of the current stations and the transects which frame the Pentland Firth. This transect data is very useful as it provides a means of determining how the model reproduces the flow through the various entrances/exits to the Pentland Firth.

Figures 3-10a-d present the comparison between the observed current speeds (which have been depth-averaged) and the depth-averaged model predictions for the same period in September 2001. Additionally further figures are presented in Appendix B to reduce the number in the main report. Each plot consists of four frames. The top right frame shows the geographic location of all of the transects in black, with the one represented for each figure in red; the yellow dot indicates the start of the transect. The bottom right frame shows the tide curve for the period of the model simulation, with the period of each transect marked in red. The top left frame shows the depth-averaged observed current speed in black, with the predicted current speed in red. Similarly for the current directions in the bottom left frame.

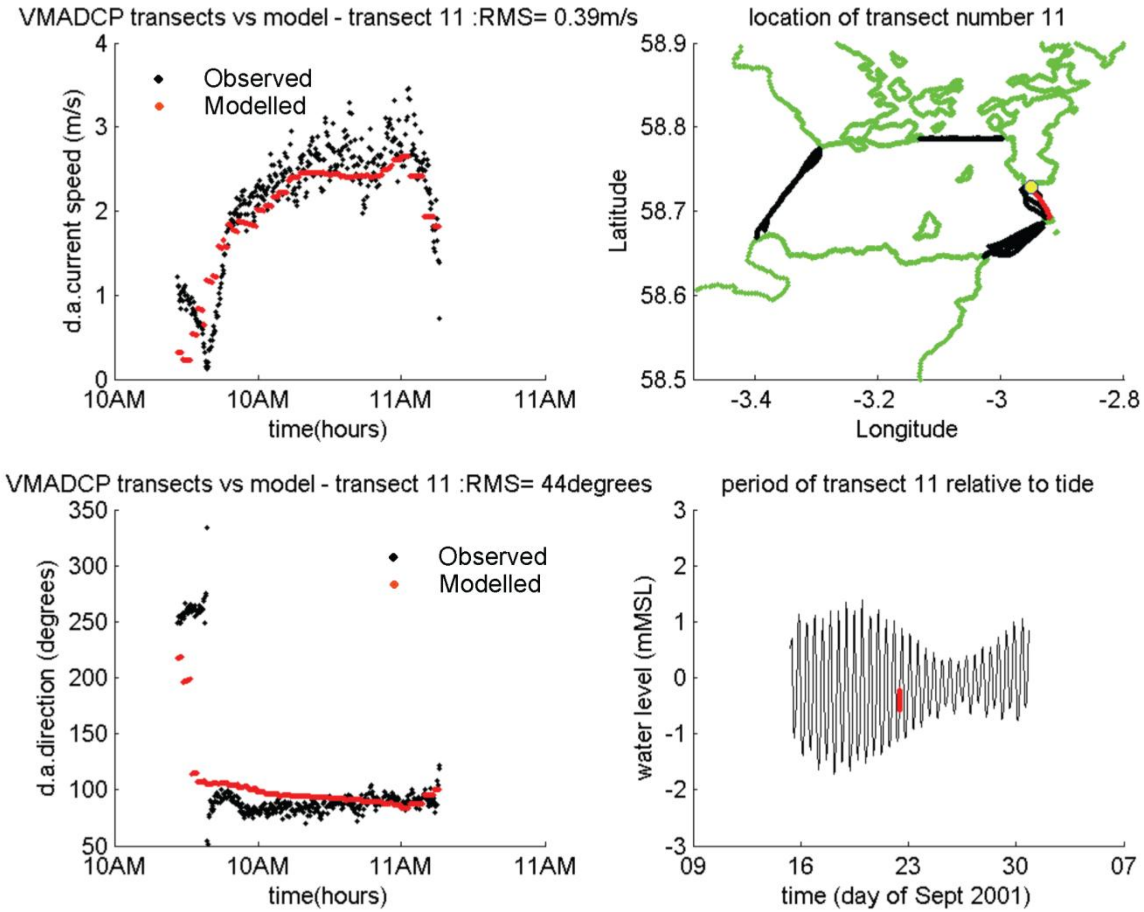
It can be seen in Figures 3-10a-d (and Appendix B, Figures B.1 to B.13) that the current speeds and structure within each transect are reproduced well. The root mean square (RMS) errors are also provided on each figure. There does appear to be some scatter (variability in the data over short time and space intervals) in the transect data in the order of 0.5m/s. It appears that there are multiple data points at each time however this is due to the scale of the figure and the variation in the recorded magnitude from one measurement to the next. The variation of current speed across each transect is fairly well predicted in the model (RMS error/Peak speed < 20 to 40%).



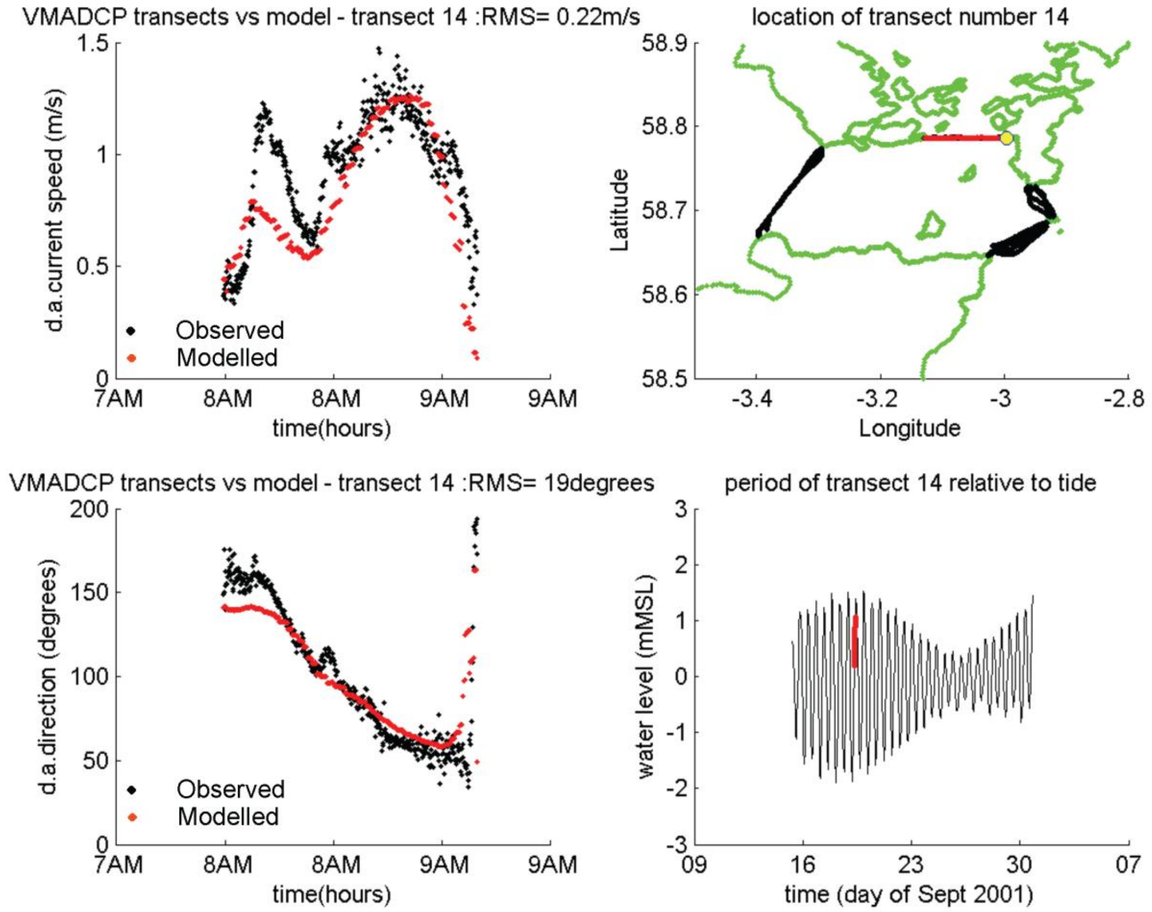
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with transects in the Pentland Firth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with transects in the Pentland Firth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with transects in the Pentland Firth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



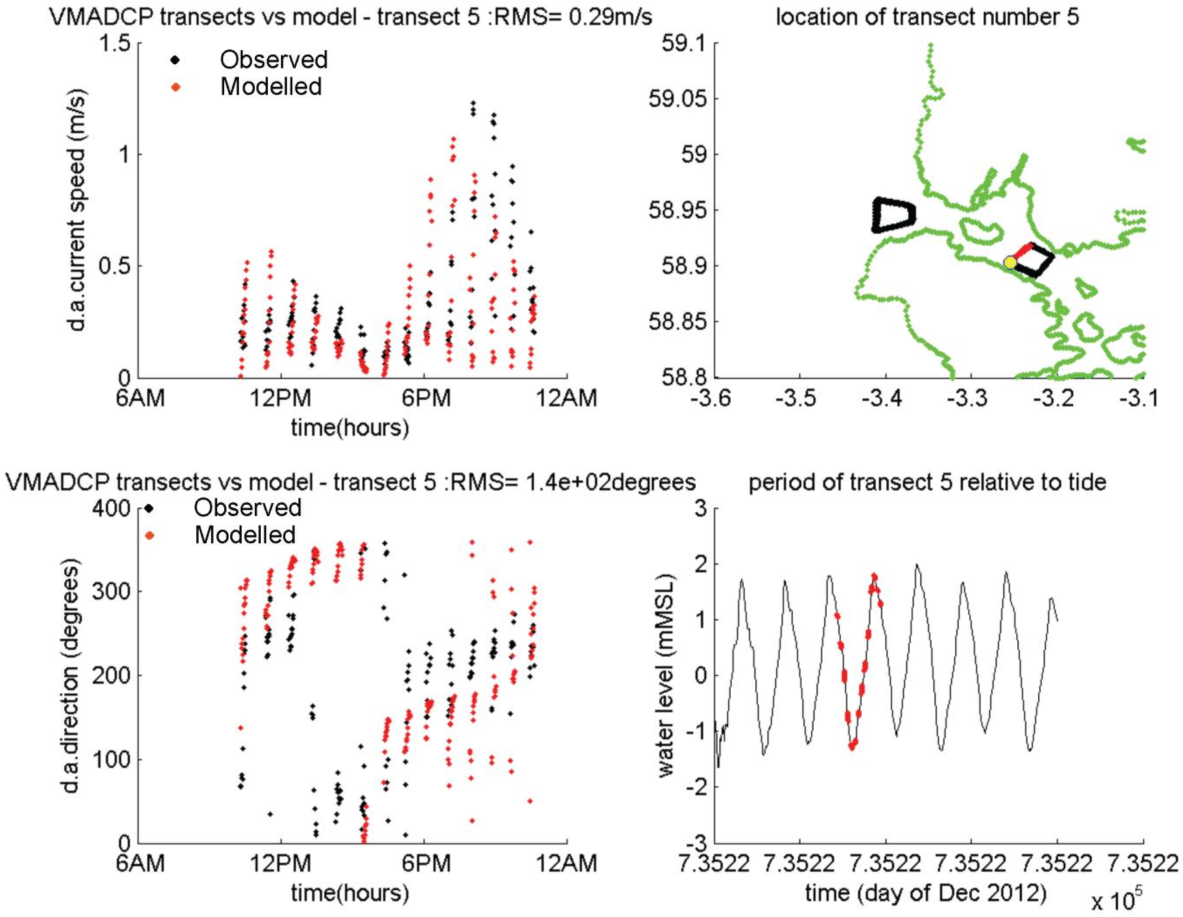
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10d		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with transects in the Pentland Firth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.3.5 2012 transect data – Hoy Channel

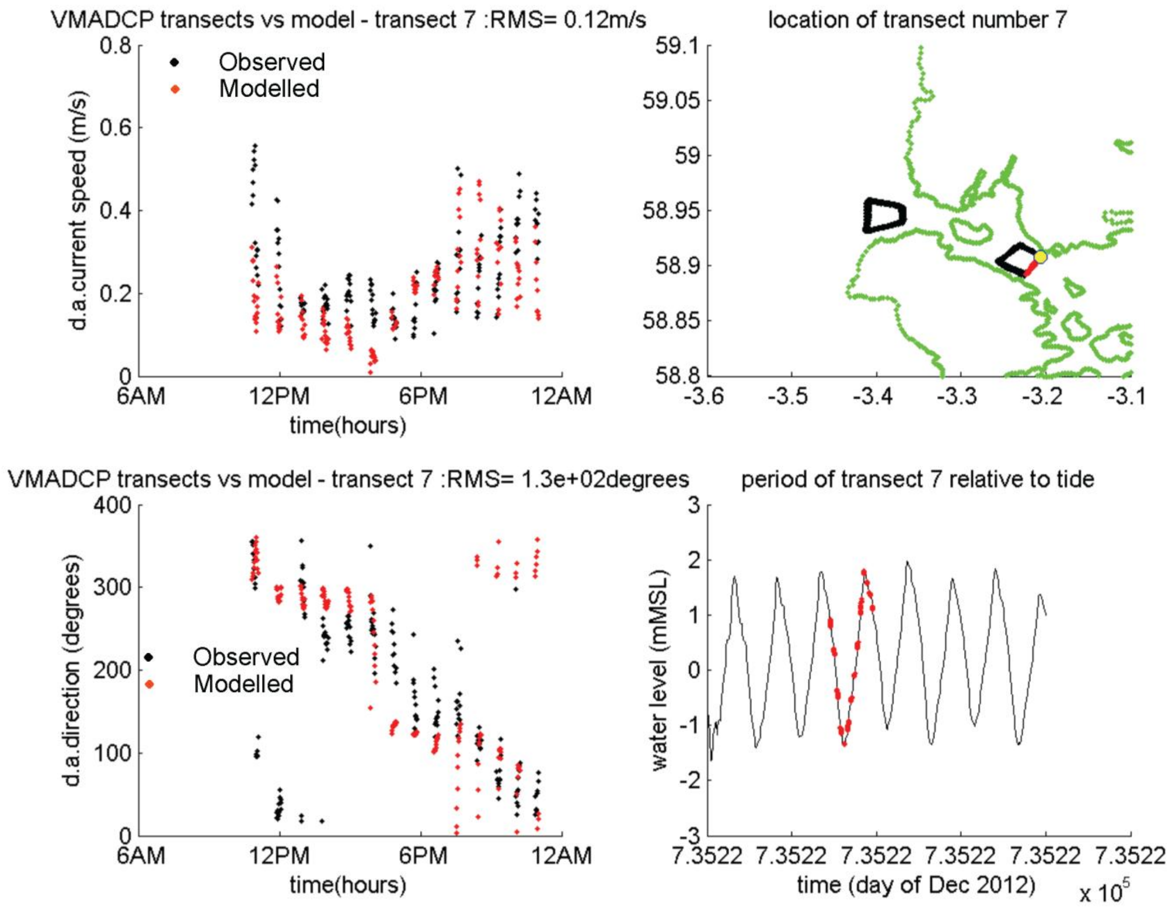
Flow data across a number of transects in the Hoy channel was recorded in December 2012 by Marine Scotland. The model was run for this period to validate the flow model. Figures 3-11 a-b and the Figures in Appendix C (C.1 to C.6) present the comparisons between the observed depth-averaged current speeds across each transect with those predicted by the model.

For this survey two box shapes were traversed throughout a tide by the MV Scotia and transects extracted for each side. Transects 5 and 7 can be seen in Figure 3-11a and b and shows that current speeds are a reasonable match throughout the tide.

The comparisons for transects 1-4 (Appendix B) are not as good as would be hoped and the reason for this is not known. The comparisons against transects 5-8 are better but still do not provided the level of agreement shown in the comparisons against the transect data in the Pentland Firth. Bathymetry in Scapa Flow is derived predominantly from digitised Admiralty Chart data rather than more recent high density bathymetric data which may be part of the reason.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-11a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Stage 2 modelling – PFOW model comparison with transects in the Hoy Channel.	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 14/112012

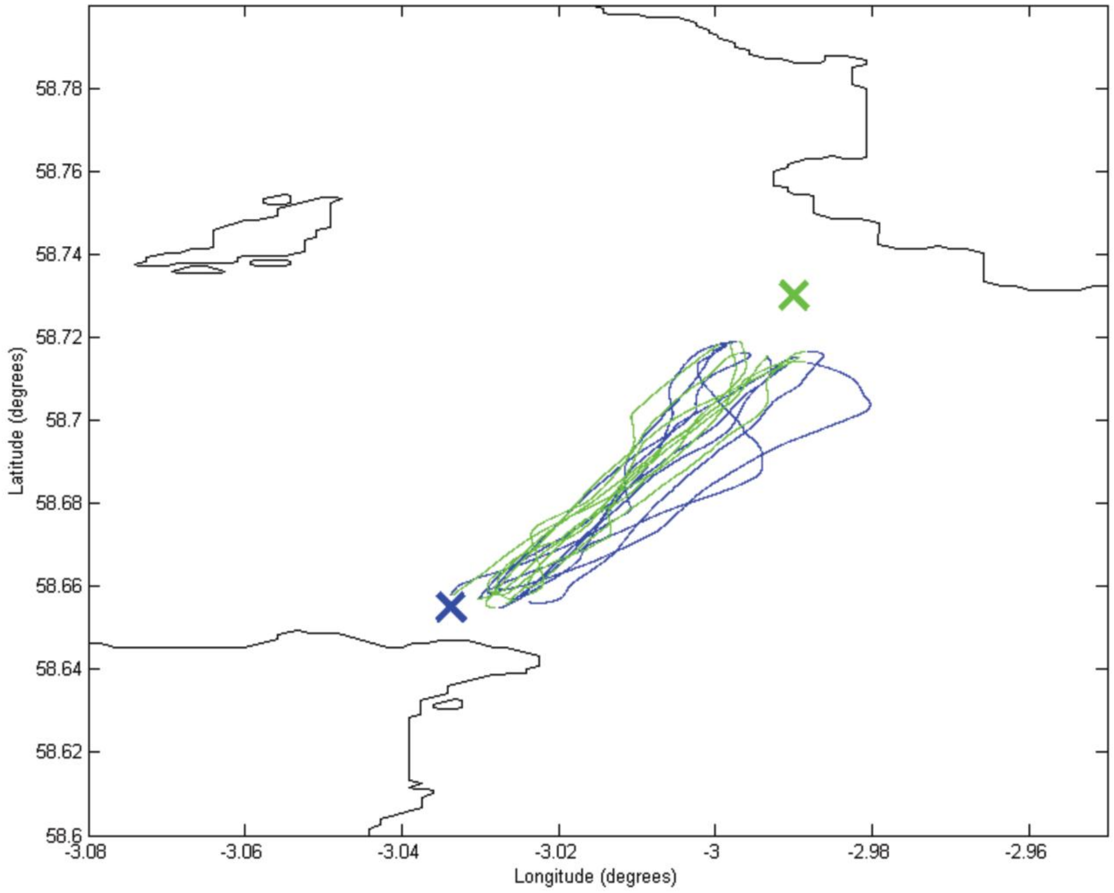


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-11b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Stage 2 modelling – PFOW model comparison with transects in the Hoy Channel. With Hoy channel Deepened as shown	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.3.6 2013 transect data – Eastern Pentland Firth

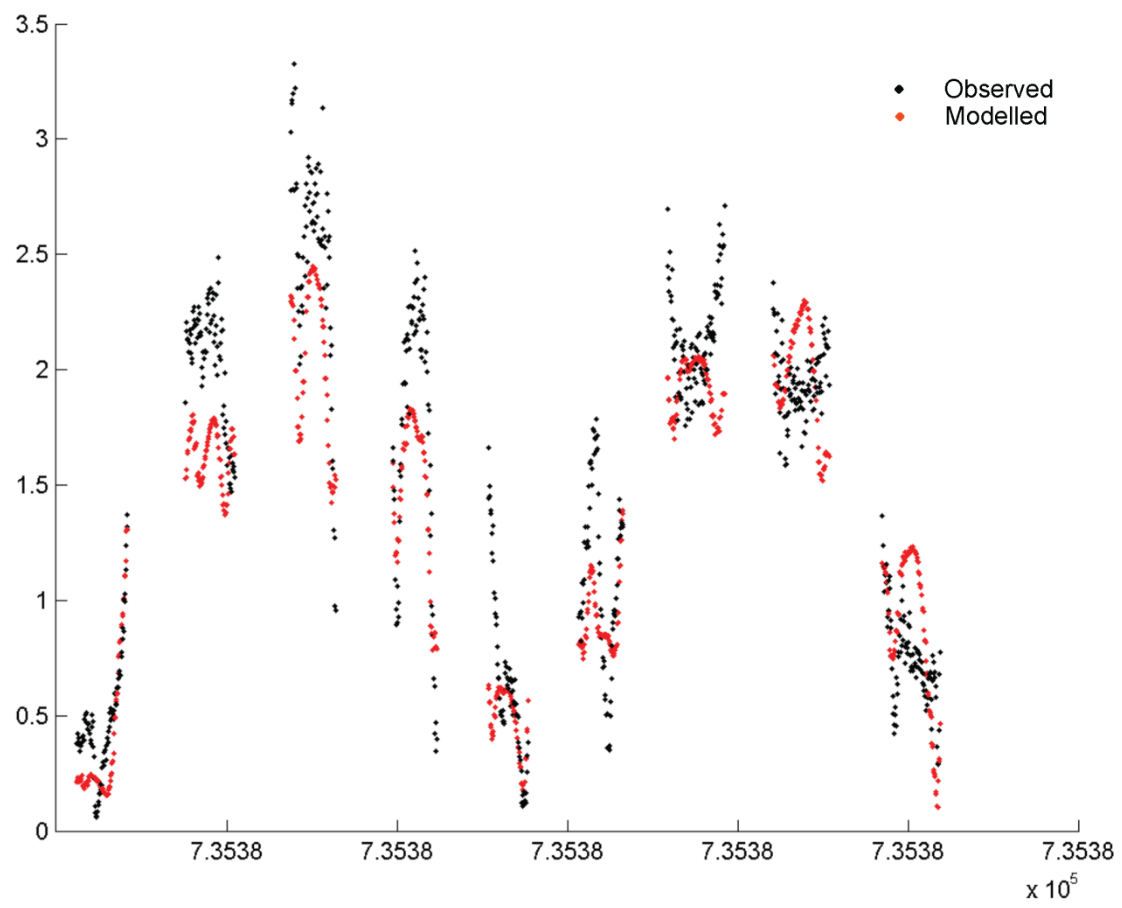
Figure 3-12a shows the locations of transect current observations recorded by Marine Scotland in 2013. One issue in producing the comparison was that boundary conditions from the AMM model were not available and therefore results from the 2001 simulation were used. This was done by first finding the location and time of the observed current speed measurement (depth-averaged), then undertaking a harmonic analysis of the current speed components from the 2001 simulation. Finally the current speed was re-predicted for the period of the survey and the corresponding speed at the time required extracted and plotted. Differences would be expected due to the harmonic analysis and re-prediction process; however it provided a reasonable approach to validate the model in this region.

The comparisons are shown in Figures 3-12 b-c. In general the comparisons are good and reproduce the variation across each traverse. Peak speeds however are under-predicted which may in part be due to the re-prediction of the current speeds from harmonics derived from only one month of model results.



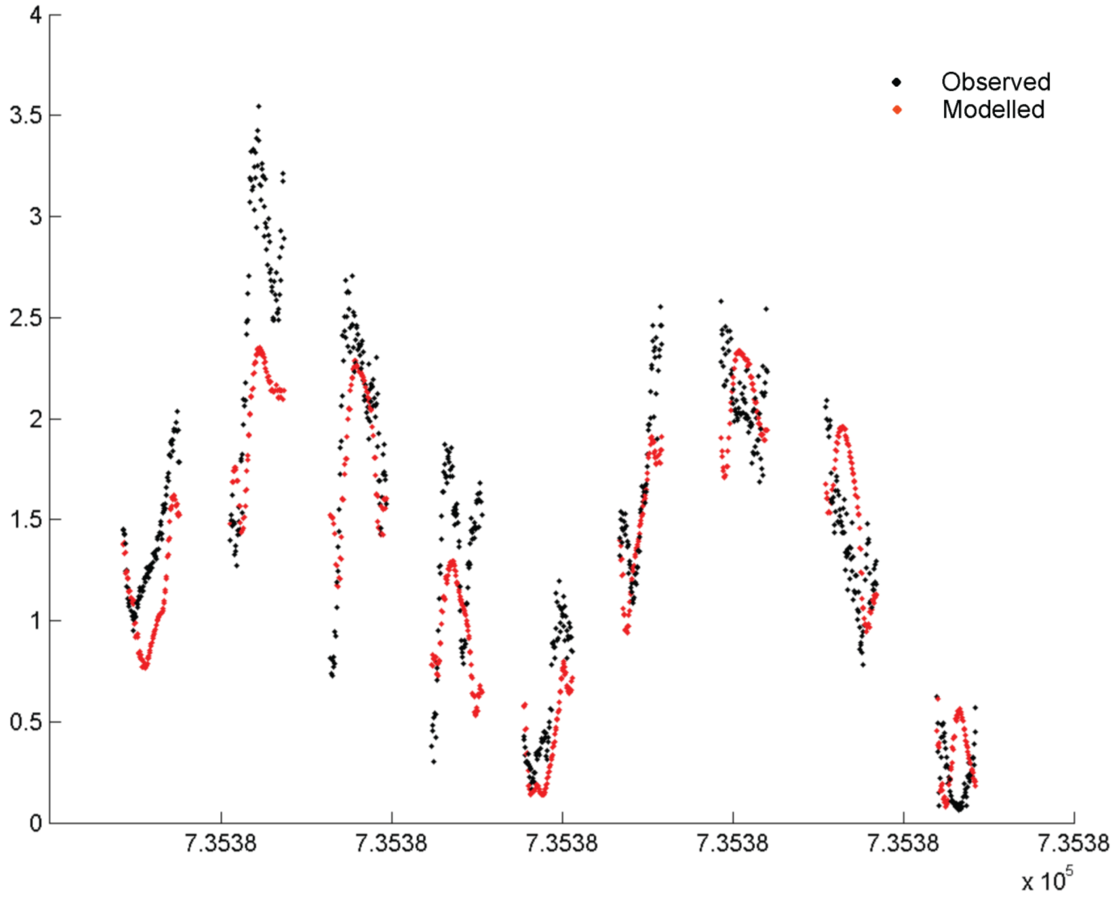
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-12a		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Location of 2013 transects in the Eastern Pentland Firth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

Comparison of measured depth-average current speed transects in the Pentland Firth (MS-2013) against harmonically predicted current speeds based upon 1 month simulation in 2001 -



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-12b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with 2013 transect 1	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

Comparison of measured depth-average current speed transects in the Pentland Firth (MS-2013) against harmonically predicted current speeds based upon 1 month simulation in 2001 -



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-12c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	PFOW model comparison with 2013 transect 2	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.3.7 Summary

An FVCOM flow model has been setup for the Pentland Firth and Orkney Waters region. This model has been run in three-dimensions with ten vertical layers and constant temperature and salinity in order to focus on the calibration of the tidal levels and flows. Meteorological forcing, river input and time-varying temperature and salinity have been included in the baroclinic simulations described in Section 3.4.

The measured water level data and current speed data during a 15-day period in October 2001 have been used to calibrate the model. Statistical analysis along with visual inspection of the model results have provided guidance on how to adjust the model parameters (mainly bed roughness and boundary water level datum) in order to improve on the model predictions.

It was found that the boundary conditions extracted from the 2001 AMM model did not appear to be centred on mean sea level when compared against observed water levels. Therefore, it was found that a vertical shift of 0.62m to the water level boundary conditions was required for the model to match the observed water levels more closely.

There also appeared to be a phase error of 0.5 hours in the water level model results compared to the measured data. Analysis of the current data showed that this phase error was not apparent in the current speed results. Data from the AMM model used to create the boundary conditions was provided at one hour intervals. Therefore it is possible that the temporal resolution of this data may in part be attributable to the 0.5 hour phase difference.

Sensitivity tests to bed roughness were performed, which required the default bed roughness to be reduced to a value of 0.04m from the original value of 0.1m. However although locations 1 and 2 compared favourably, location 3 was not as good with higher peak current speeds. This was also observed in the study carried out by Baston and Harris (2011). It should be noted that the observed data was depth-averaged for comparison, although there is no data in the top 11-13m of the water column.

Comparisons of the model results with measurements along transects also show good agreement within the Pentland Firth, but less so in the Hoy Channel.

In conclusion, it is considered that the model has achieved a good level of calibration for the water levels and current speeds compared against the timeseries data. The calibration statistics is within the guidance on water level and current speed calibration provided in Bartlett (1998). Furthermore the agreement between the modelled and the measured current speeds and directions along transects is considered to be satisfactory (by visual inspection).

3.4 Baroclinic model simulations and validation

3.4.1 Introduction

Following on from the calibration of the tidal water levels and currents, the next step in the process of developing the PFOW model is to introduce temperature and salinity boundaries, followed by full meteorological forcing and river inputs and to validate the model against measured data. In this section of the report, the process undertaken to get the model running with the additional forcing and comparison of the model results with observed data is described.

For the purpose of model validation, the period of May 2009 has been chosen as a target period in which to run the model; vertical profile data of temperature and salinity is available during this period within the PFOW model area. The model was originally taken forward as a 3 layer (4 level) model, initially due to run times. There were many stability issues in getting this 3 layer baroclinic model running. These were eventually overcome and the 3 layer baroclinic model was successfully calibrated. However the 3 layer model did not provide the vertical resolution that was felt to be required, especially to enable the reproduction of stratification. The use of the nesting boundaries (see Section 3.2.3) enabled the 10 layer model to run without the stability issues that had earlier been a problem.

3.4.2 Water levels and current speed boundaries

As with the tide-only hydrodynamic model presented in Section 3.3, water level boundary conditions for the baroclinic model have come from the same source; namely the Atlantic Margin Model (AMM) developed by NOC-L. A water level boundary file was extracted from the hourly AMM-model data for the period June 2009. Additionally as the nesting boundary approach was being used depth-averaged current speeds from the AMM model (vertical variation was not available) were also extracted and applied equally through the vertical for all of the nodes attached to the boundary elements.

3.4.3 Mesh updates

During the process of getting the baroclinic model running, many stability issues were encountered (which were not observed during the tide-only simulations), some of which required adjustments to the mesh. It was brought to our attention that each model node should not be connected to more than 8 adjacent elements. Following inspection of the mesh, it was found to have a number of nodes which had 9 connecting elements. The mesh was adjusted by the addition of extra nodes to remove these features from the mesh. Subsequently the mesh was converted to an SMS format so that the SMS quality checking functionality could be used.

Another issue was with river inputs. If the node at which the river input is applied is connected to two other land boundary nodes in the same element then the water cannot escape from the element and builds up over time to an unrealistic value. A routine was written which moves the location of the river node to the next nearest node.

Bathymetry along the offshore shelf boundary on the western side of the model was also smoothed so that any instability created in this area could be reduced. There were some steep areas which may have caused problems. It is unclear if this alone helped to make the model stable, but it appeared to help prior to using the nested boundary approach.

3.4.4 Temperature and salinity boundaries

As with the water level boundary and nested current boundary, the temperature and salinity nested boundaries have been extracted from the AMM model. Salinity and temperature data is available as daily data over the entire AMM model domain (which encompasses the PFOW model domain). The AMM model has 40 vertical layers with layer numbering starting from the bed. This is in contrast to FVCOM where layer numbering starts at the surface. MATLAB code was written to read in the FVCOM mesh and boundary node locations and extract the relevant data from the AMM model to produce a netcdf format nested boundary file (including the current speed data). Vertical interpolation was employed to provide data at the correct FVCOM level.

3.4.5 Initial conditions

In order to avoid long warm-up periods to get the temperature and salinity to be in dynamic equilibrium, the AMM model results have been used to provide initial conditions for temperature and salinity. First, the hydrodynamic model is run from cold with temperature and salinity applied with constant values. A restart file is then processed using a MATLAB script which interpolates results from the daily AMM model and inserts this data into the restart file overwriting the temperature and salinity data. Then when the PFOW model is started up again using this restart file, not only are the water levels and velocities included (already warmed-up) but so are the temperature and salinity fields.

3.4.6 River input

River data was obtained from CEH (received June 2013 and subsequently updated in August 2014 with data in Shetland waters) and encompassed all of 2009 at 15 minute intervals (Shetland had daily average data). This data was processed using a MATLAB tool which determined which mesh node to apply the river flow to. It also moved the location of a river node to the nearest land node if it was connected to two other land nodes in the same element (if connected in this way, then the river flow cannot escape the element and water levels build up artificially too high).

A river namelist file was produced along with a netcdf file for each of the rivers named in it. On further application of the Shelf model it was found that reading in over 500 river files impacted upon model performance (input/output overhead). The PFOW model was also exhibiting performance issues and therefore all of the rivers (118) were combined into one netcdf file. This, in conjunction with using the latest version 3.1.6 of FVCOM, helped to stabilise runtimes.

The salinity in the river flow was set to 0 psu, and the temperature set to 7 degrees Celsius as this was appropriate for the nearshore temperatures from the AMM model. The river flow is distributed equally amongst all of the vertical layers.

3.4.7 Meteorological forcing

There are two option when including heat input into the FVCOM model; either the net heat flux inputs are provided by way of netcdf files, or FVCOM calculates it internally (from input meteorological parameters). NOC-L found that the shelf model was heating up too much with this approach over a 4-month simulation. Furthermore, they found that this overheating problem was solved by allowing FVCOM to calculate the heat inputs internally. The reason for the overheating problem is due to the difference in sea surface temperature used in the Met Office model and the AMM model used for deriving initial conditions. In the PFOW model the impact is not as obvious as the model boundaries are comparably closer to the middle of the model than for the wide area Shelf Sea model. However it does appear that the PFOW model in its current form using this pre-calculated Met data does produce temperatures which are too high. The boundaries will tend to rectify this but there will be a time lag of a few weeks or more. It is therefore considered advantageous to follow the NOC-L approach and have the heating calculated within the model. This method was adopted in this study.

The meteorological forcing data was retrieved by NOC-L for 2009. This was processed and a Matlab tool produced which provided the necessary meteorological file for FVCOM. A more detailed description of the Meteorological forcing used in both the Shelf Model and the PFOW model can be found in Section 3.2.5 of the report for the Shelf model, Halcrow (2015).

There were some issues with the meteorological forcing data with rain falling on dry elements, some negative evaporation(and precipitation) as well as cooling of elements that were disconnected from the main water body (at a few places along the coastline). Additionally the Met data grid did not always overlap fully the PFOW model. In order to remove issues associated with these problems, the met data was post processed to make the values zero in these locations. It was felt that this would not have a significant impact upon the overall model results.

3.4.8 Stability issues

During the process of obtaining a stable baroclinic model run with all of the met forcing, temperature and salinity boundaries and river inputs, many simulations were performed.

Some of the solutions that were investigated to alleviate model instabilities are highlighted below.

- 9 element connectivity – although the model ran okay for tides only, once this issue was highlighted the mesh was adjusted. This did not appear to solely solve the instability problems, however it was noticed that some instabilities occurred close to a number of these 9 connected nodes, especially close to intertidal areas.
- Sponge nodes – sponge nodes were applied all around the models open boundary. This did provide partial cure to instability

issues, however when the model was rerun for the tidal current calibration period, current speeds were lower than previously obtained along with a reduction in tidal range. This was not satisfactory, a range of values were chosen in order to reduce the impact upon water level and speed, however in the end sponge nodes have not been used.

- Roughness – As previously reported during the setup of the model increased roughness around the boundary and specifically higher in the region closest to Aberdeen were applied to the model in order to reduce stability problems and recirculation at the model boundaries.
- Smooth bathymetry at boundaries – For some simulations, instabilities at the model boundaries were observed. It was not always the reason for the model to crash however smoothing the bathymetry did appear to help.
- Deepened river nodes – although this was not observed as a direct cause of instabilities, it was surmised that it may cause a problem if the river flow is being applied to a dry node. The surrounding elements were therefore deepened to 2m below MSL so as to be wet throughout a tidal cycle.
- Timestep – Although the hydrodynamic model with tide forcing only ran successfully with a timestep of 1s, the baroclinic model had stability problems. It appeared that on top of the adjustments made above to reduce instabilities, it was the reduction of the External timestep to 0.75s, and then subsequently to 0.5s which finally produced a model that would run through to a month long-simulation.

Many of the approaches above were investigated due to the problems experienced using only elevation boundaries (no current boundary) and nudging boundaries for temperature and salinity. There was a vast improvement in model stability when the nesting boundary approach was used. The model therefore did not require a spatially varying roughness map but used a constant one in the end. The external timestep did need to be reduced to 0.5 seconds because of the high flows through the Pentland Firth (combined with mesh resolution and depths) although the river nodes did not need to be deepened. The bathymetry was smoothed four times (with coefficient 0.5) using the FVCOM toolbox smoother.

3.4.9 Comparison of tide levels

As for the tide-only model, the water levels predicted with the 10-layer baroclinic model have been compared against tide gauge data at Wick (on the mainland, southeast of the Pentland Firth) and Lerwick on Shetland; the comparisons can be seen in Figures 3-13a and 3-13b respectively. Comparisons at Wick are very good, with a good reproduction of the surge around the 7th May 2009, with under-prediction in the order of 0.1-0.15m. There does appear to be some under-prediction of the tidal range during neap tides, but in general during spring tides differences between observed and predicted water levels are within 0.1m. The rms error at Wick for the full month is 0.137m with a bias of less than 3cm. At Lerwick, the prediction of the tide curve is good, however the mean sea level appears to be about 0.1m lower than observed. The rms error is 0.14m with a bias of -0.1m. If the observed water level is lowered by 0.1m (if there is a consistent error with the gauge or model MSL at this location) then the rms error drops below 0.1m.

3.4.10 Comparison of model results against vertical profile data and the AMM model – ten layer baroclinic model, May 2009

This section presents results derived from the 10 layer baroclinic model. Temperature and salinity profile data was obtained from the BODC website (www.bodc.ac.uk) and filtered for the PFOW model area. This showed that there were a number of locations within the model domain where vertical profiles existed in May 2009. This data provides a means to show how the baroclinic PFOW model performs against temperature and salinity through both the vertical and horizontal planes.

A 20 hour coldstart run was undertaken first so as to build up the water level and flow conditions, and then the hotstart file had the temperature and salinity fields inserted into it from the AMM model. The hotstart simulation was run until the end of May 2009. The results from this simulation have been compared against the available vertical profile data as well as the AMM model results and are presented in Figures 3-14a to i and Appendix Figures D.1 to D.28. Commentary on a few are picked out for discussion below.

Each Figure consists of four subframes. The top right frame shows the location of the measurement; a red circle shows the exact location, and the blue dot shows the nearest model node at which the model results have been extracted. Observations which are slightly outside of the model domain beyond the shelf edge have not been presented. The bottom right frame shows the time at which the profile was taken in relation to the tide curve at that location. The top left frame presents the salinity plotted against water depth (0 being the water surface), and the bottom left frame shows the water temperature against water depth.

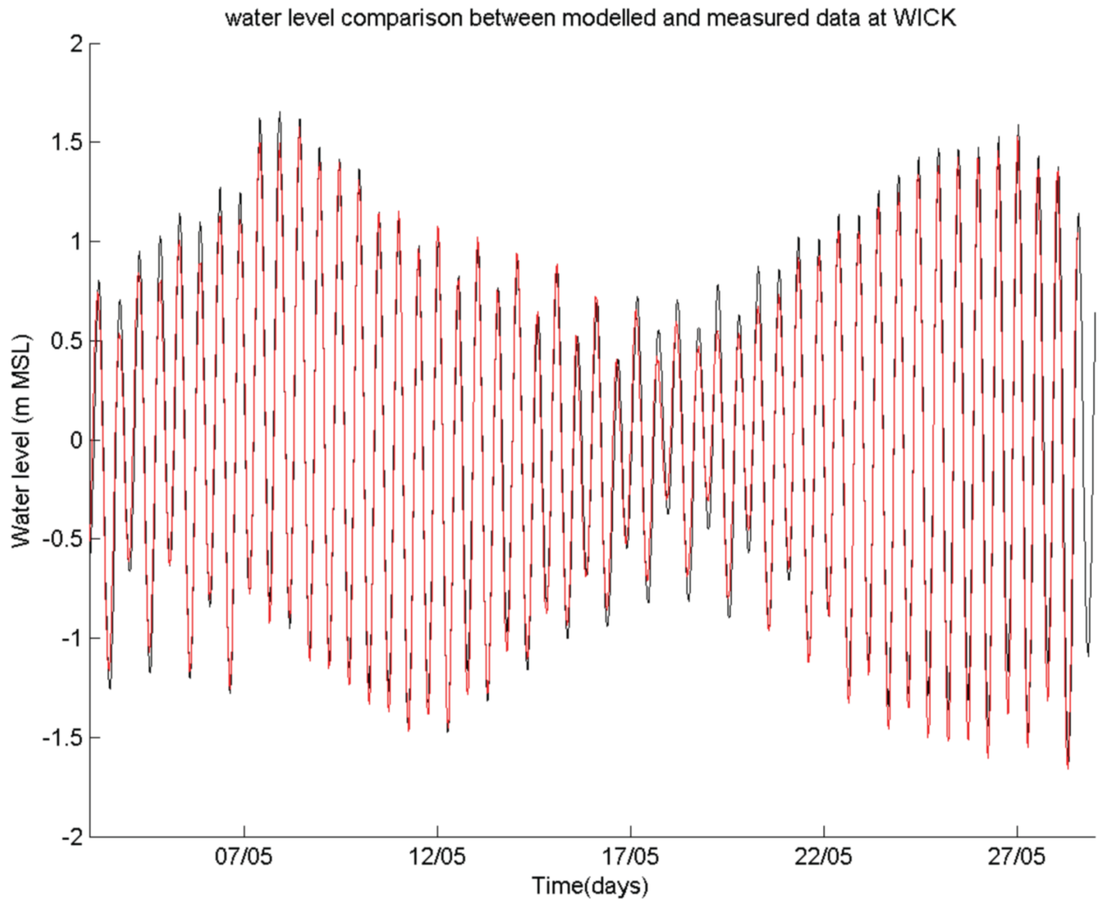
The aim has been to get the salinity predictions to be within +/-1psu, and temperature within 0.5 degrees Celsius. Figures 3-14 a-d show comparisons of vertical profiles in between the Orkney and Shetland Isles during periods of neap tides. In general the salinity comparisons are within the target of 1psu, with the largest differences being close to the surface where the effect of fresher water is apparent. As the PFOW model is being driven by boundary conditions from the AMM model there are some limitations as to how close the PFOW model can get to the data, in addition it should be noted that the river flow included in the AMM model is different to that used in the PFOW model which may also account for some differences between the two models. Figures 3-14a and b show similar features to the data in the vertical salinity profile whereas the AMM model is showing no vertical difference. Figures 3-14c and d are located further north than the locations in Figures 3-14a and b, they also do not show quite as good a comparison with the salinity.

The temperature profiles in Figures 3-14 a-d are very similar in shape to those of the observed data, although it can be seen that the underlying temperature is being dominated by that introduced through the boundary from the AMM model. It is therefore not possible to meet the criteria of 0.5 degrees difference between the PFOW model and the observed temperature data given the AMM model results have an underlying over-prediction of 0.5-1 degrees. At these locations in the channel between the Orkney and Shetland Isles, temperatures predicted by the PFOW model are however within 1 degree of the observations.

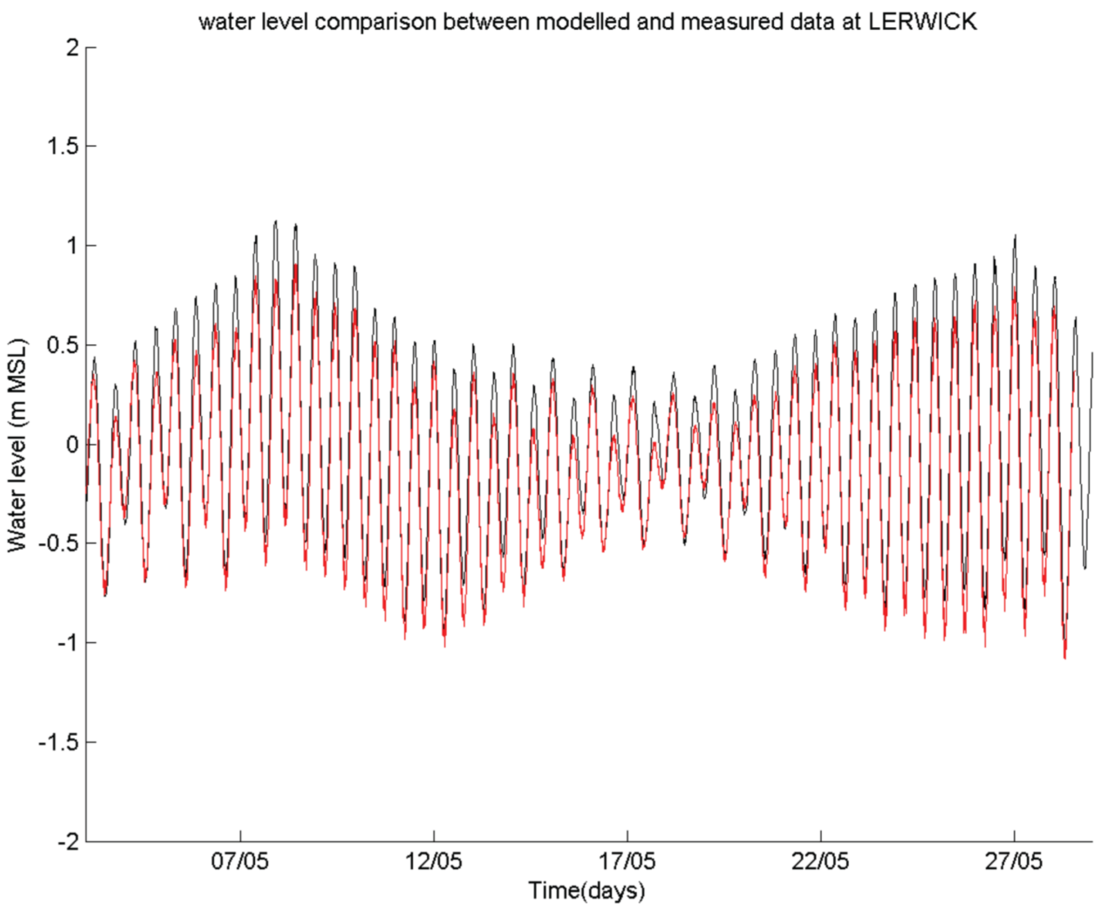
Figures 3-14e-i show comparisons of temperature and salinity between the models and data in an area around Shetland. In general the comparisons for salinity are very close, although the PFOW model shows slightly higher salinity (order of 0.2PSU) close to the surface than the data or the AMM model. Figure 3-14i shows a much closer comparison with the data however closer to the surface. The influence of freshwater at this time and location appears to be less than that further to the south. It has been observed in the model results that the influence of freshwater from the west coast of Scotland and the north coast enters the Pentland Firth from the west but also is pushed northwards around the Orkney Isles which is probably why the earlier figures (3-14a-d) showed a larger variation of salinity close to the surface.

Figures 3-14e-i also show the temperature profiles from the PFOW model compared against the data and the AMM model. These locations are closer to the model boundary and therefore a stronger influence from the AMM model could be expected. As previously noted, temperatures are generally over-predicted by the AMM model (in the order of 1 degree Celsius) which has been passed into the PFOW model. The PFOW model however does reasonably reproduce the vertical features in the observed data.

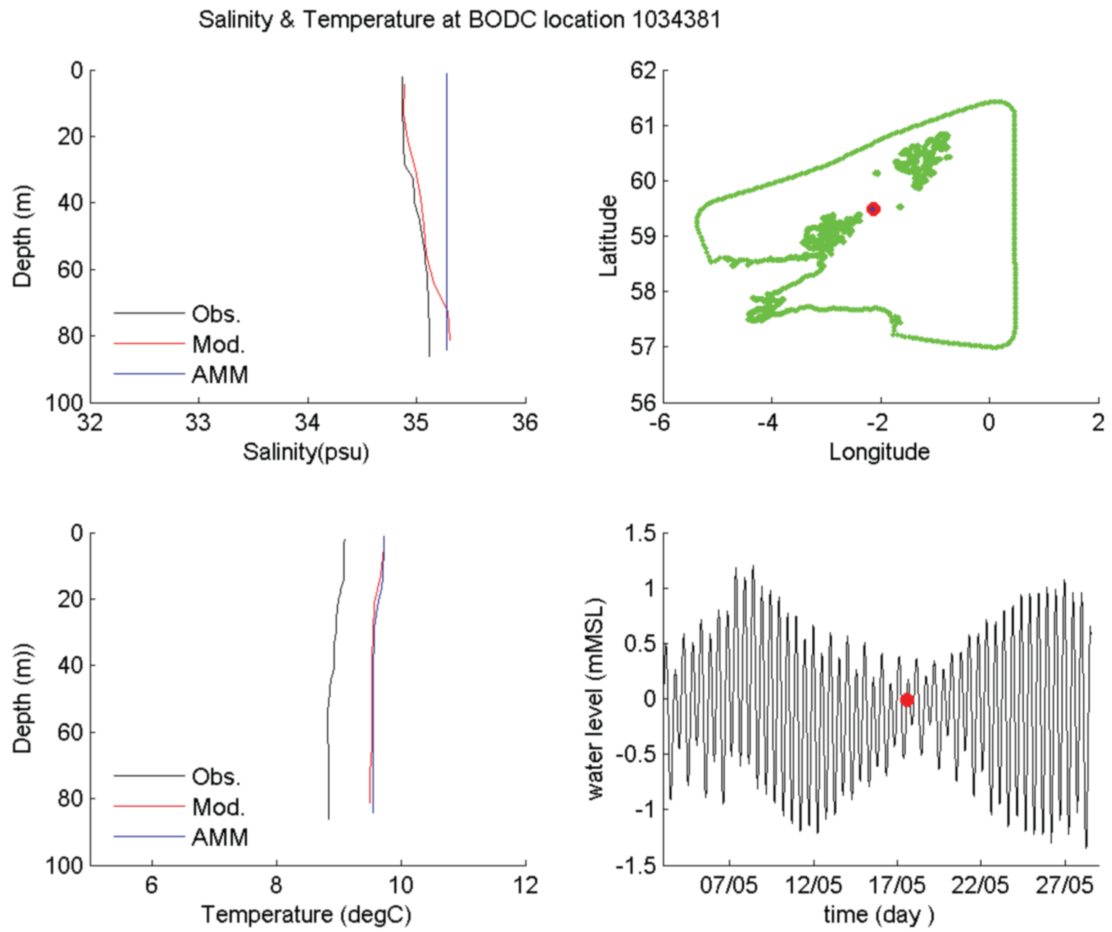
So to conclude, the 10 layer PFOW baroclinic model is able to reproduce salinity within the 1 PSU target. However, the PFOW model has not been able to achieve the 0.5 degree target for temperature but this is thought to be mainly due to the AMM model boundary conditions introducing temperatures which are slightly too high at the model boundary. In general however temperatures predicted by the PFOW model are within 1 degree Celsius of the observed data.



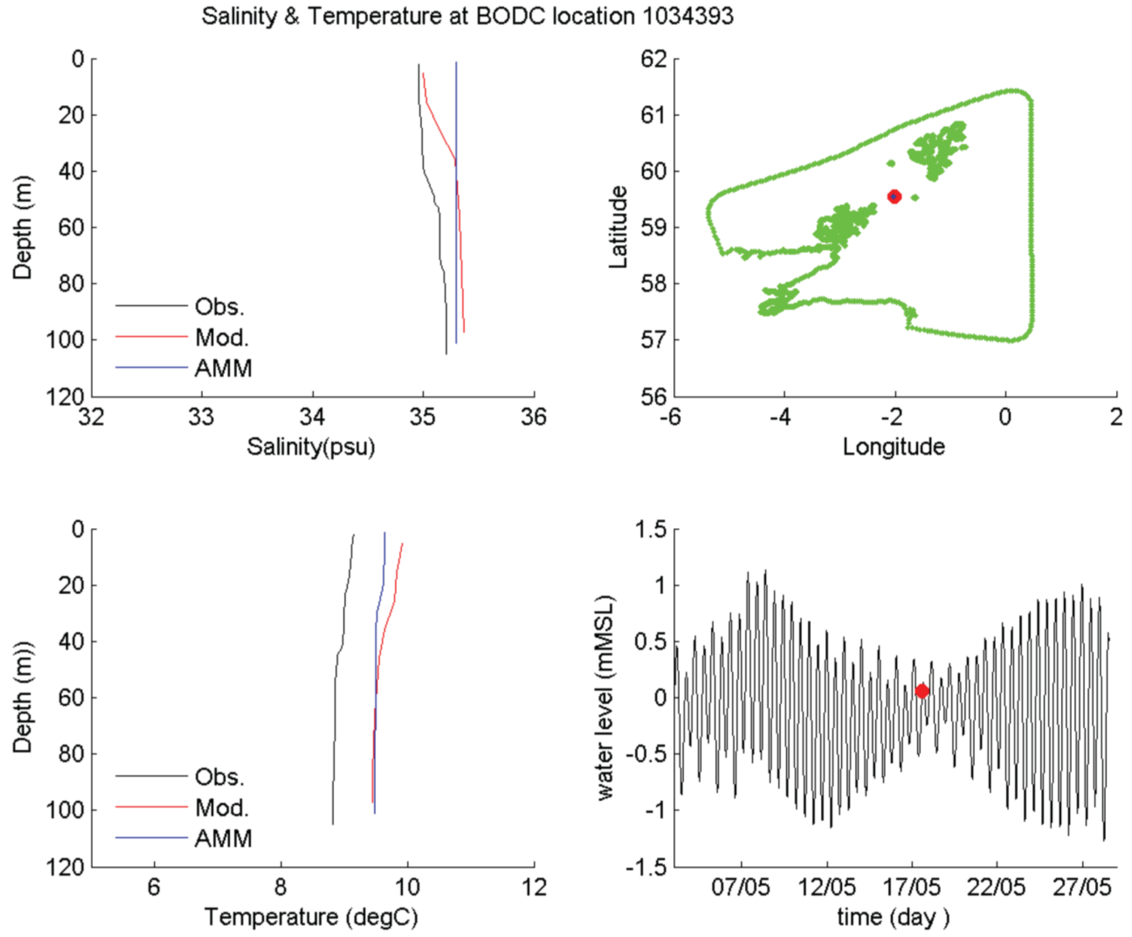
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-13a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Wick	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



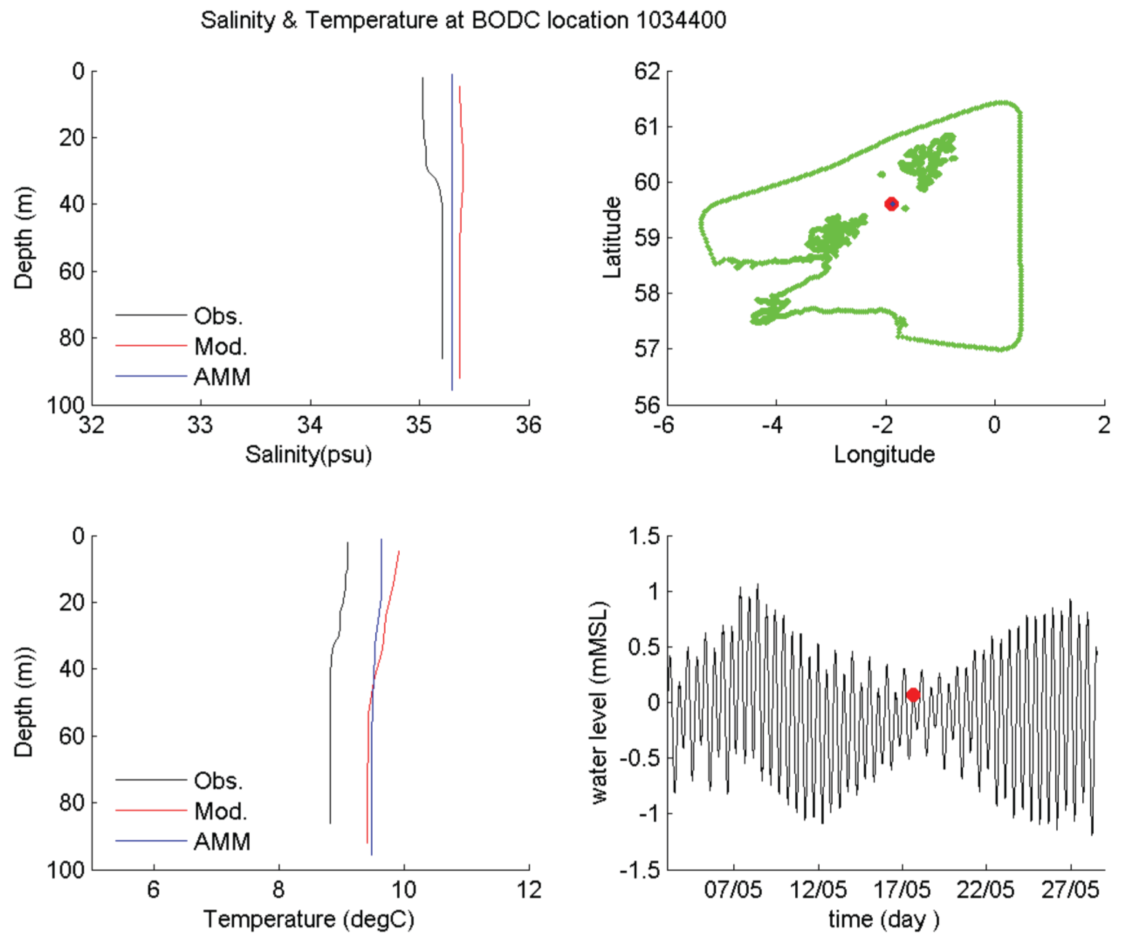
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-13b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of water levels at Lerwick	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



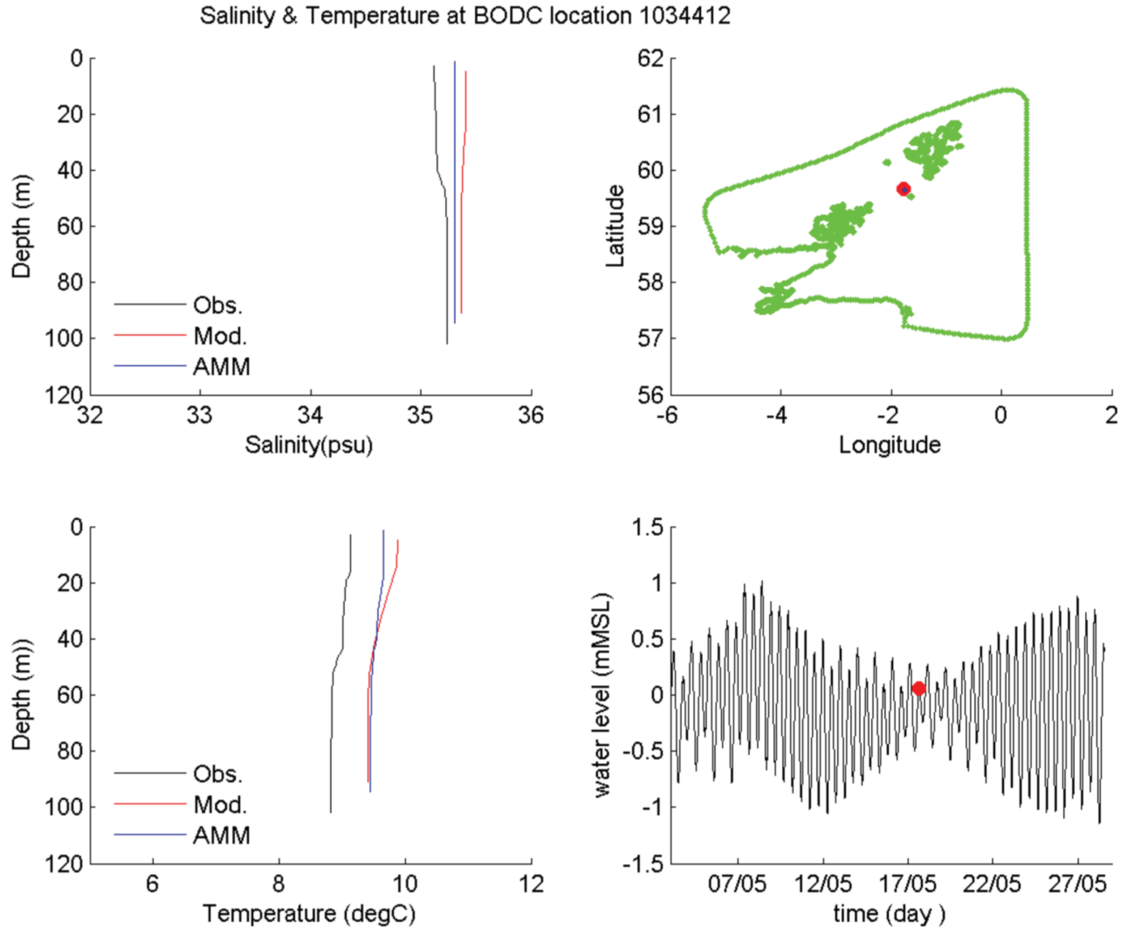
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



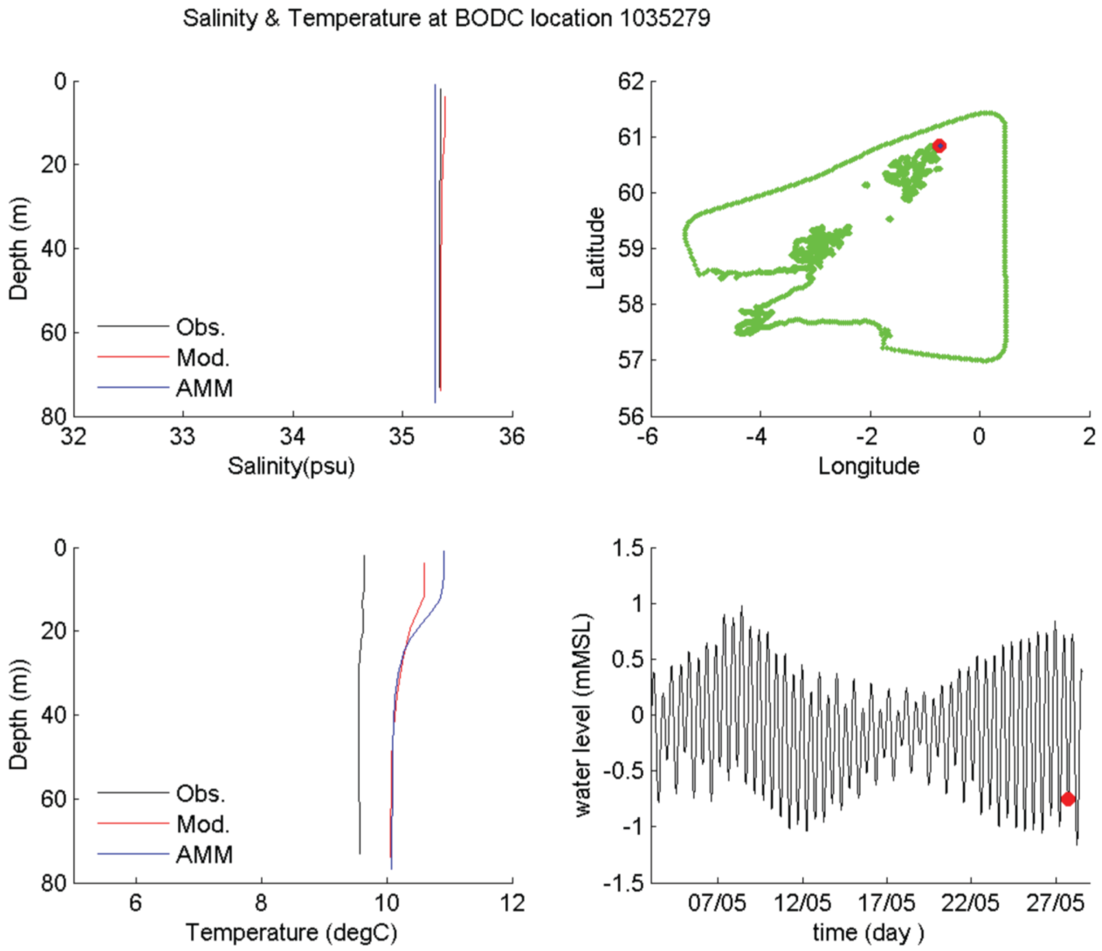
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



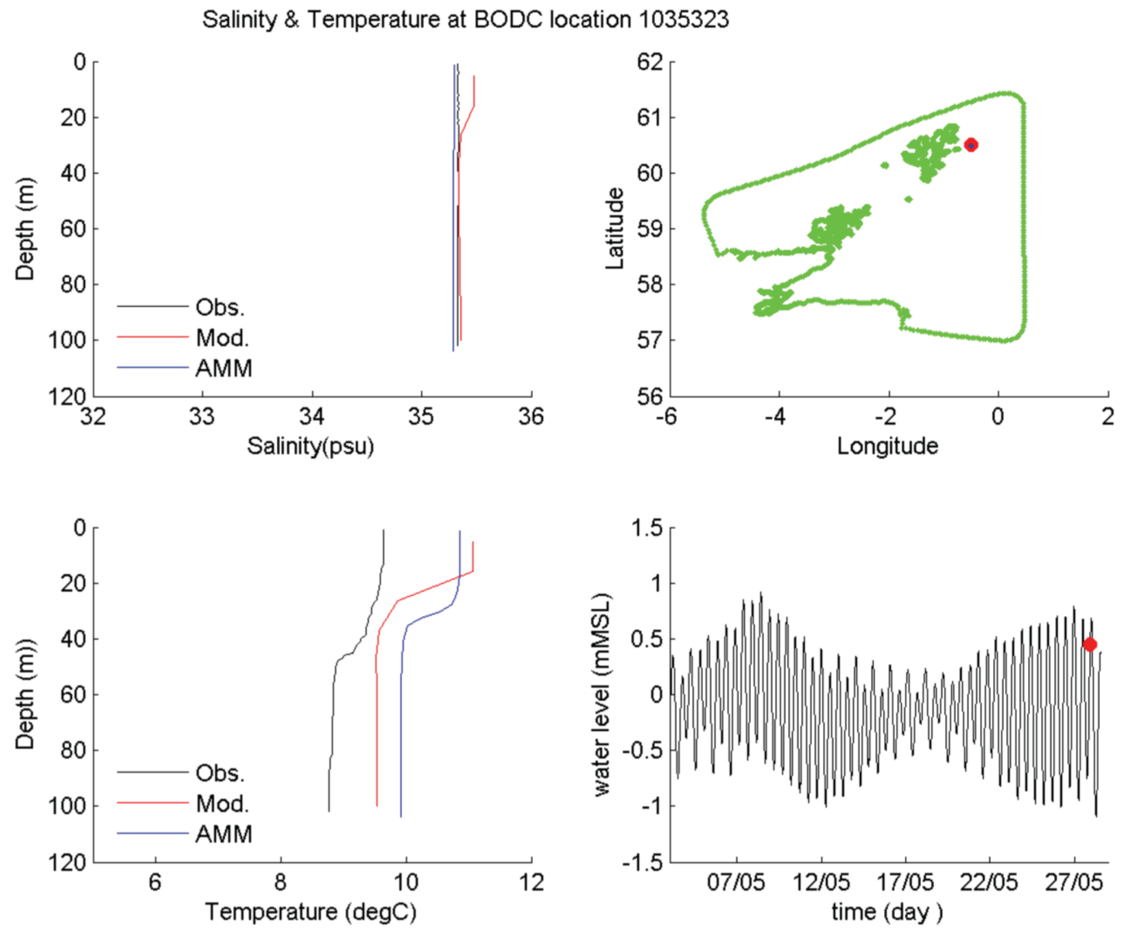
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14c		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



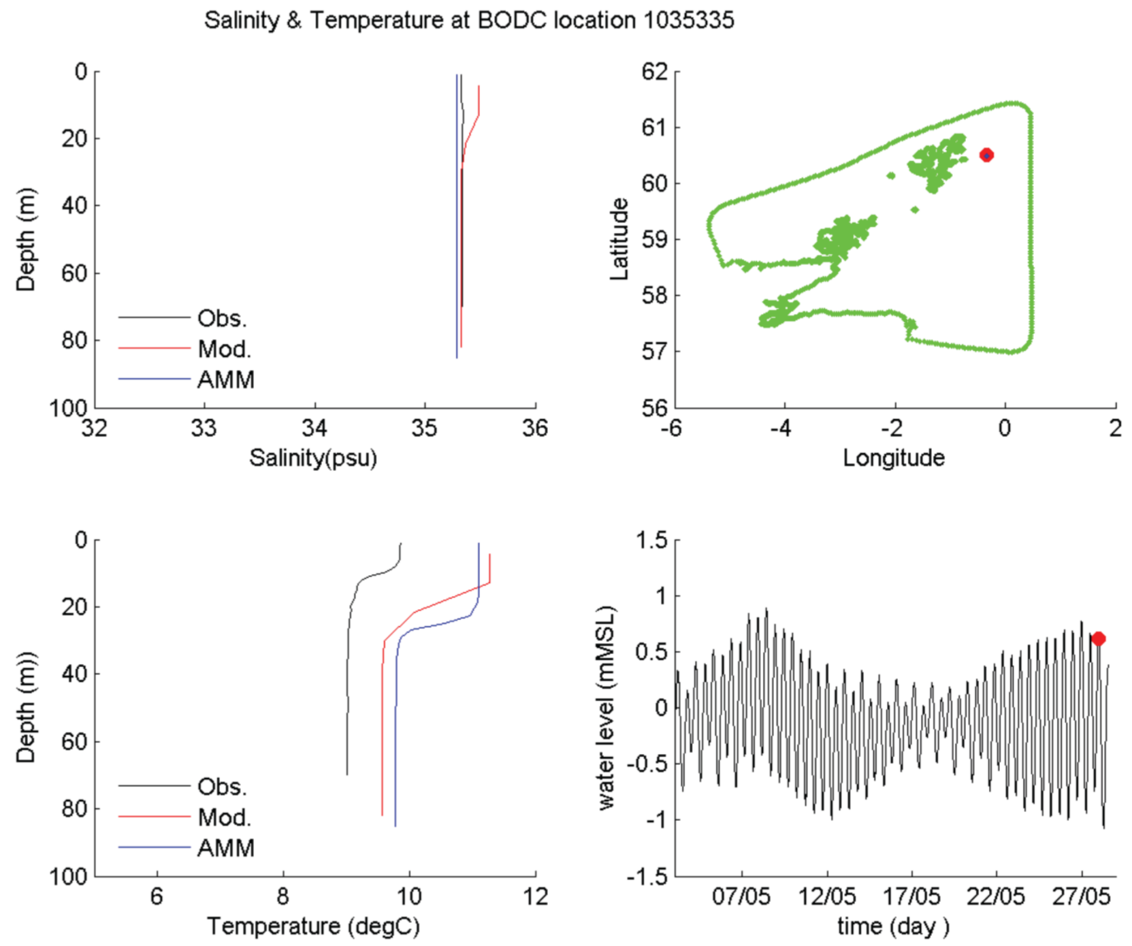
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14d		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



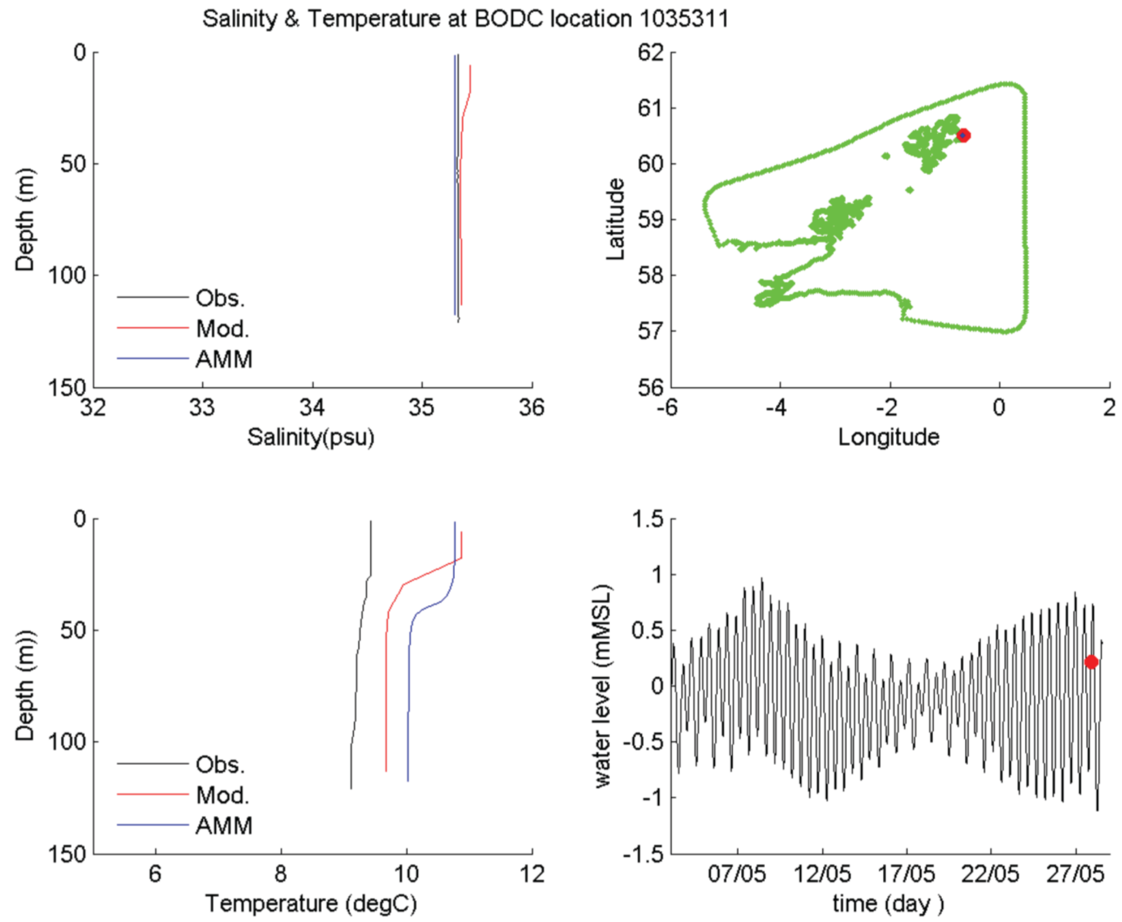
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14e		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



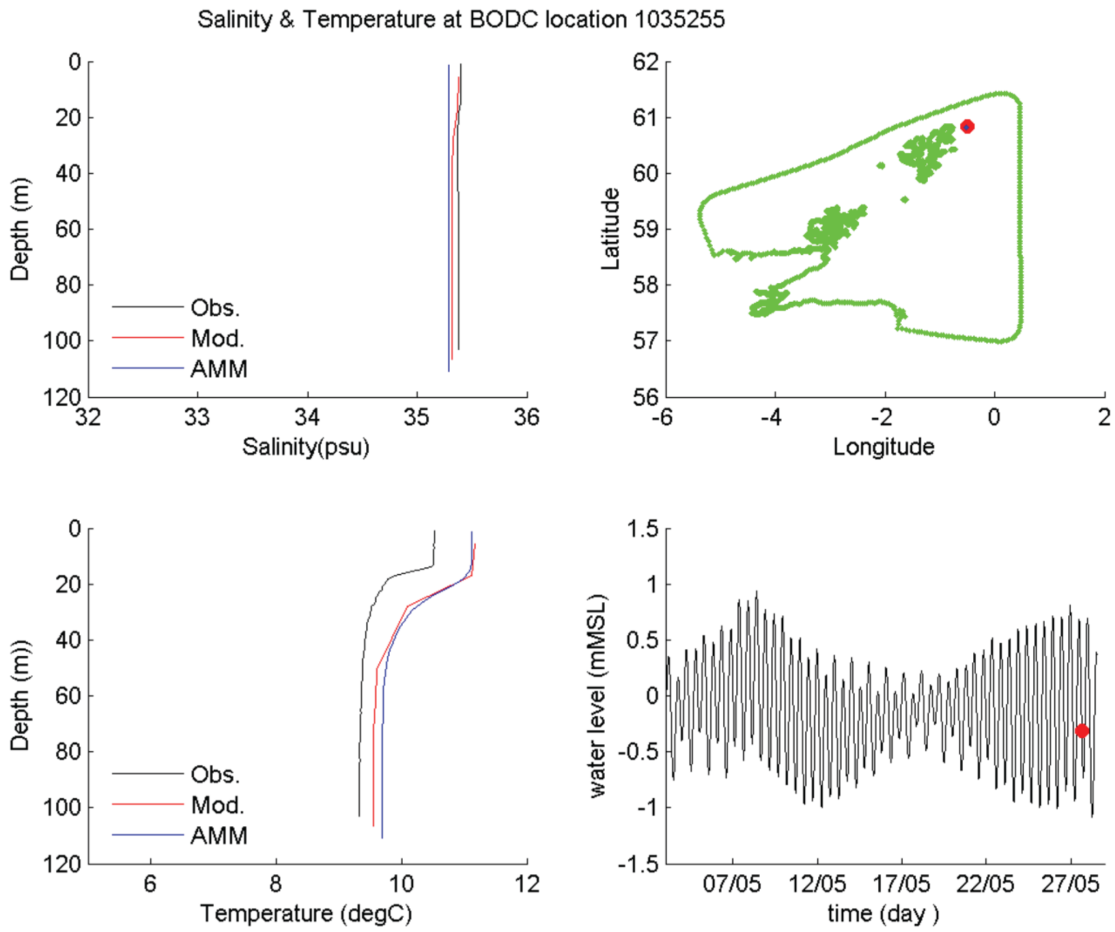
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14f		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14g		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14h		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14i		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of temperature/salinity from baroclinic model with BODC profile data and AMM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.4.11 Timeseries comparisons of temperature and salinity

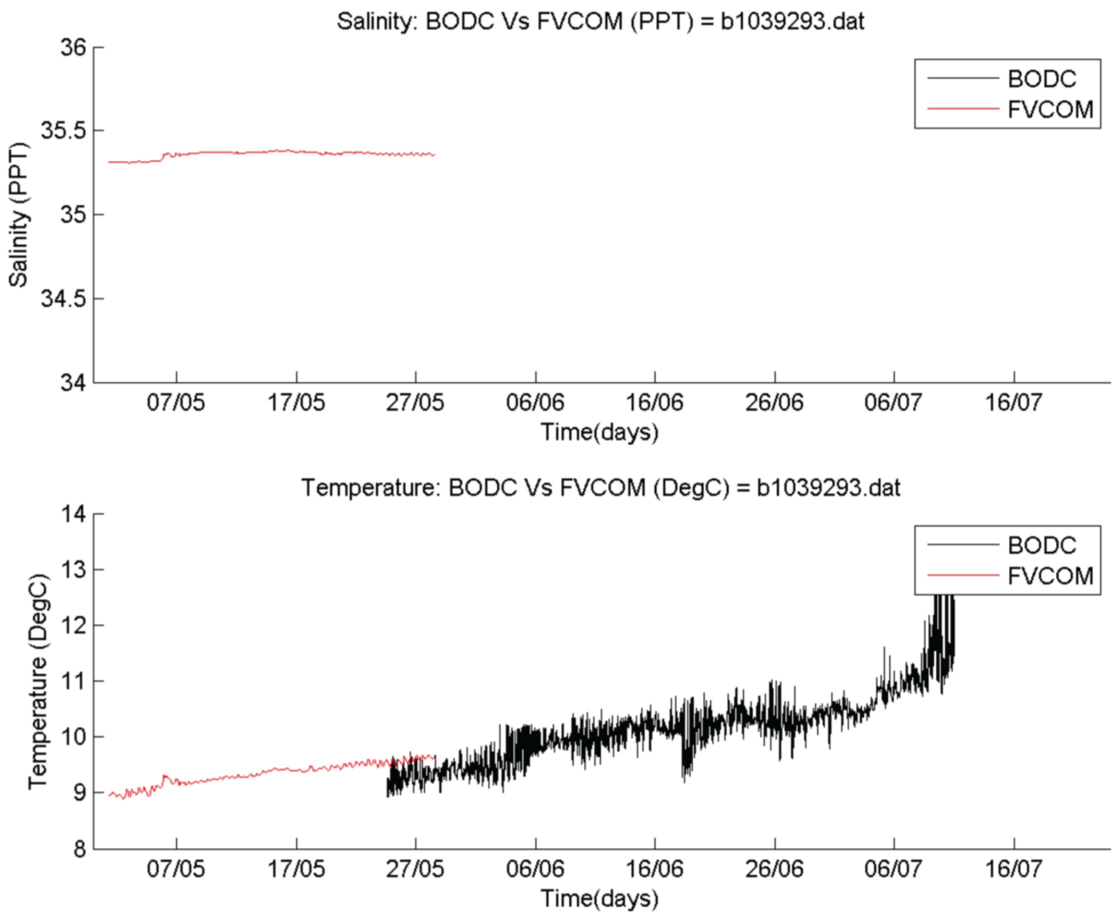
In addition to the vertical profiles, timeseries data of temperature and salinity were available at two locations to the east of the Shetland Isles (obtained from the BODC). Two locations are available, recording at mid-depth and near-bed. There is a short overlap with the results from the simulation in May 2009 which provides a good indication of how the model is performing in relation to variation over time.

The comparisons between the model predictions and the observed data can be seen in Figures 3.14a-d. The model results from the appropriate layer has been presented.

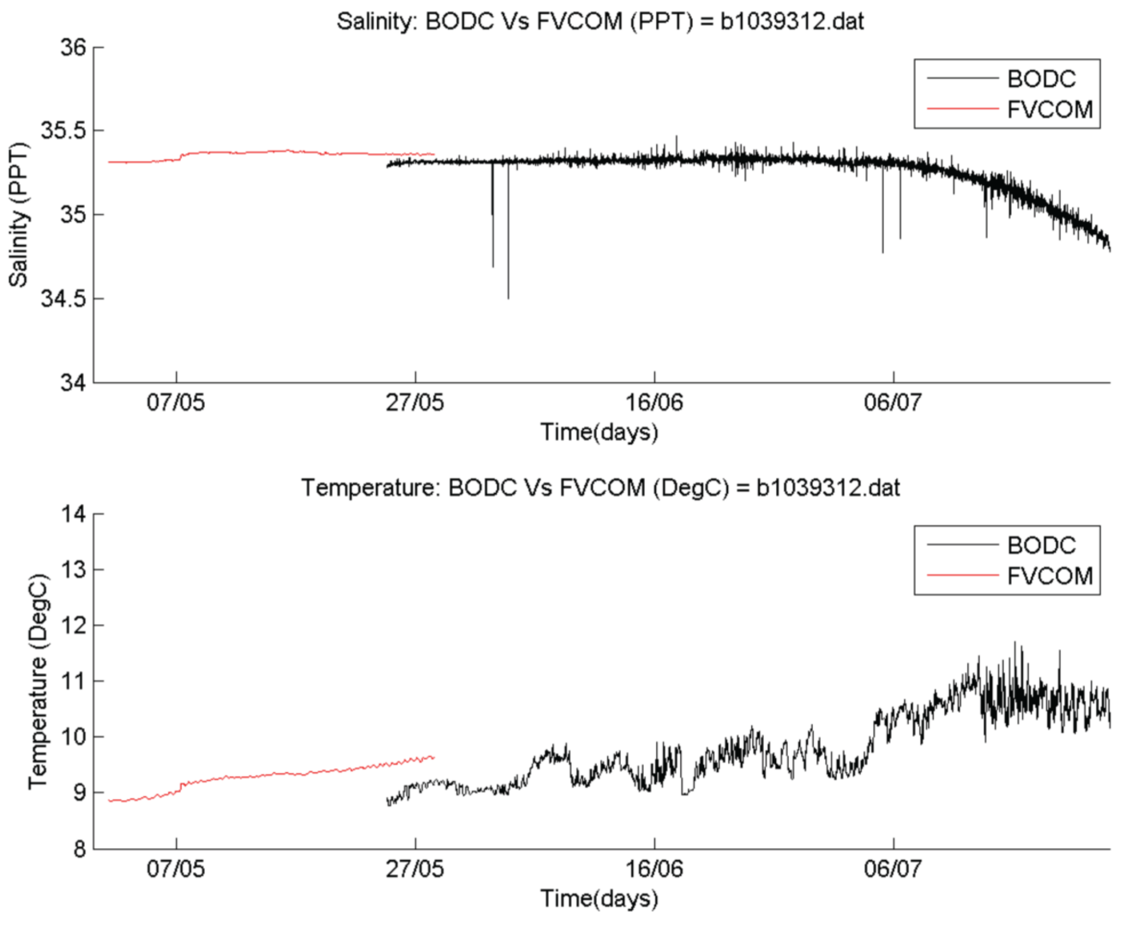
Figure 3-15a shows only temperature comparisons. The build-up of temperature in the mid-depth of the water column appears to be increasing at the same rate as observed with the data and is reproducing the observed temperature within 0.5 degrees Celsius. Figure 3-15b presents the comparisons at the same location but close to the sea-bed. There appears to be less scatter/variation in the temperature measurements with this instrument. Again the model (red line) is approximately 0.5 degrees higher than the temperature observed. This may in part be due to the temperature introduced from the AMM model as discussed in the previous section.

Figures 3-15c and 3-15d present the comparisons of temperature and salinity at the other location at mid and near-bed depths. The mid-depth is at 42m out of a total 124m. Both temperature and salinity have reproduced measurements closely at this depth (salinity within 0.2ppt, temperature within 0.5 degrees Celsius). At the near-bed measurement, the salinity comparison is within 0.2ppt whereas the temperature is very close to that observed.

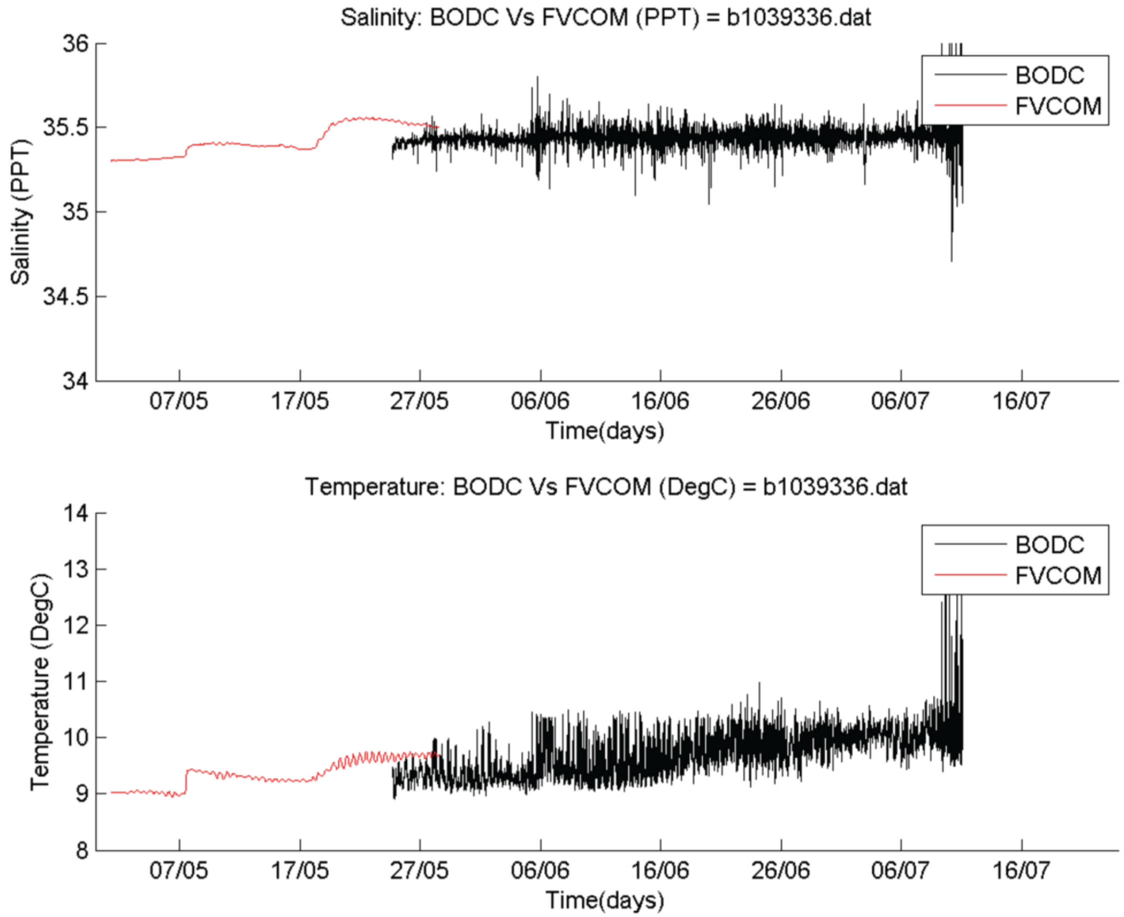
In general the comparisons have shown the background temperatures and salinities within the model are reproduced fairly well although there are indications that the boundary conditions introduced from the AMM model have increased the PFOW model temperatures by up to one degree Celsius.



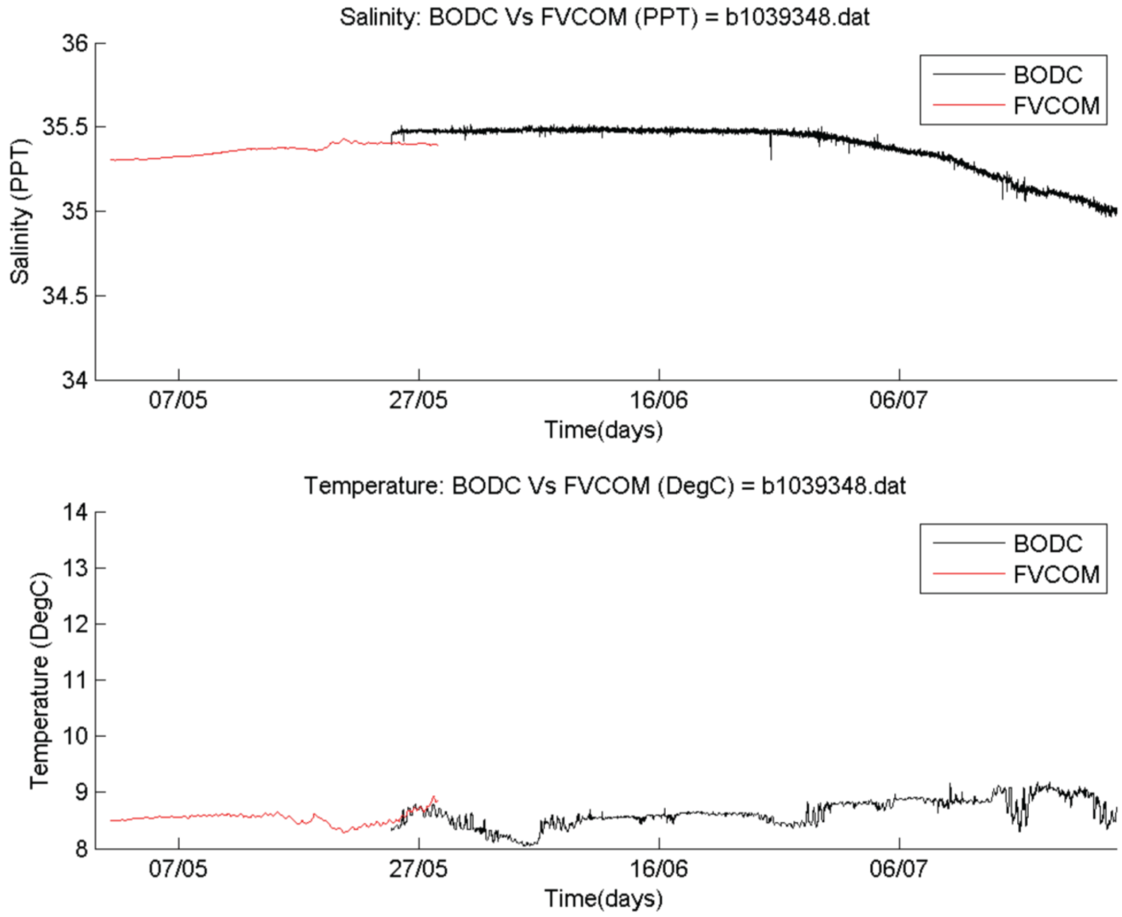
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity comparisons between BODC and FVCOM model (1039293) mid-depth 42m out of total 94m water depth.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity comparisons between BODC and FVCOM model (1039293) mid-depth 42m out of total 94m water depth.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15c		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Temperature and salinity comparisons between BODC and FVCOM model (1039336) mid-depth 42m out of a total depth of 124m water depth	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15d		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Temperature and salinity comparisons between BODC and FVCOM model (1039348) near-bed 115m out of total 124m water depth.	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.4.12 Summary

In Section 3.4, the model setup and validation of the baroclinic model has been presented. There were a number of issues relating to model stability that were eventually overcome in order that the 10 layer version of the model could run satisfactorily. The original model setup used a water level boundary only with nudging boundaries for temperature and salinity; velocities at the boundary were derived by the model. With this configuration there were many problems encountered with stability. Eventually after much work trying to improve the stability the move to using nested boundary conditions was undertaken. This approach has provided a much more robust and stable model built upon the earlier work on improving stability. All other Stage 2 models in this study were developed using the nesting boundary approach. The internal calculation of the heat fluxes was also chosen after initial findings from the Stage 1 shelf model. River flow data was updated late in the study with the inclusion of daily river flow data for Shetland (all other river locations include 15 minute data).

Comparisons of the 10 layer baroclinic model against vertical profiles and timeseries have shown a reasonable comparison against the observed data. Salinity is generally within 1 psu in line with our target. Comparisons of temperature however have in general been within 1 degree Celsius but outside the 0.5 degrees Celsius which was our target. Much of this difference however can be attributed to the AMM model boundary conditions (which are also too high) that have been used to impose temperatures at the PFOW model boundary.

3.5 Climatology model simulations

3.5.1 Introduction

The requirement is to produce a one-year climatic run based on climatological forcing, which will represent a typical annual cycle. This was carried out using the Scottish Shelf model climatology results as initial conditions and boundary conditions. The input data sets for climatological meteorological forcing and climatological river fluxes used in the shelf model were also used for the PFOW model. For a full description of the input data, the sources and how it was processed for climatological runs see the Scottish Shelf Modelling report, Halcrow (2015)

The results from the climatic run have been compared with climatological atlas information for temperature, salinity and currents. This provides a distribution of the typical tidal and residual currents over PFOW used as input for particle tracking and to develop connectivity indices in Stage 3.

3.5.2 Boundary conditions

Mean boundary forcing for water levels (mean yearly tides), currents, temperature and salinity were taken from the Scottish Waters Shelf model climatology results. Hourly results were interpolated on to the nested boundary nodes and elements using a Matlab script. Because the shelf model is run with 20 layers while the PFOW model is run with 10 layers it was also necessary to interpolate the current components, temperature and salinity from 20 to 10 layers. This was also carried out in the Matlab script.

3.5.3 River input

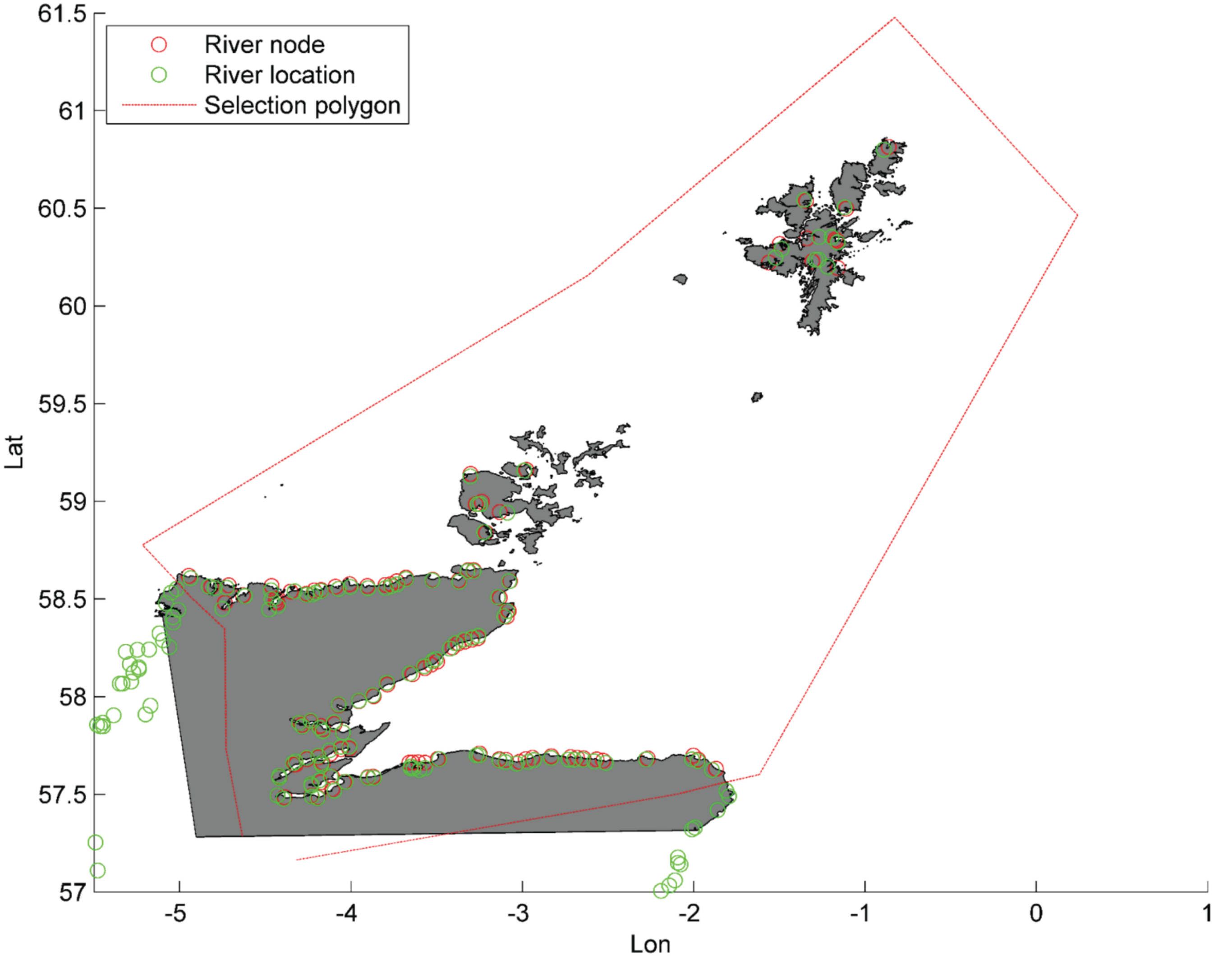
River climatology data was processed by NOC-L from G2G river climatology (1962-2011, 577 rivers) provided by CEH. For full details of how the river data was reconstructed to give climatological daily averages see the Scottish Shelf Modelling Report (Wolf et al. 2015).

Only 113 of these rivers fall within the PFOW model domain. The rivers were processed in the same way as those for the Baroclinic model runs. Figure 3-16 shows the location of the rivers and the location of the nodes the rivers were applied at.

3.5.4 Meteorological forcing

Met forcing data for the climatological simulations were interpolated on to the PFOW mesh from the Shelf model met forcing input files at 6 hourly intervals. The met forcing was derived by the NOC-L from ECMWF (ERA-40 and ERA-Interim, licence granted). The ERA-interim data cover 1989 - present, and ERA-40 1957 to 2002. These data were processed to derive monthly mean wind-stress, pressures, heating and evaporation minus precipitation for the period 1981-2010, to match the boundary forcing period.

The met forcing were derived as monthly means, which were then linearly interpolated to 6-hourly smoothed forcing data for each grid-point of FVCOM i.e. mean February data were applied at the middle of February; then mean March data were applied mid-March etc., with time-interpolation between. For full details see the Shelf Modelling report, Halcrow (2015)



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-16		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Locations of rivers (Green) and the node locations at which the river flows were applied at (red)	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

3.5.5 Temperature and Salinity Comparisons

Average monthly sea surface temperature (SST) and sea surface salinity (SSS) observations are available from two sources:

1. The ICES dataset (http://www.ices.dk/marine-data/data-portals/Pages/ocean.aspx) gridded and averaged for 1960-2004 (45 years) by Jason Holt. Data are also available from the NOAA/NDBC World Ocean Atlas (2013;
2. The WOA (World Ocean Atlas) http://www.nodc.noaa.gov/OC5/woa13/) based on over 100 years of observations interpolated on to a 0.25° resolution grid.

These datasets are used for qualitative comparison with the PFOW FVCOM results for Febuary and August. These months were chosen based on the findings of Berx and Hughes (2009) that the maximum and minimum of the SST occur in February and August.

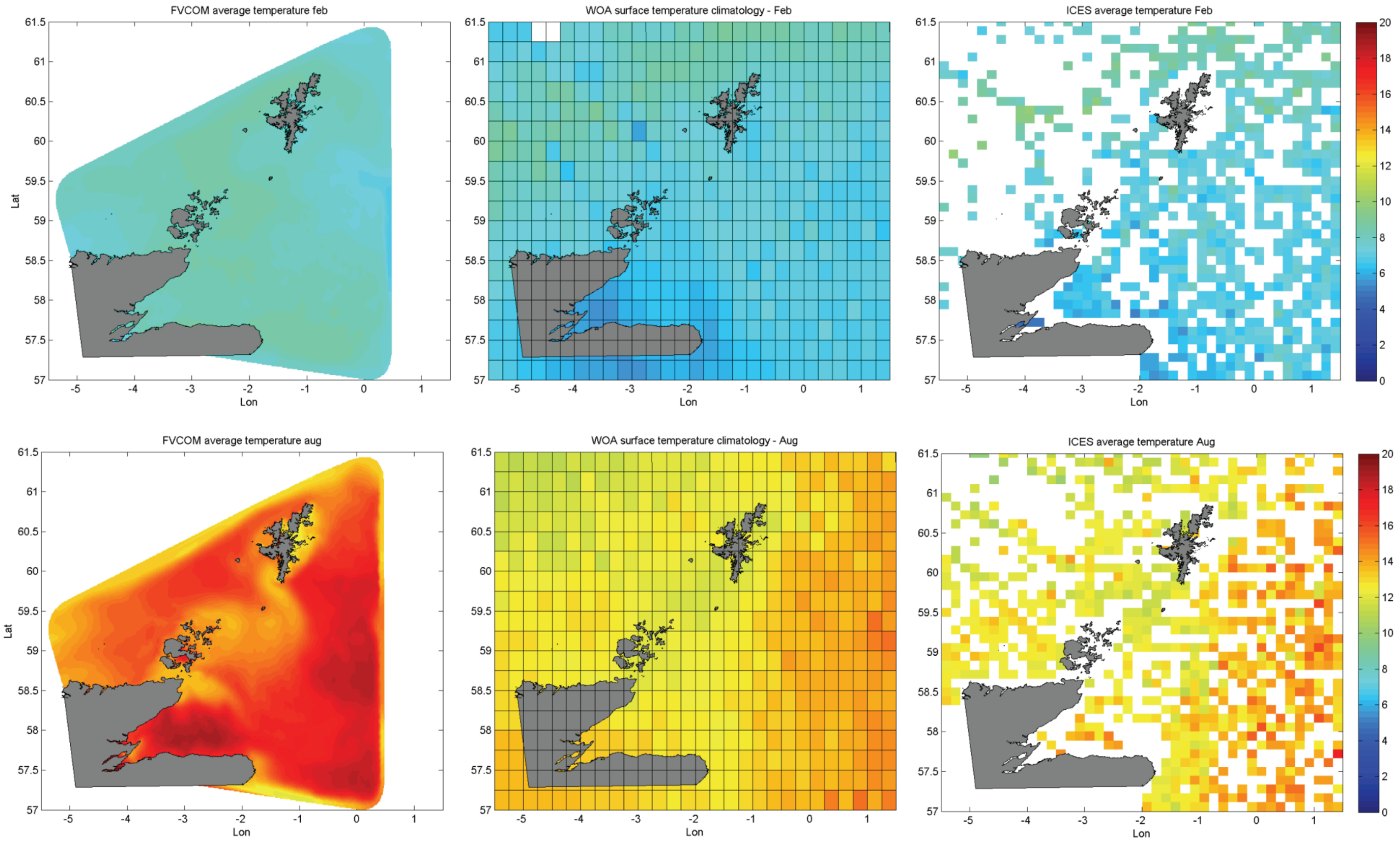
Figure 3-17 shows the comparison of the data sets for SST. The spatial variations in SST, i.e. cooler to the east of Shetland and Orkney in February is not clear in the PFOW FVCOM results. The variation in the August temperatures (i.e. warmer to the east of the islands in August is seen in the PFOW FVCOM results. However, the FVCOM results give slightly higher average SST for February and August, than the WOA or ICES data sets. The PFOW SST are greater that the shelf model temperatures. Figure 3-18 shows the SSS comparison for February and August. The salinity close to land were rivers are discharging are lower in February than August due to the relative levels of rainfall. Compared to the WOA and ICES data sets the FVCOM results give lower salinity levels close to land.

3.5.6 Mean Residual Currents

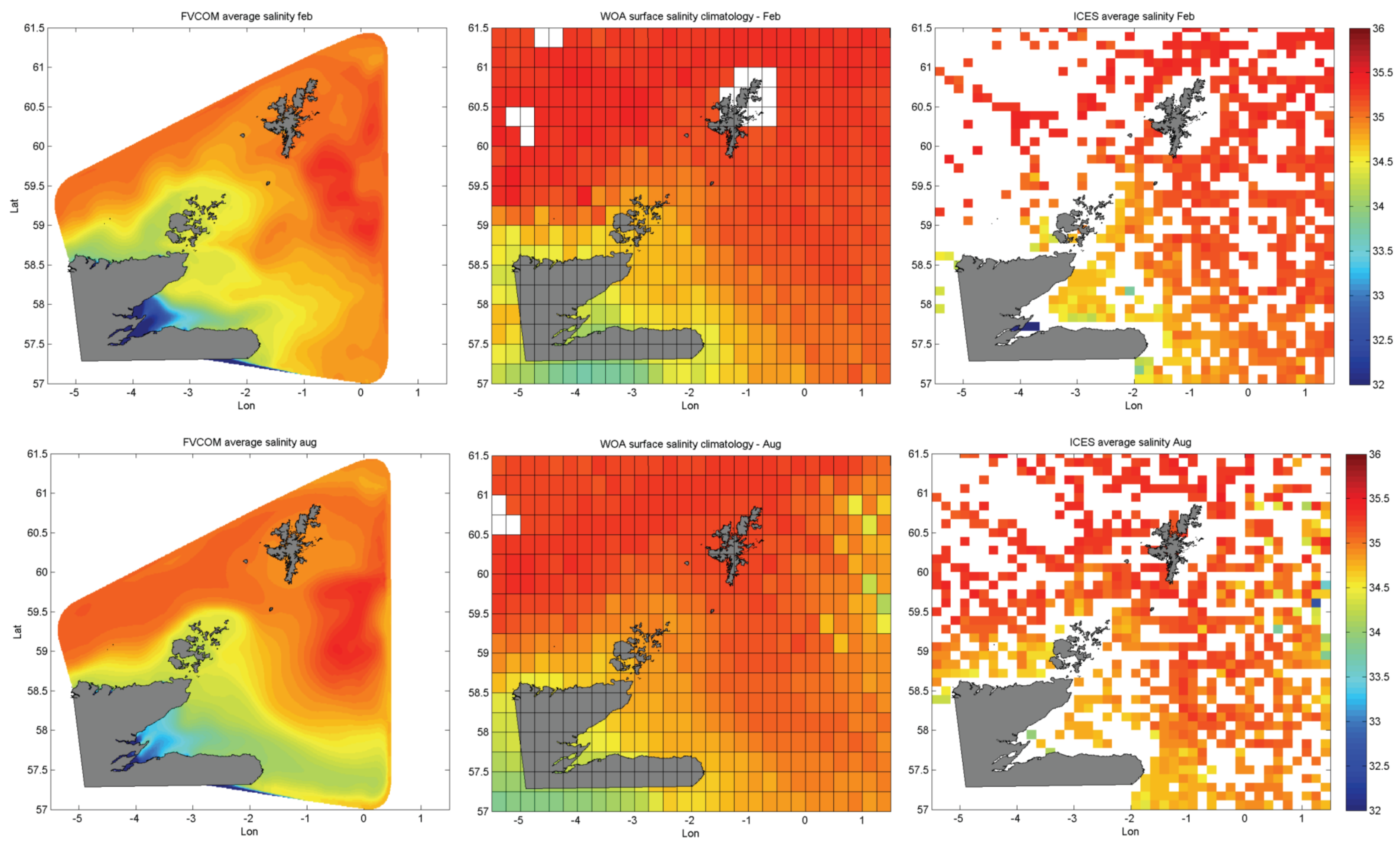
Mean residual currents are shown in Figure 3-19 for February and August. The residual currents from the Shelf model and data from OSPAR (2000) and Holt and Proctor (2008) are presented for comparison in Figure 3-20 and Figure 3-21 respectively. These show general agreement for the magnitude and patterns of the residual circulation.

3.5.7 Summary

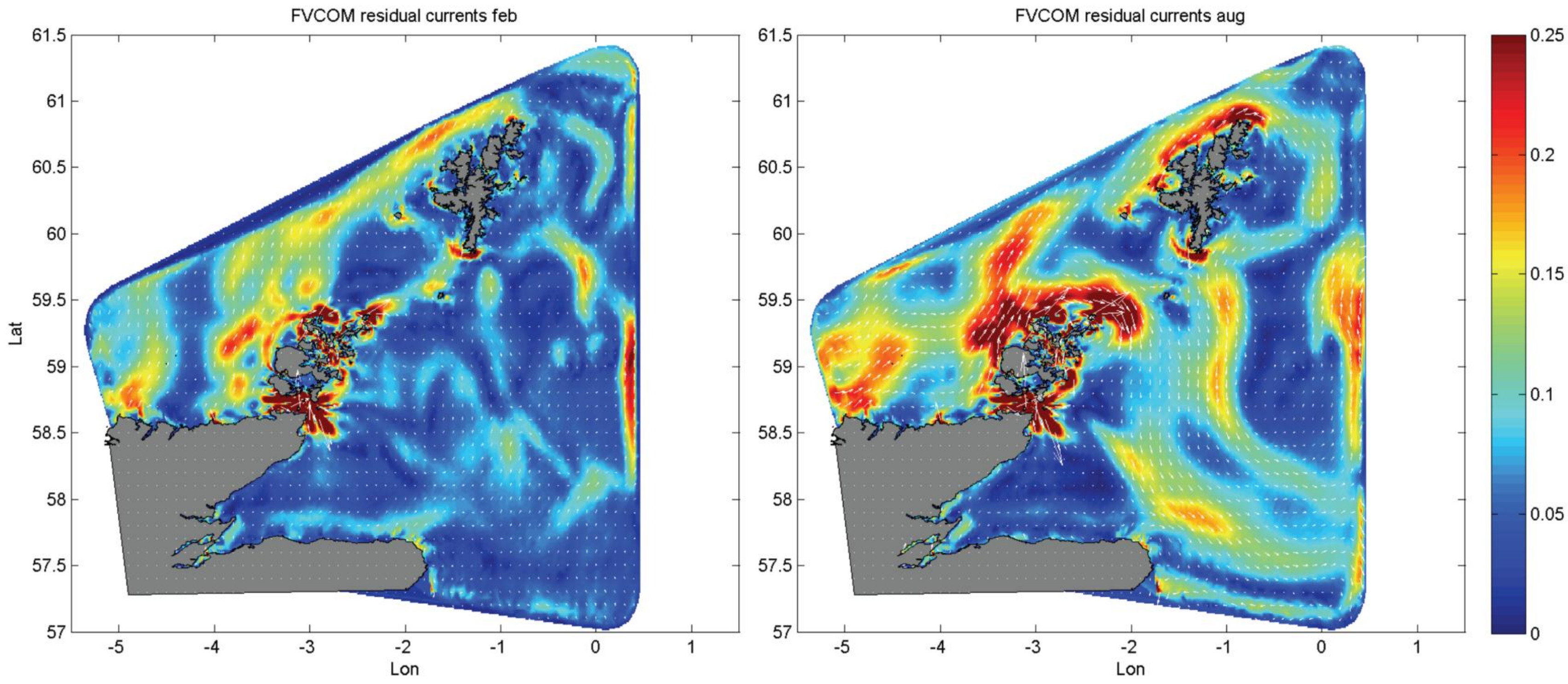
Section 3.5 describes the climatology run for the PFOW model. The input data used was taken from the Shelf Model for boundary conditions, CEH for rivers and ECMWF averaged data for the meteorological forcing. The model was run for one year the results have been compared with sea surface temperature and salinity climatological data sets and residual currents for the months of February and August. These results compared well with the available data.



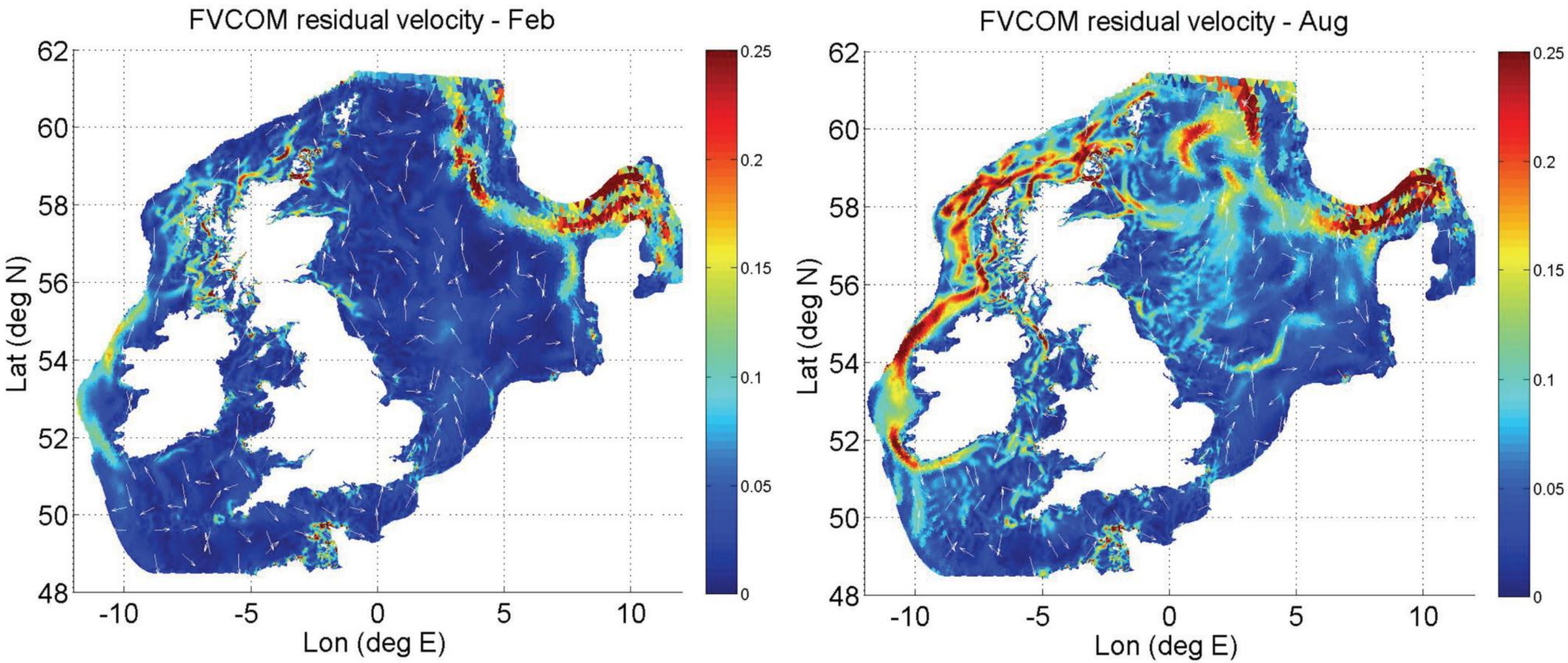
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of sea surface temperature averaged for February and August from the climatology run, WOA and ICES data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



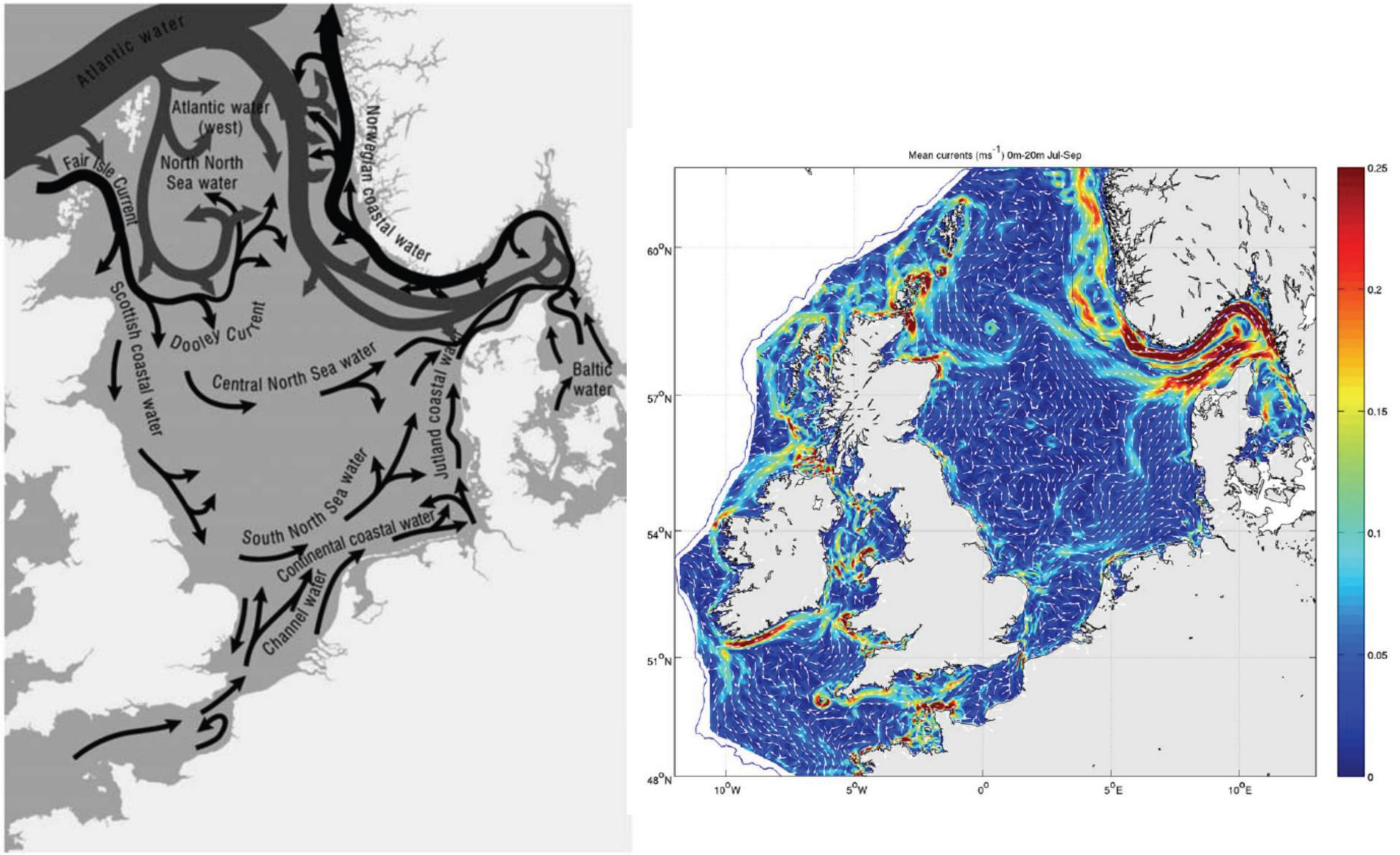
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18		
Marine Scotland		Pentland Firth and Orkney Waters Model	Comparison of sea surface salinity averaged for February and August from the climatology run, WOA and ICES data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-19		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Residual currents for February and August from the climatology run of the PFOW model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-20		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Residual currents from the shelf model climatology run (a) February (b) August	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-21		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	(a) Canonical circulation on NW European shelf (from OSPAR 2000) (b) Results from Holt and Proctor (2008), July-September	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

4 Wave Model Development

4.1 Introduction

The objective of the wave modelling study is to construct a calibrated and validated wave model for the Pentland Firth and Orkney Waters (PFOW) using the fully spectral wave model, FVCOM-SWAVE. Furthermore, the wave model is used to carry out one-year long simulation for mapping available wave energy resources in the PFOW model area.

Originally, the one year simulation was to be carried out using idealised forcing. After discussions with Marine Scotland (MS), it was agreed that the one-year simulation be carried out for the year that best represents the average year from the available dataset. This year is referred to as the representative year.

The remainder of this section of the report is organised as follows. A description of the wave model setup is given in Section 4.2, followed by the wave model calibration in Section 4.3. The analyses carried out to determine the representative year is presented in Section 4.4 together with key simulation results from one-year simulation. Lastly, the conclusions from this study are presented in Section 4.5.

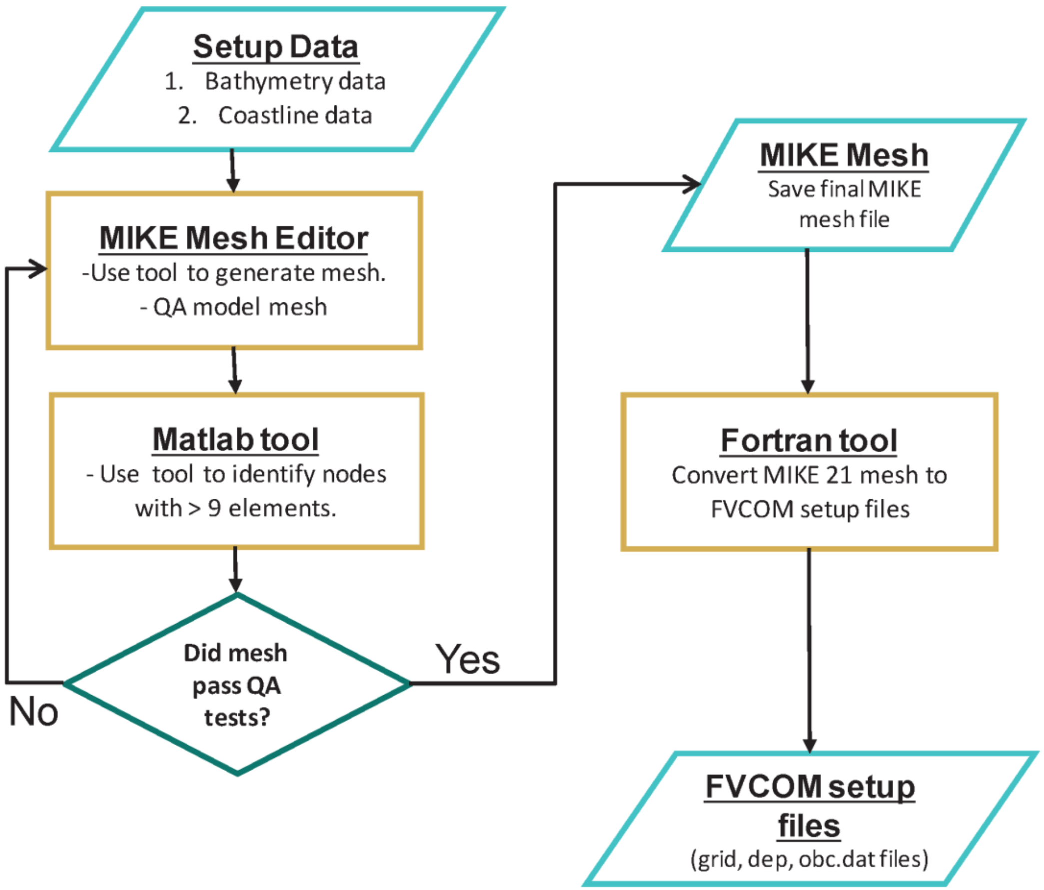
4.2 PFOW wave model setup

FVCOM-SWAVE is an unstructured-grid finite-volume spectral wave model, developed by implementing finite-volume algorithms within SWAN (Qi et al, 2009).

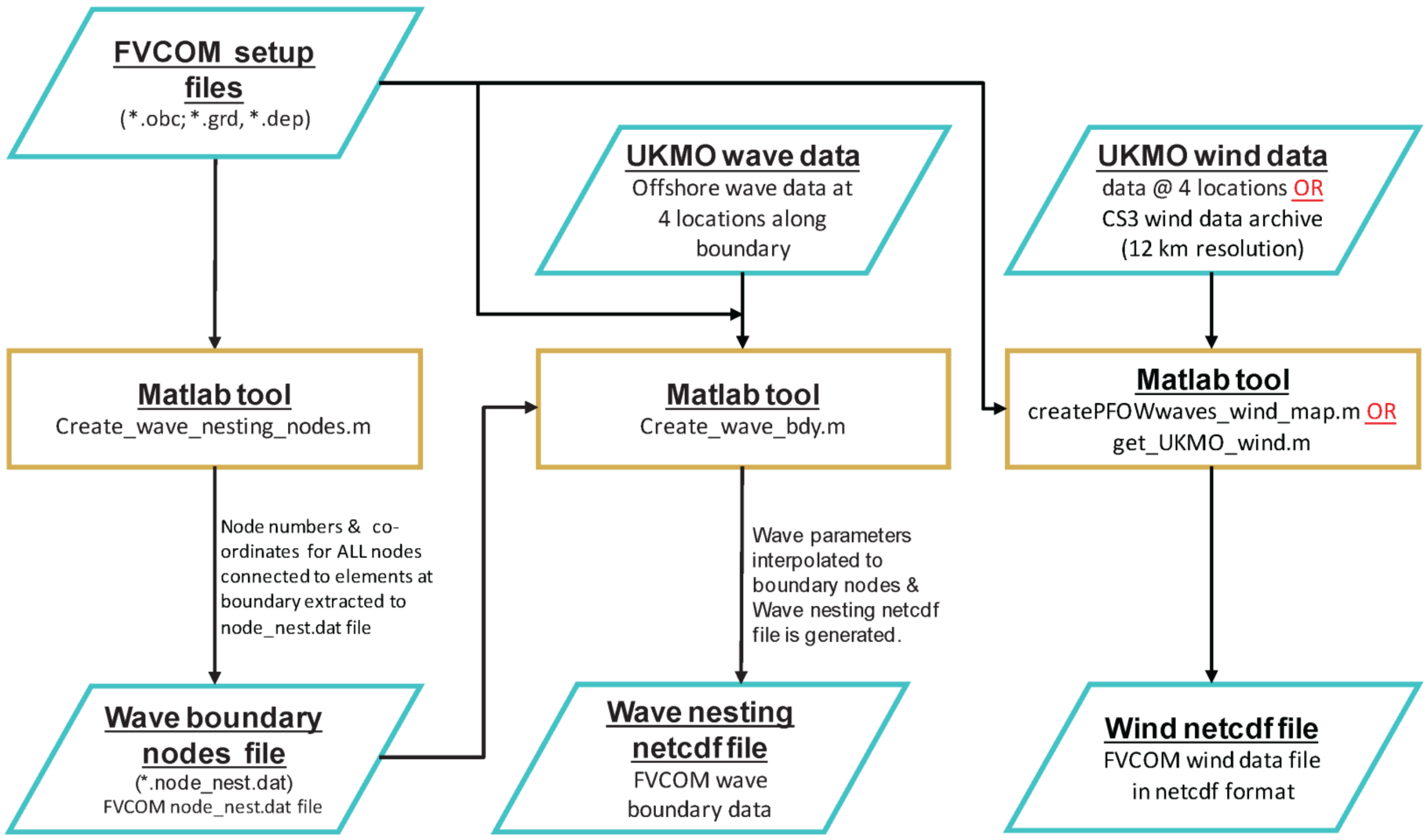
SWAN (Simulating WAves Nearshore) is the third-generation spectral wave model developed originally by Booij et al. (1999) and improved through a team effort (SWAN Team, 2006a). The model solves the wave action balance equation and takes into account the effects of refraction and shoaling due to varying depth, diffraction, local wind-wave generation, nonlinear wave-wave interaction, wave-current interaction and energy dissipation due to bottom friction and wave breaking. The model is used to simulate local wind-wave generation and the transformation of offshore waves into shallow waters.

Since FVCOM-SWAVE is an unstructured grid implementation of SWAN, it includes all the key processes included in SWAN, with the added flexibility of using an unstructured grid (mesh). This provides the user the flexibility to use coarser meshes away from the area of interest and gradually increase the mesh resolution towards the coastline or specific areas of interest.

Schematic block flow diagram for preparing the required model setup files are shown in Figure 4-1 and 4-2. The steps in these figures are discussed in the sub-sections below.



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-1		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Block Flow diagram for preparing the FVCOM setup files.	Checked ..	Scale Not to scale	Rev. 0
				Designed HKJ	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-2		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Block Flow diagram for generating boundary wave data and wind data for FVCOM model.	Checked ..	Scale Not to scale	Rev. 0
				Designed HKJ	Drawn	Date 26/02/2014

4.2.1 Model mesh

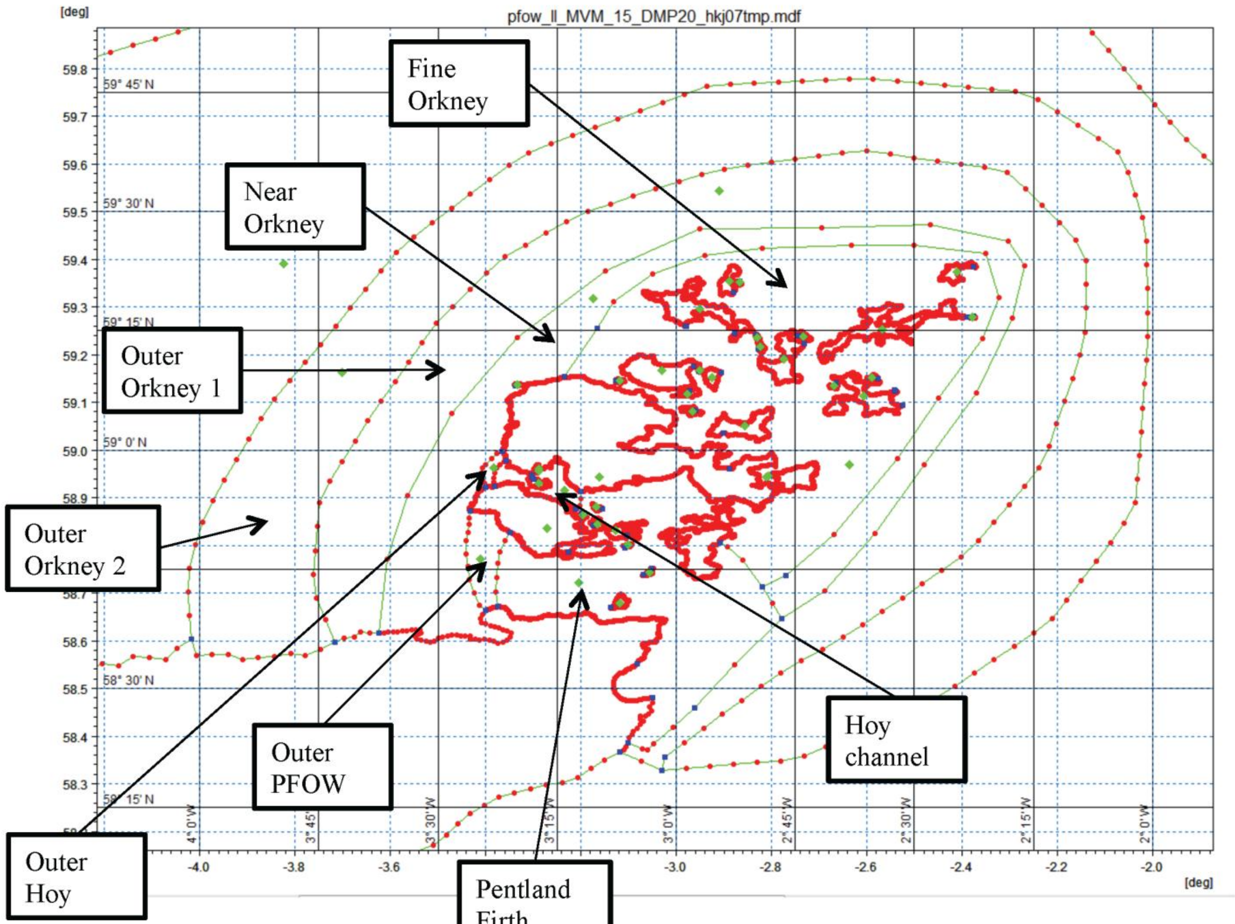
The model area covered by the wave model is identical to the model area covered by the hydrodynamic model (discussed in Section 3). The initial consideration was to use the same mesh as that developed for the hydrodynamic model for the wave modelling task. However, initial tests showed that this leads to unrealistic computational times using the available IT resources (Dell R815 with 64 processor cores). For an illustration, the hydrodynamic model mesh (at the time of evaluation) has 85,840 nodes (161,141 cells). With the wave energy spectrum divided into 25 discrete frequencies and 24 discrete directions, the wave model simulation (excluding any coupled wave-current interaction) is estimated to take 13 hours for every 24 hr simulation period (using 30 cores on the Dell R815). This is considered unrealistic, and a new model mesh was constructed for the wave model.

The wave model mesh has been created using DHI's MIKE 21 mesh generator tool (described in Section 3.2.1). The horizontal coordinate system used is latitude and longitude with a vertical datum of mean sea level.

The bathymetry and coastline data used are the same as described in Section 3.2.1. These data are loaded into the mesh generator tool (Figure 4-1) and the tool used to generate triangular meshes throughout the model area. The mesh resolution in different areas have been varied by specifying maximum element area sizes in various polygons, see Figure 4-3. In order to improve the computational time for the wave model, the following modifications were made in generating the mesh:

- All islands in the open sea with length scale < 1km are deleted. These islands usually require high resolution to resolve the island boundary, and this forces the mesh to have very dense meshes in the immediate vicinity of the island.
- The resolution used to describe the boundary of the polygons and the coastlines were modified as shown in Table 4-1.

The indicative mesh sizes for the different polygons are shown in Table 4-1. The highest resolution is in the Pentland Firth and Orkney waters, where the resolution is typically about 250m to 500m.



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-3		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Examples of polygons used for generating the wave model mesh in the MIKE 21 mesh generator tool.	Checked ..	Scale Not to scale	Rev. 0
				Designed HKJ	Drawn	Date 26/02/2014

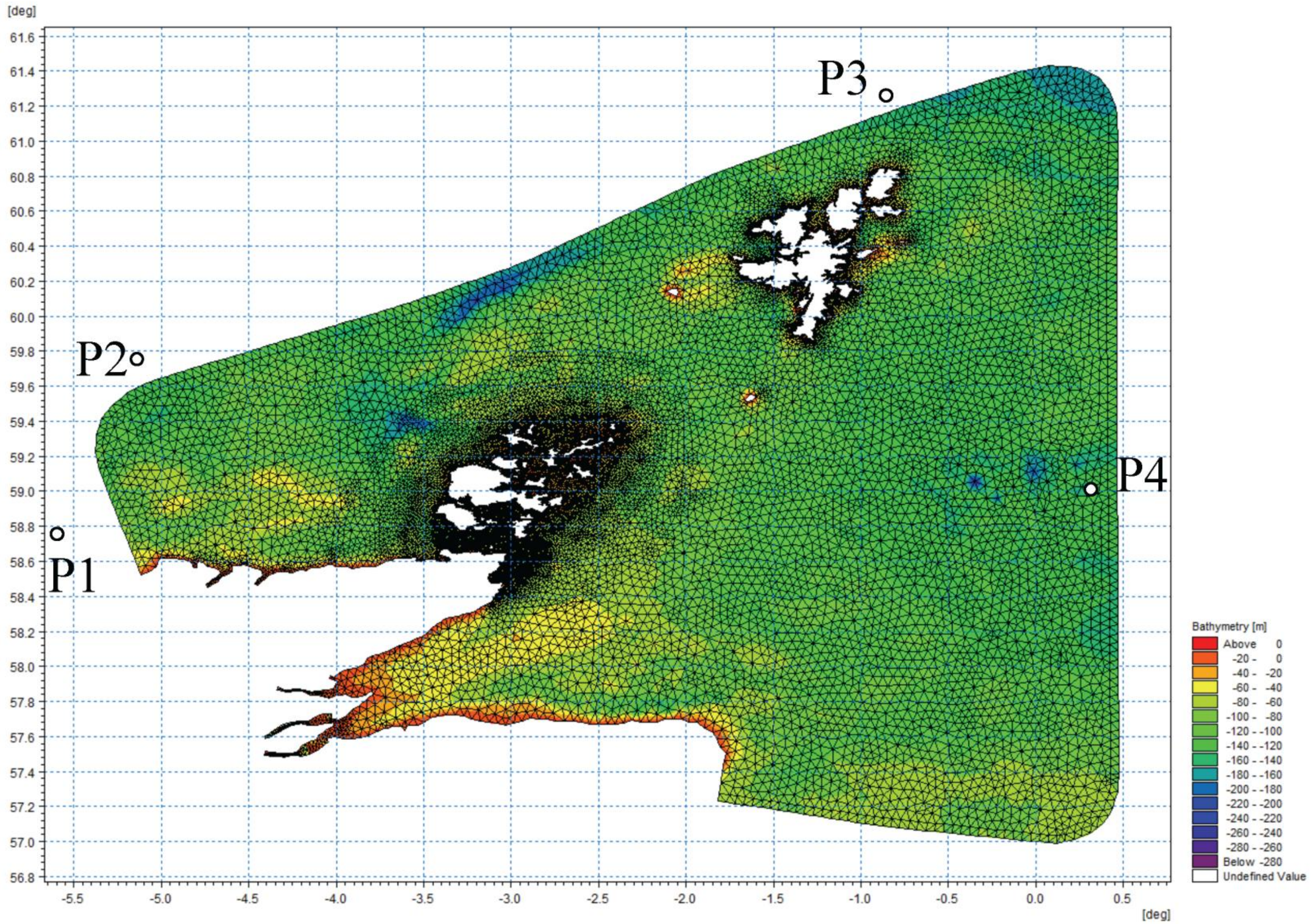
TABLE 4-1 MESH RESOLUTION IN THE FVCOM-SWAVE MODEL FOR PFOW.

Polygon	Resolution (deg) along polygon / shoreline	Max element area (deg^2)	Indicative resolution (km)
Outer	0.1 / 0.050	20E-04	5.00
Shetland	0.1 / 0.050	15E-04	4.00
Orkney 2	0.1 / 0.035	10E-04	3.50
Orkney 1	0.1 / 0.020	5.0E-04	2.00
Near Orkney	0.1 / 0.010	2.5E-04	1.00
Fine Orkney	0.1 / 0.005	1.2E-04	0.50
Outer Hoy	0.1 / 0.005	1.2E-04	0.50
Hoy channel	0.1 / 0.005	0.8E-04	0.50
Outer PFOW	0.1 / 0.005	0.8E-04	0.50
PF	0.1 / 0.005	0.5E-04	0.25

The process for generating the mesh is an iterative process as schematised in Figure 4-1. The iterative process is used to ensure that the model mesh complies with the FVCOM-SWAVE model mesh requirements. These are:

- The number of elements connected to any mesh node should not exceed 8.
- The areas of the mesh should vary smoothly (not more than a factor of 2 to 3) throughout the model area.
- The mesh triangles should not have angles that are too acute (less than 30^o).

Experience has shown that the model is especially sensitive to violation of the first two constraints, as this typically results in early development of model instabilities or the model not running. The PFOW wave model mesh is shown in Figure 4-4.



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-4		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Model mesh and digitised bathymetry for FVCOM-SWAVE model.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.2.2 Model bathymetry

The bathymetry data used for the wave model is the same as used for the hydrodynamic model (see Section 3.2.2). The bathymetry data consists of the following datasets in order of priority: a) UKHO (United Kingdom Hydrographic Office) and Marine Scotland datasets; b) EMODnet/NOOS datasets; and c) digitised bathymetry data from Admiralty Charts. Further details are given in Section 3.2.2.

The bathymetry data was interpolated onto the model mesh to create the digitised model bathymetry. The digitised model bathymetry is shown in Figure 4-4. The mesh file produced by the MIKE 21 tool includes information about the mesh (node co-ordinates and element connectivity), bathymetry (depths at all nodes) and special markers for open boundary nodes. This file is used as input file to a FORTRAN tool that generates the required FVCOM setup files for describing the mesh (grid file), the bathymetry (dep file) and the nodes along the open boundary (obc file).

4.2.3 Boundary wave data

Wave data are obtained from the UK Met office (UKMO) under a licence agreement with Marine Scotland, at locations P1 to P4 (see Figure 4-4). The wave data cover a 13-year period, from January 2000 until December 2012. The data is from three UKMO wave hindcast models, namely: a) European model for the period 01/2000 – 03/2000; b) UK Waters model for 03/2000 – 11/2008; and c) WaveWatch III (WW III) model for 1/2008 – 12/2012.

The wave data is in the form of 3-hourly time series of wave parameters (wave height, period and direction) for swell component, wind-wave component and the resultant (combined swell and wind-waves). The model was forced using the resultant wave parameters. The two dimensional energy spectrum was specified by imposing JONSWAP frequency spectrum (peakedness parameter, Gamma =3.3) and cos^5 directional distribution function.

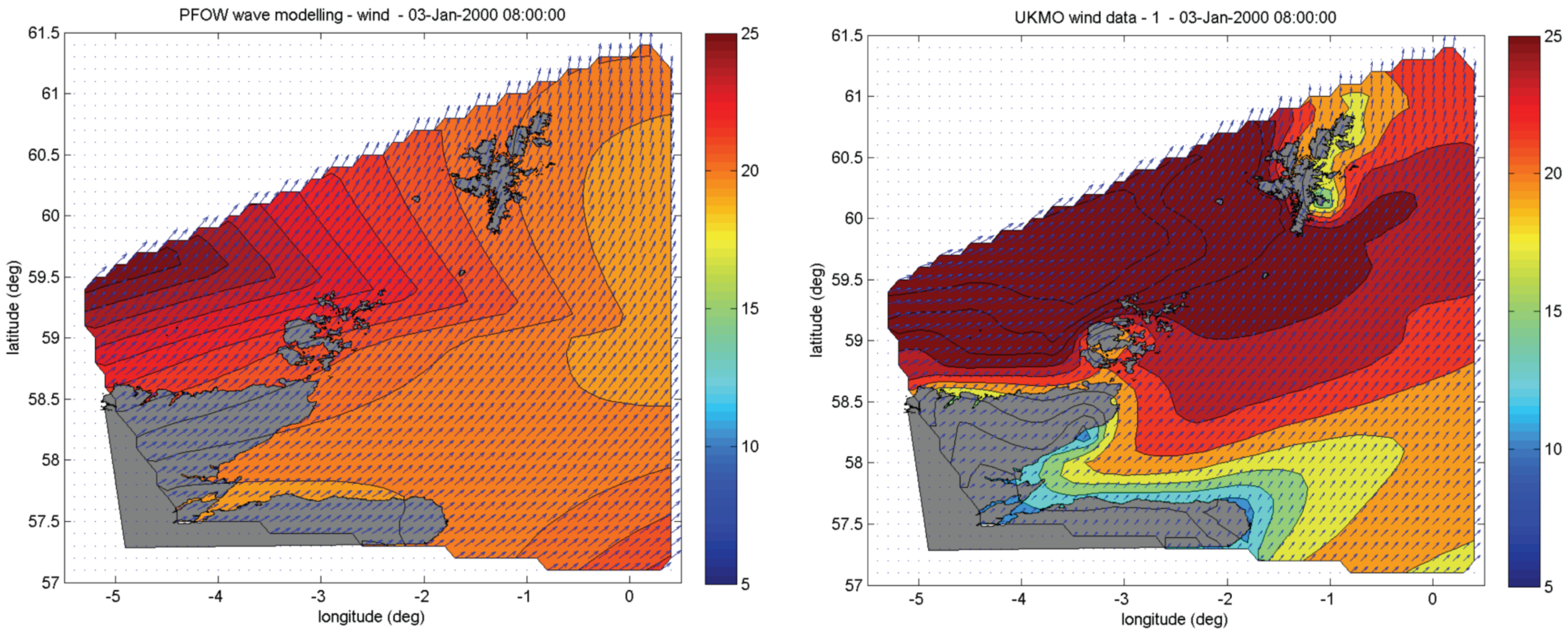
The wave data at P1 to P4 are interpolated along the boundary of the wave model (*note that the wave parameters should be interpolated to all nodes connected to elements located along the model boundary*) to create an FVCOM wave nesting file. This file is used to specify the wave conditions along the boundary of the model. A block flow chart illustrating how the wave boundary data file is derived is shown in Figure 4-2.

4.2.4 Wind data

Two sources of wind data were available for this study. These are:

- Wind data (hourly averaged wind speed and direction) provided by UKMO at locations P1 to P4. The wind data cover the same period as the wave data and are available as 3-hourly time series data. This dataset is hereafter called 4-pt wind data.
- Hourly wind fields from the UKMO (UK Met Office) forecast models that have been archived at NOC-L . This dataset have been presented in Section 2.3.2.1. The relevant dataset for the wave study is the post-1995 surface wind data, which is available at 12km resolution. This dataset is hereafter called the 12km wind data.

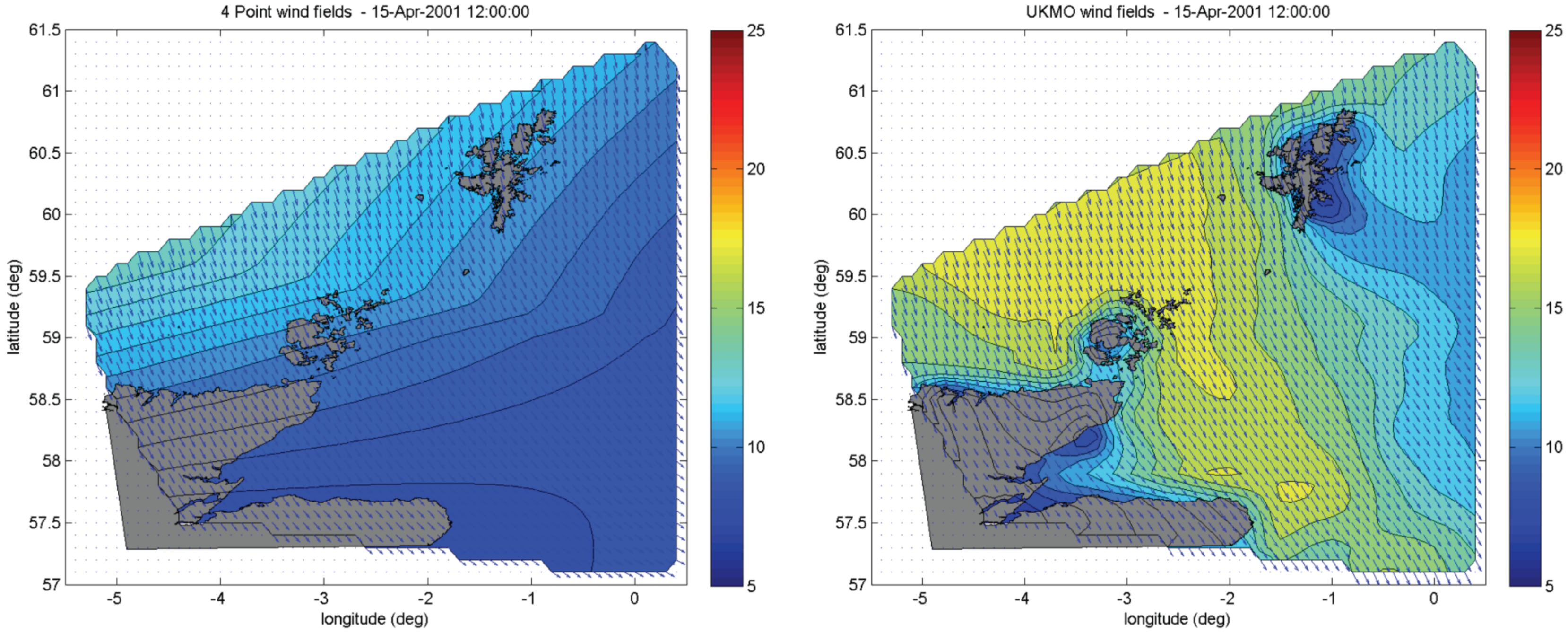
In order to use these data for the wave simulation, the wind data for the selected simulation periods are interpolated onto the FVCOM grid using Matlab scripts (see Figure 4-2). Example comparisons of the interpolated wind fields using the 4-pt wind data and the 12km wind data are shown in Figure 4-5 (peak of storm on 3-Jan-2000), Figure 4-6 (peak of storm on 11-Apr-2001), and Figure 4-7 (peak of storm on 9-Jan-2004). These figures show that the broad features of the wind fields are reproduced in the 4-point data; however, the 4-point data omit a number of details that are seen in the 12km wind data.



Wind field interpolated from 4-point dataset

Wind field interpolated from 12-km UKMO dataset

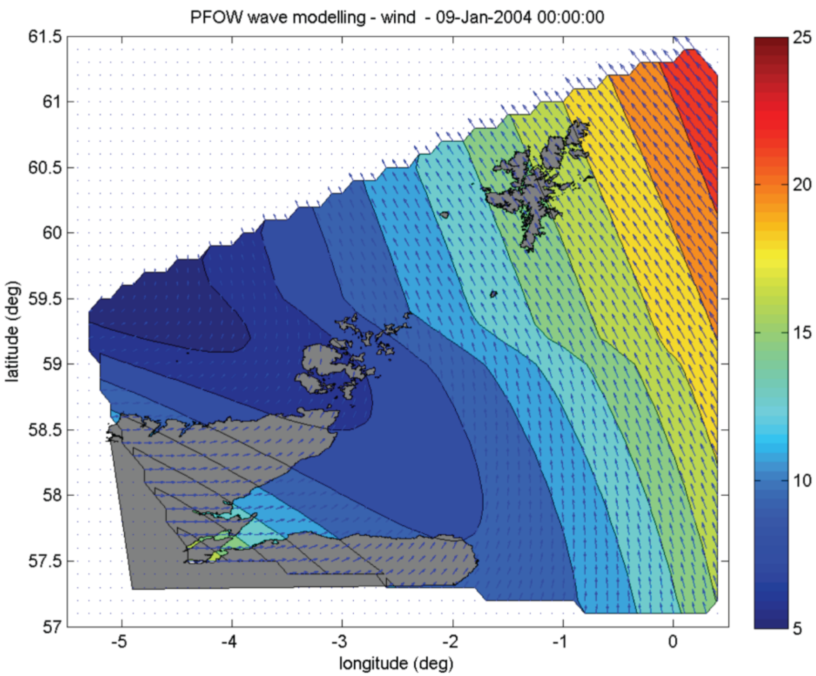
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-5		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of wind fields interpolated from UKMO 4-point data and 12km UKMO wind data obtained from NOC-L archive. Wind data at peak of storm on 3-Jan-2000	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



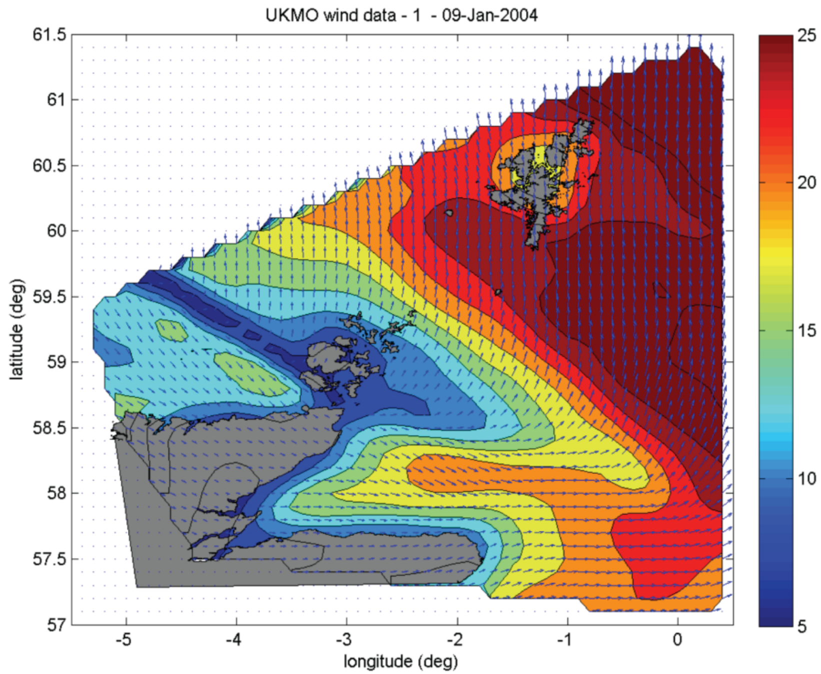
Wind field interpolated from 4-point dataset

Wind field interpolated from 12-km UKMO dataset

Client	Consulting Engineer	Project:	Figure Title:	Figure 4-6		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of wind fields interpolated from UKMO 4-point data and 12km UKMO wind data obtained from NOC-L archive. Wind data at peak of storm on 15-Apr-2001	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Wind field interpolated from 4-point dataset



Wind field interpolated from 12-km UKMO dataset

Client	Consulting Engineer	Project:	Figure Title:	Figure 4-7		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of wind fields interpolated from UKMO 4-point data and 12km UKMO wind data obtained from NOC-L archive. Wind data at peak of storm on 9-Jan-2004	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.3 Wave Model calibration

Model calibration is a procedure where the following tasks are undertaken:

- Numerical model is run with selected model parameters
- Model results are compared with measurements (in the area of interest) to check if the agreement between the model results and measurements is acceptable. Relevant model parameters are adjusted and the model re-run.
- The preceding step is repeated until acceptable agreement between the model results and measurements is achieved. When this is achieved, the model is considered to be calibrated.

In order to carry out model calibration, the following information is required: a) measured wave data, and b) target quality measure/s for quantifying and accepting the level of agreement between model results and measurements.

4.3.1 Wave calibration data

Measured wave data that can be used as calibration data are available at the three locations shown in Figure 4-8 and Table 4-2.

TABLE 4-2 CALIBRATION DATA USED FOR WAVE MODELLING

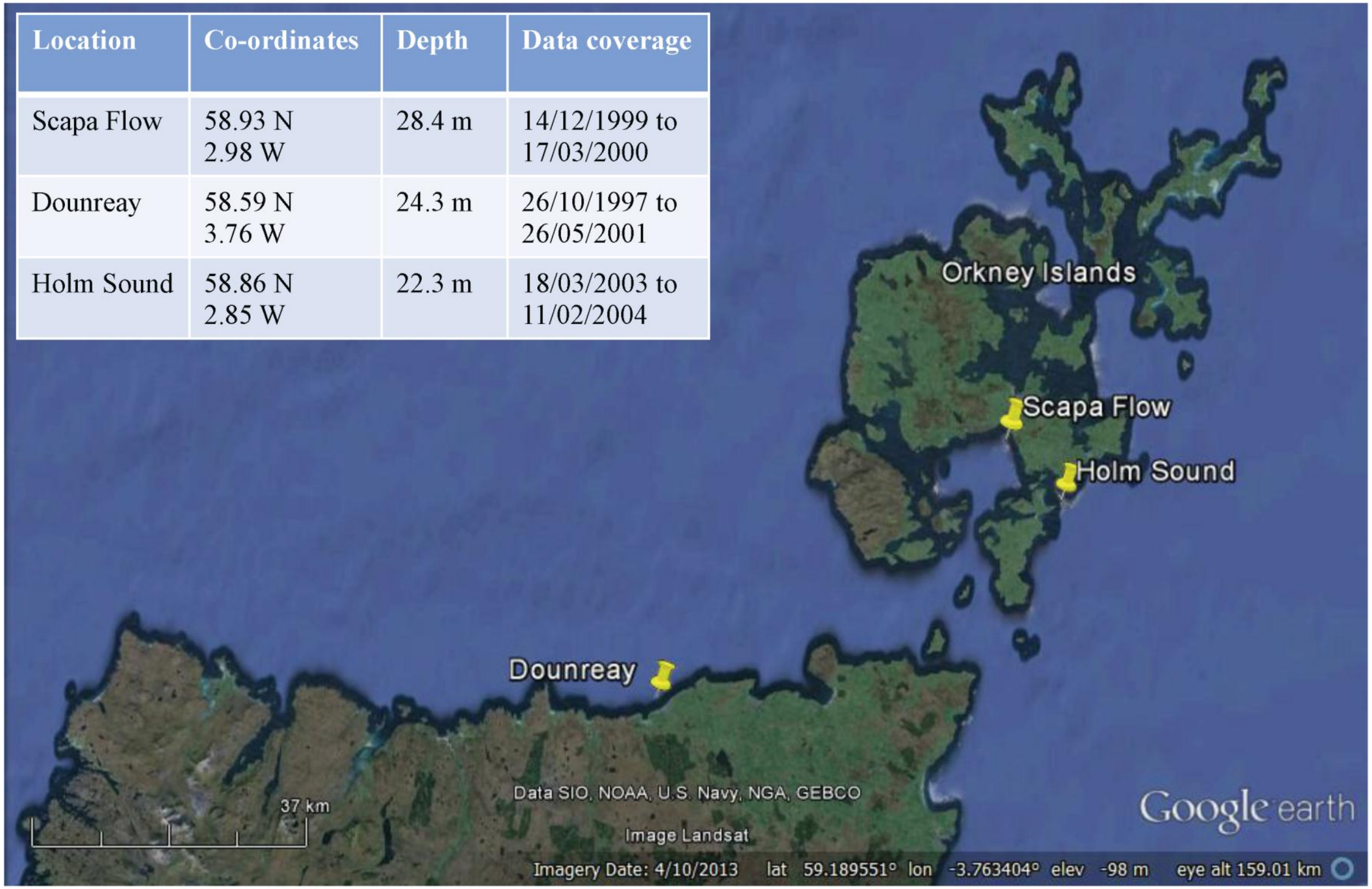
Location	Co-ordinates	Water depth (m)	Data coverage
Scapa Flow	58.93 N, 2.98 W	28.4 m	14/12/1999 to 17/03/2000
Dounreay	58.59 N, 3.76 W	24.3 m	26/10/1997 to 26/05/2001
Holm Sound	58.86 N, 2.85 W	22.3 m	18/03/2003 to 11/02/2004

4.3.2 Wave calibration targets

In a publication by ECMWF, (―The Wave Model", http://www.ecmwf.int/en/learning/education-material/lecture-notes, slide 114), the modelled wave data was compared with buoy measurements for the period February to April 2002. The root mean square error (RMS error) for wave height was calculated as 0.44m, and the corresponding scatter index (SI = RMS error/mean of the measured data) is about 18%. The RMS error for peak wave period was 1.75s and the SI was 19%.

Lawrence et al (2009) carried out calibration of the MIKE 21 SW wave model at a location near the Orkney Islands. They described agreement between the modelled and measured wave height with a SI of 12% as "exceptionally good results" using improved wind forcing. The OWI wind forcing that was initially used gives SI of 18% for November 2005. This is still considered good. No quality metric was provided about the agreement with wave period or wave direction. Based on experience at Halcrow, the agreement between measured and modelled wave height is usually considered good if the RMS error is less than 0.3m or the scatter index is less than 20%. However, this is not always achievable depending on the accuracy of the best available boundary wave data and wind data. In such cases, the target is to get the best quality measure that can be realistically achieved.

Location	Co-ordinates	Depth	Data coverage
Scapa Flow	58.93 N 2.98 W	28.4 m	14/12/1999 to 17/03/2000
Dounreay	58.59 N 3.76 W	24.3 m	26/10/1997 to 26/05/2001
Holm Sound	58.86 N 2.85 W	22.3 m	18/03/2003 to 11/02/2004



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-8		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Locations of measured data used for wave model calibration	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.3.4 Model parameters

The parameters used in the model simulations are summarised in Table 4-3.

TABLE 4-3 WAVE MODEL SETUP PARAMETERS

Parameter	Value
Software:	FVCOM v3.1.6 (latest FVCOM, released in August 2013).
Spatial grid:	PFwv07, spherical grid co-ordinates (lon/lat); 23,508 nodes; 41,666 cells
Frequency grid:	JONSWAP shape, f_low= 0.05; f_high = 0.5, No of frequencies = 24
Direction grid:	Cos^5 spreading, D_low= 0; D_high = 360, No of discrete directions =24
Forcings:	Boundary waves: Varies (depending on the simulation) Wind conditions: Varies (depending on the simulation)
Water level:	0.0m (i.e. MSL)
Model physics	Wind Generation: GEN=3, GROWTH=KOM/JANS, AGROW=F Bottom Friction: Jonswap formulation, Cfjon=0.067 Whitecapping: WCAP= varies (Komen & Janssen – KOM/JANS) Wave breaking: alpha=1, gamma=0.73 (Battjes & Janssen) Wave-wave interaction: Quadruplet wave interaction
Time steps:	Flow part: OFF in Waves ONLY run, but should be specified External timestep = 1s; ISPLIT= 6 Waves part: Propagation: NS_DELTC = 12.0s Source terms: DTMIN = 1.0, DTMAX = 12.0s
Others:	Minimum water depth = 1.0m Nautical=True PWTAIL=4 (Non-diagnostic high frequency tail)

The following parameters are used as calibration parameters:

1. Wind-wave generation source term.
   This term controls the rate at wind adds energy to the growing waves in the model. It is particularly important in areas where waves are dominated by locally generated wind waves. Different formulations are available for this term in FVCOM-SWAVE. For

this study, we have investigated: 1) Janssen formulation and 2) Komen formulation.

2. Whitecapping source term.
   This term controls the rate at which energy is dissipated in the waves due to whitecapping (waves becoming too steep leading to wave breaking and whitecapping). Different formulations are available for this term in FVCOM-SWAVE. For this study, we have investigated: 1) Janssen formulation and 2) Komen formulation.

3. Bottom friction.
   This term controls the rate at which energy is dissipated in the waves due to the effect of bottom friction. This is mainly important in shallow and intermediate waters. It is not important in deep water as the waves do not feel the bottom. Different formulations are available for this term in FVCOM-SWAVE, and the effect can also be controlled by the bed roughness parameter (or bottom friction coefficient).

4. Wind data.
   Various studies have shown that the adequacy of the wind data is one of the most important parameters for wave modelling. Two wind datasets are available for this study (4-point wind data and 12 km data). The latter is the most detailed wind information that is available.

4.3.5 Initial simulation runs

After completing the model setup, it was found that the model did not run (stopped with error messages) for the initial test runs. The following FVCOM files were modified in order to get the wave model to run using our installed version of Intel Fortran compiler:

- Mod_nctools.F
  This was modified to fix the error message: ―CAN NOT UPDATE TIME FOR INVALID FLOATING POINT TIME VARIABLE.”

  An alternative fix is to include:
  DATE_REFERENCE = ‗default‘ in the namelist file
- Swanmain.F
  This was modified to fix error message in subroutine SWINCO: VARS_WAVE: Name in only list does not exist [M, MT, N, NGL, NPROCS, MYID].

These variables are not defined explicitly in Module VARS_WAVE. However, they are defined in Module LIMS which is embedded in module ALL_VARS which is also used in this subroutine. The fix was to remove the ‗offending' variables from VARS_WAVE, ONLY list.

- Mod_nesting.F
  For building the FVCOM code, the file mod_nesting.F in FVCOM v3.1.6 is replaced with a new version provided by Dr J. Qi (from Prof Chen's group) in Nov 2013. He mentioned that this is required to keep the unit of time as default modified Julian Day (MJD).
- INPUT (specification file for SWAN):
  PWTAIL should be set to 4 or higher. Setting PWTAIL=3 triggers an error message: ―error tail computation"

After making these modifications, a number of initial simulations were carried out using constant wind forcing. The key lessons learnt from these simulations are summarised below:

- FVCOM v3.1.6 model was found to be more stable than earlier versions of FVCOM (that included a wave model).
- As expected, the wind wave growth in the model is quite sensitive to the wind formulation used.
- The instability in the model is removed by using a wave propagation time step (NS_DELTC) determined using the Courant condition:
  - $Cr = Cg_{max} * dt / dx \leq 1$
  - $dt \leq dx_{min} / Cg_{max}$
  - Using $f_{min} = 0.05$, $dx_{min} = 250m$, $dt \leq 16s$. In practice the time step used is lower than the maximum value.

4.3.6 Calibration runs

The wave model calibration runs were carried out for selected periods in January 2000, April 2001 and January 2004. The calibration was carried out using available wave measurements at Scapa Flow, Dounreay and Holm Sound.

The locations of the measurement data make it possible to investigate the adequacy of model description of a number of key physical processes in the study area, see Table 4-4.

TABLE 4-4 CHARACTERISTICS OF THE LOCATIONS WITH MEASURED DATA

Location	Site Characteristics	Processes checked in the model
Scapa Flow	Sheltered from offshore waves approaching from the North, West or East.	Local wind-wave generation
Dounreay	Located at an exposed location on the western approaches to the Pentland Firth.	Offshore wave propagation towards the western section of the Pentland Firth.
Holm Sound	Located at an exposed location on the eastern side of the Orkneys.	Offshore wave propagation from the North Sea towards the eastern coast of the Orkneys and the Pentland Firth.

Measured wave data in the Pentland Firth would have been useful for investigating the effect of wave-current interaction in the firth, as the current speeds are quite high in this area. However, we are not aware of any dataset in this area.

4.3.6.1 Jan 2000 simulation – Scapa Flow

The following model runs are carried out for selected periods in January 2000:

- Run 1: No wind
- Run 1A: 4-point wind; Janssen wind input; Janssen whitecapping
- Run 1D: 4-point wind; Komen wind input; Komen whitecapping

The modelled wave height for the ―No wind" case is less than 0.1m throughout the simulation. This is as expected, as this area is well sheltered from offshore waves.

The results with the 4-point wind data are generally similar, but the wave heights are slightly higher for the Komen formulation.

Initial simulations using the 12km wind were not successful (Run 1C, 1E, etc). It was found that the wind field (wind speed components) written into the wave output file is very different from the wind field in the input wind netcdf file. The problem was traced to errors in the matlab script used to prepare the wind netcdf file (a transpose error in the node connectivity variable written into the wind netcdf file plus a couple of additional errors in the file attributes). These errors were corrected and the 12km hourly wind field used for the calibration simulations. Table 4-5 provides a summary of investigations using the 12km wind field for calibration.

TABLE 4-5 MODEL RUNS WITH 12KM WIND FIELDS.

Run ID	Description	Remarks
01J	Wind data – 12km UKMO wind Wind input – Komen formulation Whitecapping – Komen formulation	Calculated wave heights are too low in Scapa Flow (<0.3m throughout 01-Jan-2000). Conclusion: Setup not considered viable.
01K	Wind data – 12km UKMO wind Wind input – Janssen formulation Whitecapping – Janssen formulation	The calculated wave heights were improved compared to Run 01J. However, the wave heights were still underestimated. The underestimation was about 50% at the peak of the storm (measured peak Hm0=3.2m, simulated peak Hm0=2.0m). Conclusion: Results are promising, but there is a need to increase wind forcing in the model. Alternatively, the whitecapping dissipation may need to be reduced.
01L	Wind data – 12km UKMO wind scaled by 1.2 Wind input – Komen formulation Whitecapping – Komen formulation	The calculated wave heights were significantly improved compared to Run 01K, see Figure 4-10b. Conclusion: Setup considered to be adequate.

The final setup makes use of the 12-km UKMO wind speeds multiplied by 1.2. This multiplication factor was found to be necessary in order to get reasonable agreement between the measured and modelled wave conditions at Scapa Flow. We consider that this factor adjusts the UKMO wind data from hourly averaged wind data (UKMO wind data is provided every hour) to wind data averaged over a shorter duration required in the numerical wave model (averaged duration that is consistent with the time step used in the integration of the wind-wave growth source terms). For example, Brown et al (2013) investigated the influence of wind variability at sub-hourly time scales in a numerical model and concluded that the inclusion of wind variability can lead to a difference in wave height of up to 35% compared to the use of 3-hourly wind data. This clearly suggest that if 3-hourly wind data is used, this should be multiplied by a factor (>1) in order to reproduce the correct wave heights. Resio and Westerink (2008) noted that ocean wave models use winds averaged over 10 to 30min, while CEM (2006, Part II, Chapter 2) suggests that the required wind averaging interval can vary depending on the size of the water body (1 to 5mins for small ponds, and 15 to 30mins for large lakes or oceans). For this study, the multiplication factor of 1.2 has been determined from calibration.

A summary of the calibration quality measures for selected runs is shown in Table 4-6. Only measured wave heights are available at Scapa Flow, hence no calibration measures are available for peak wave period and mean wave direction. Table 4-6 shows a very high negative bias for Run 1 (No wind). This is as expected, since the wave heights at Scapa Flow are dominated by the local wind. This is significantly improved by applying wind forcing to the simulation.

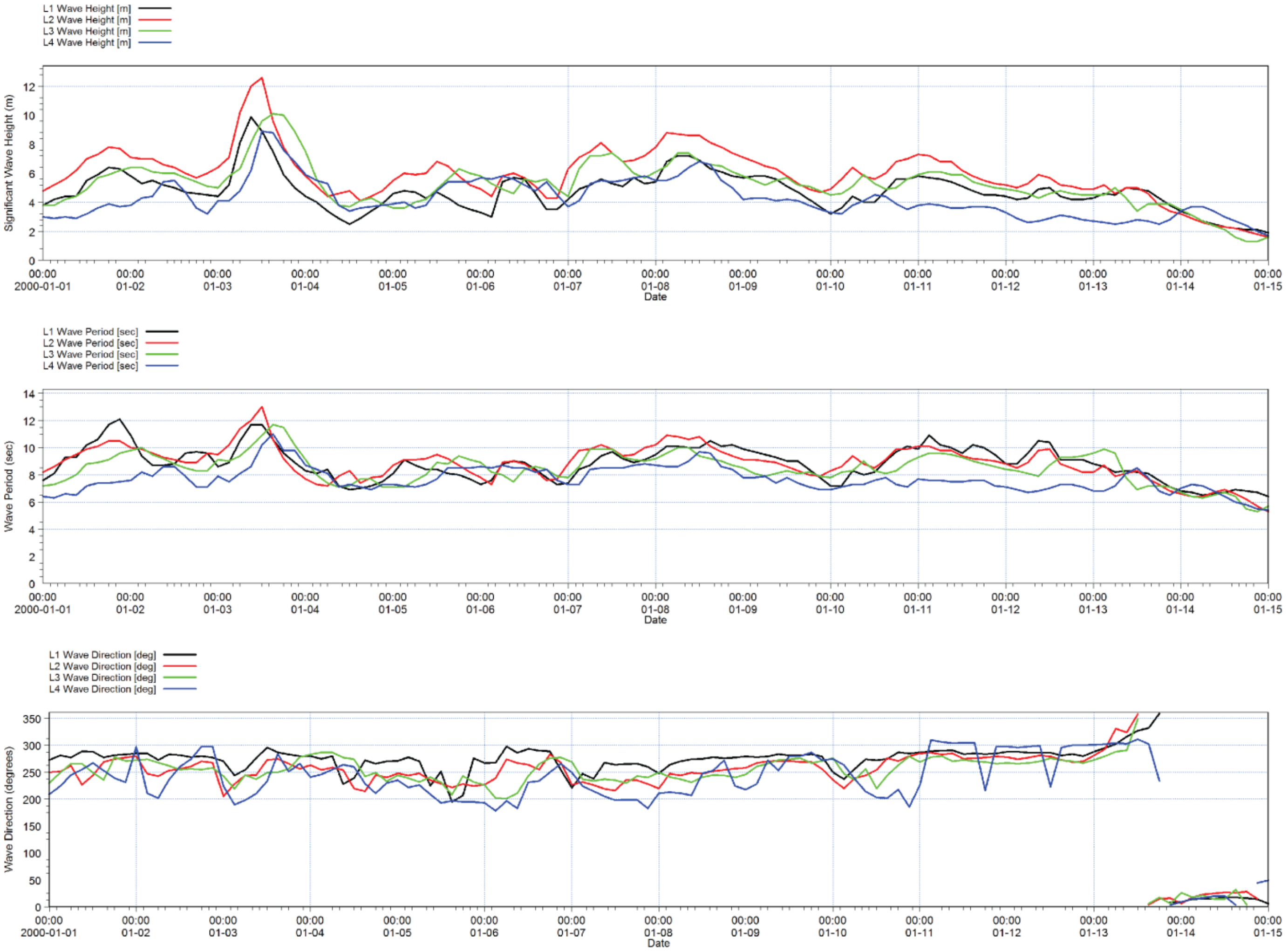
TABLE 4-6 MODEL QUALITY MEASURES AT SCAPA FLOW FOR 01 JAN - 14 JAN 2000 SIMULATION.

Simulation Quality indices	Run 1 No wind	Run 1A 4-point wind + Janssen wi + Janssen wc	Run 1D 4-point wind + Komen wi + Komen wc	Run 1L Scaled 12km wind + Janssen wi + Janssen wc
Hm0: Mean error, bias (m)	-0.80	-0.18	0.12	-0.26
Hm0: RMS error (m)	0.92	0.37	0.32	0.35
Hm0: SI (RMS/mean Hm0)	1.15	0.45	0.38	0.41
Hm0: Correlation coeff.	-1.0	0.78	0.77	0.87

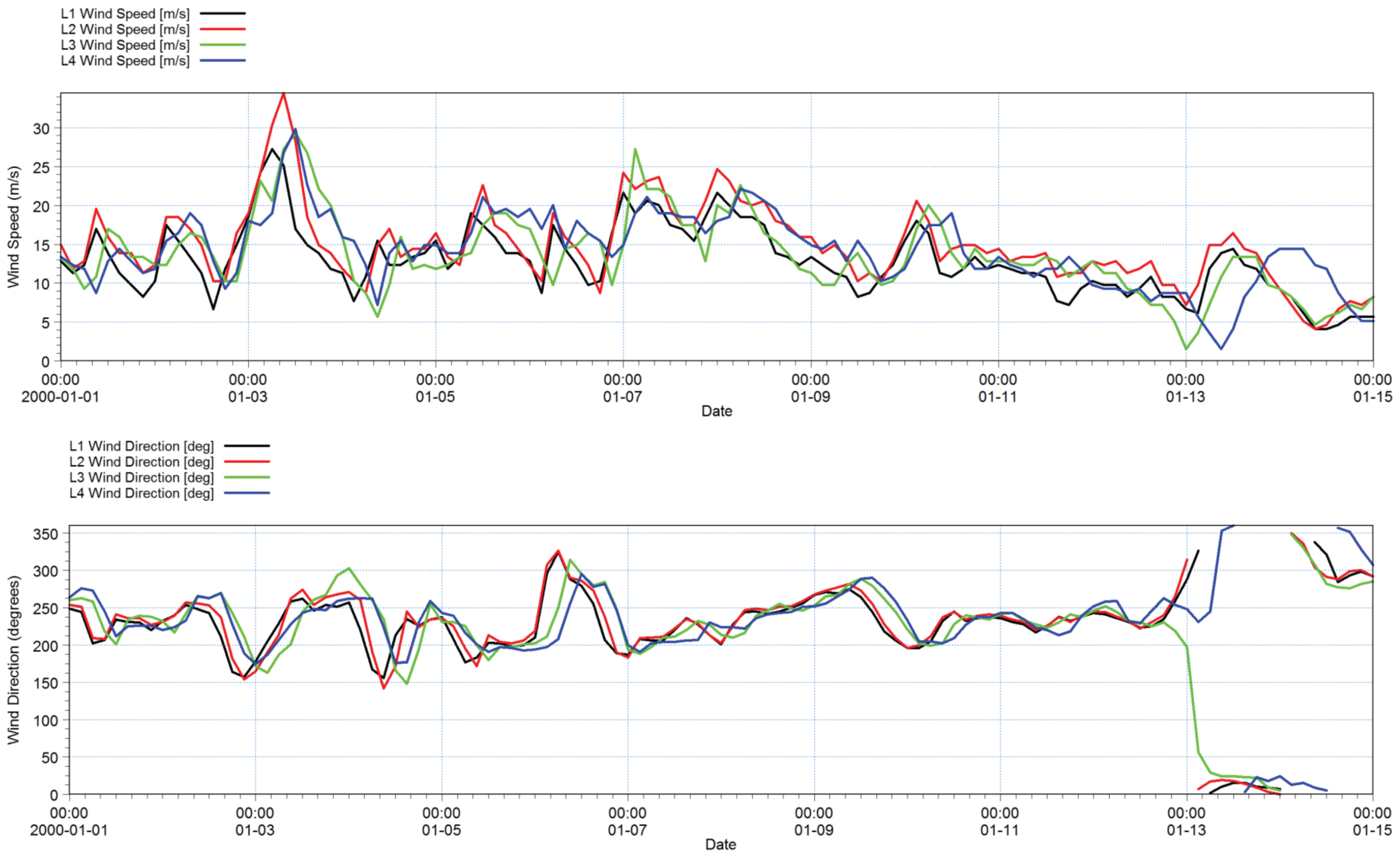
Time series of wave conditions during the simulated period at the 4 UKMO points are shown Figure 4-9a, while the time series of wind conditions are shown in Figure 4-9b. The modelled and measured wave conditions are shown in Figure 4-10a for the model setup with the smallest scatter index (Run 1D), and Figure 4-10b for the model setup with the highest correlation coefficient (Run 1L).

The largest storm during the simulation period occurred on 03 January, with offshore significant wave height of 9 to 12m, from SW to WNW sector. The corresponding maximum winds vary from 25 to 35m/s at the four locations. The observed peak wave height during the storm is about 3.3m, while the modelled peak wave height is under-estimated (just over 2.0m) for the 4-point wind data (Run 1D). On the other hand, the simulation with the 12-km wind (Run 1L) provides better agreement (peak wave height of about 3m) with the measurements (see Figure 4-10b). Overall, Run 1L is considered to provide the best agreement between the measured and predicted wave heights.

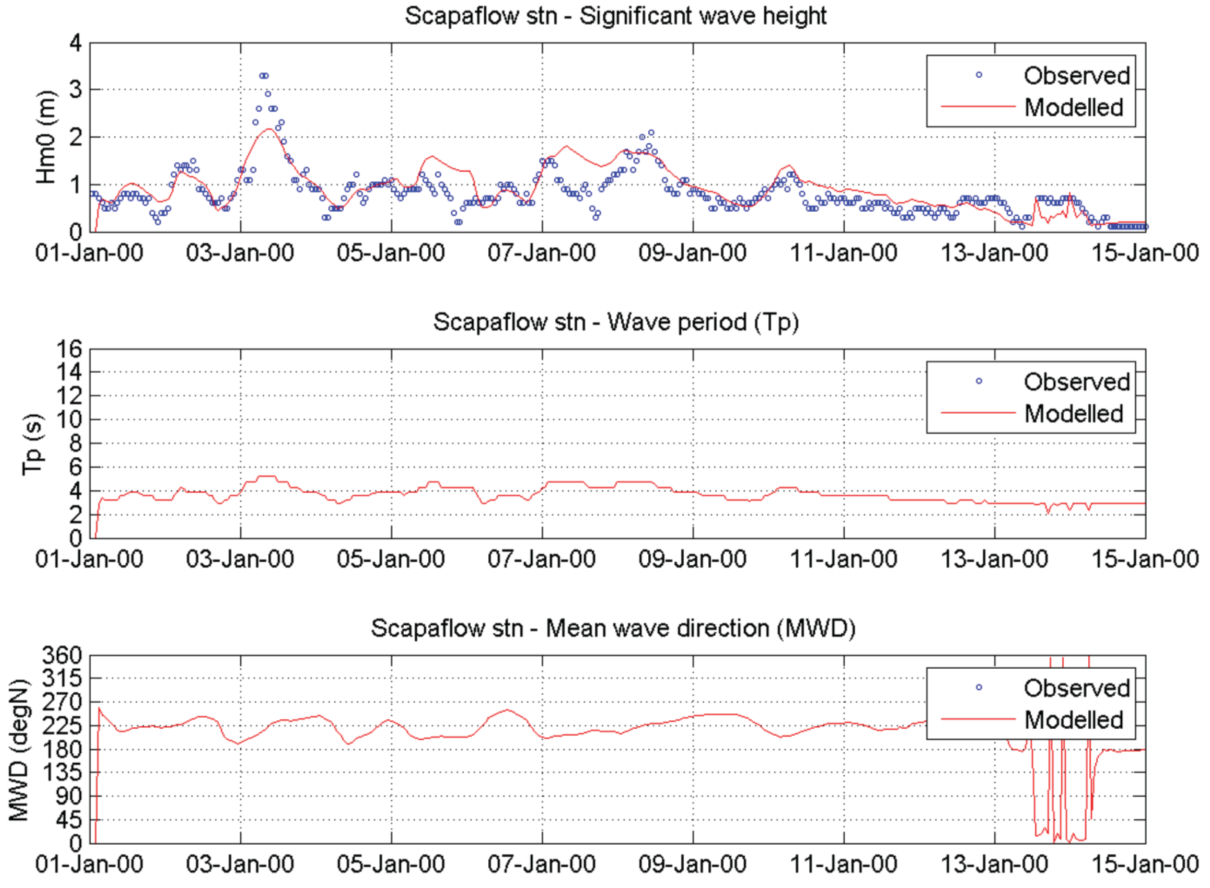
Figure 4-11 shows two-dimensional contours of significant wave heights and wave direction pattern (scaled with wave height) at the peak of the storm. The left panel shows the best result using the 4-point wind data, while the right panel shows the best result using the 12-km wind data.



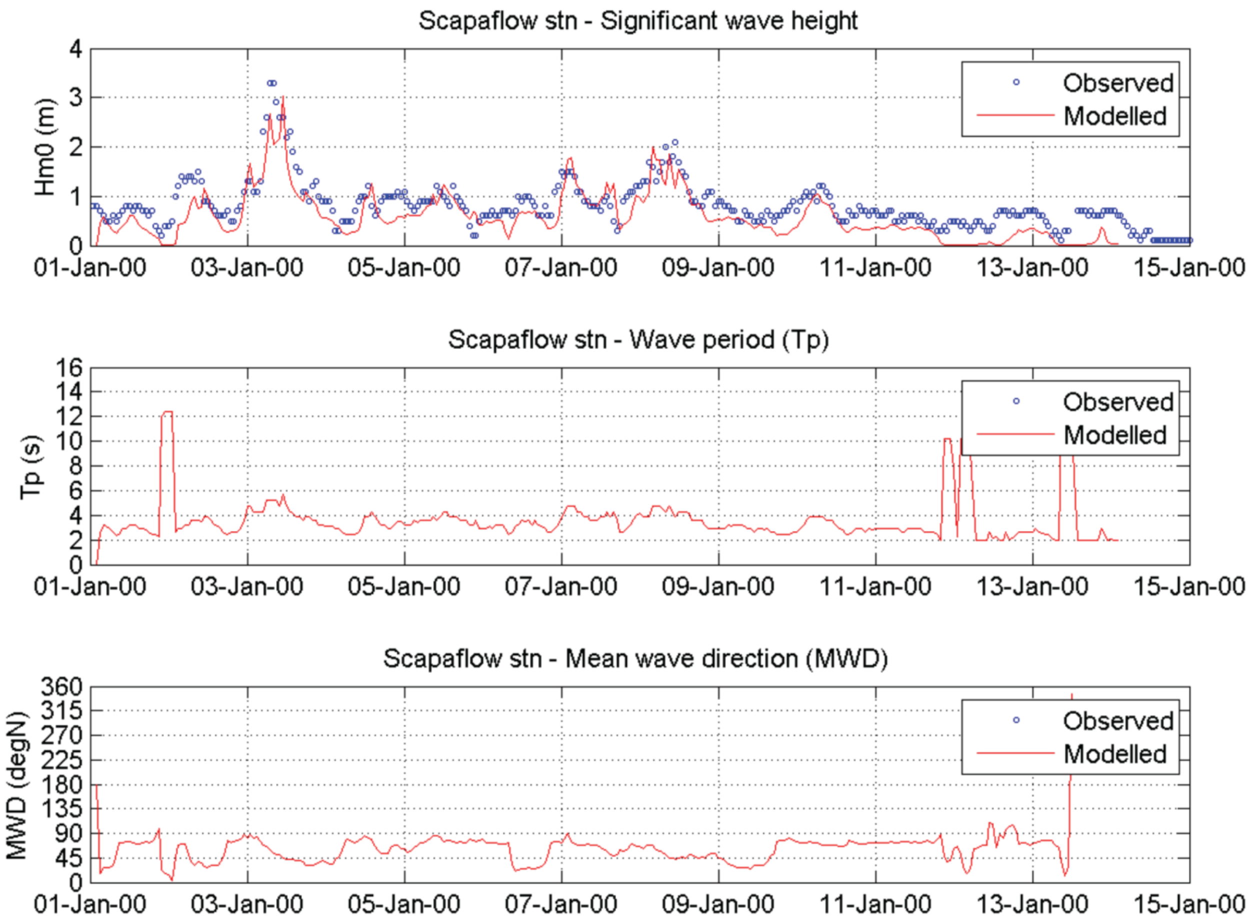
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-9a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wave conditions during January 2000. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



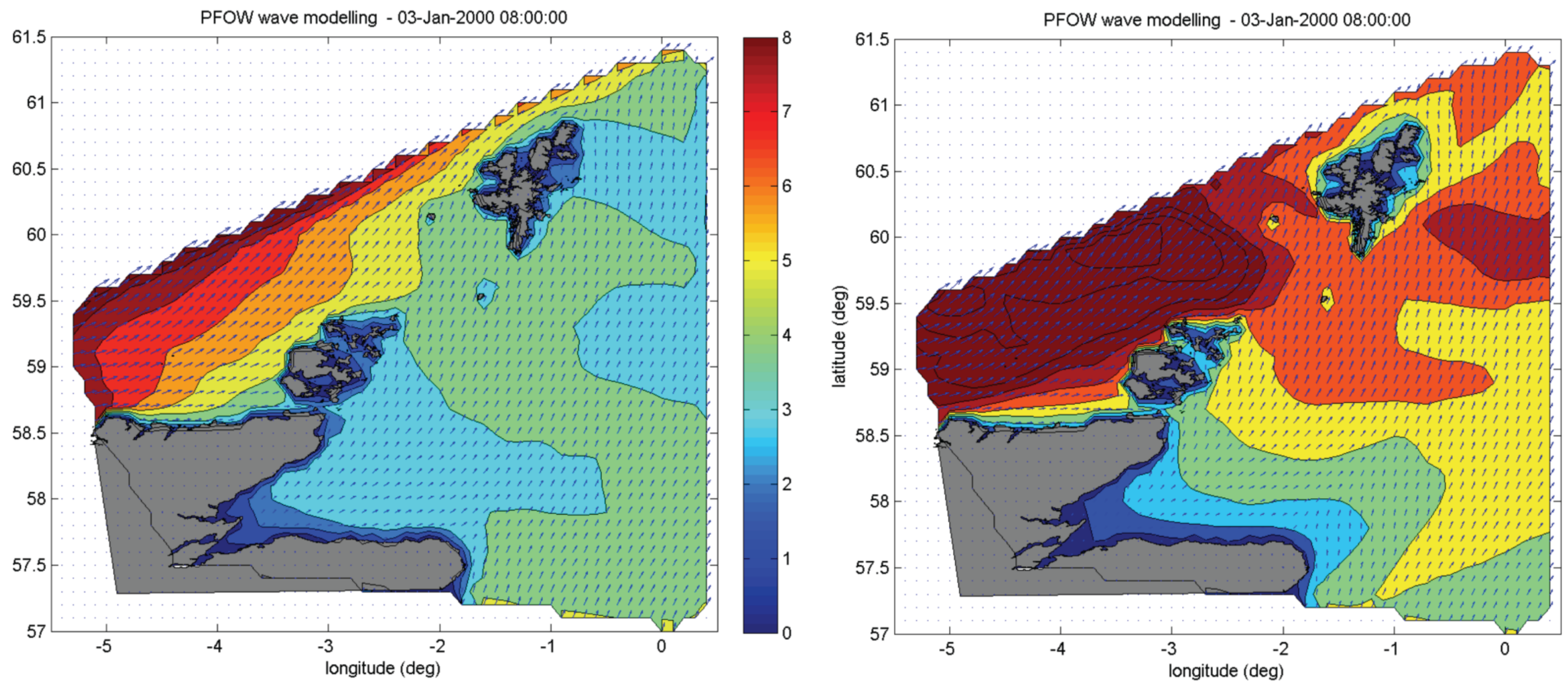
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-9b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wind conditions during January 2000. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-10a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions with measured data at Scapa Flow.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-10b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions with measured data at Scapa Flow. (UKMO 12-km wind field, wind speeds increased by 20%)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Wind forcing from 4-point dataset

Wind forcing from 12-km UKMO dataset

Client	Consulting Engineer	Project:	Figure Title:	Figure 4-11		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Contours of wave height and wave direction vectors scaled with Hm0 near the peak of storm on 03 Jan 2000. (Left: 4pt wind data; Right: UKMO 12-km wind data)	Checked: ..	Scale: Not to scale	Rev.: 0
				Designed: CS	Drawn:	Date: 26/02/2014

4.3.6.2 April 2001 simulation – Dounreay

A number of model runs were carried out to calibrate the wave model against measured data at Dounreay. Results from two selected runs are presented in this Section, which illustrate the effects of input wind dataset, and model sensitivity to the wind input and whitecapping source term formulation. The model runs are carried out for the period 12-April 00:00 to 16-Apr 23:00, including a 24-hour model spin-up period. The selected model runs are:

- Run 2F: 4-point wind; Komen wind input; Komen whitecapping
- Run 2J: 12km wind multiplied by 1.2 (Scaled 12km wind); Janssen wind input; Janssen whitecapping

Time series of wave conditions (during the simulated period) at the 4 UKMO points are shown Figure 4-12a, while the time series of wind conditions are shown in Figure 4-12b. It is difficult to pick out a definite storm during this event. The offshore Hm0 vary from 2.0 to 5.0m (mainly from West to North sector), with offshore wave period of approximately 7s. The wind speed is very variable at the 4 locations, with peaks of about 15m/s (in general) blowing from SW to NNW in the simulated period.

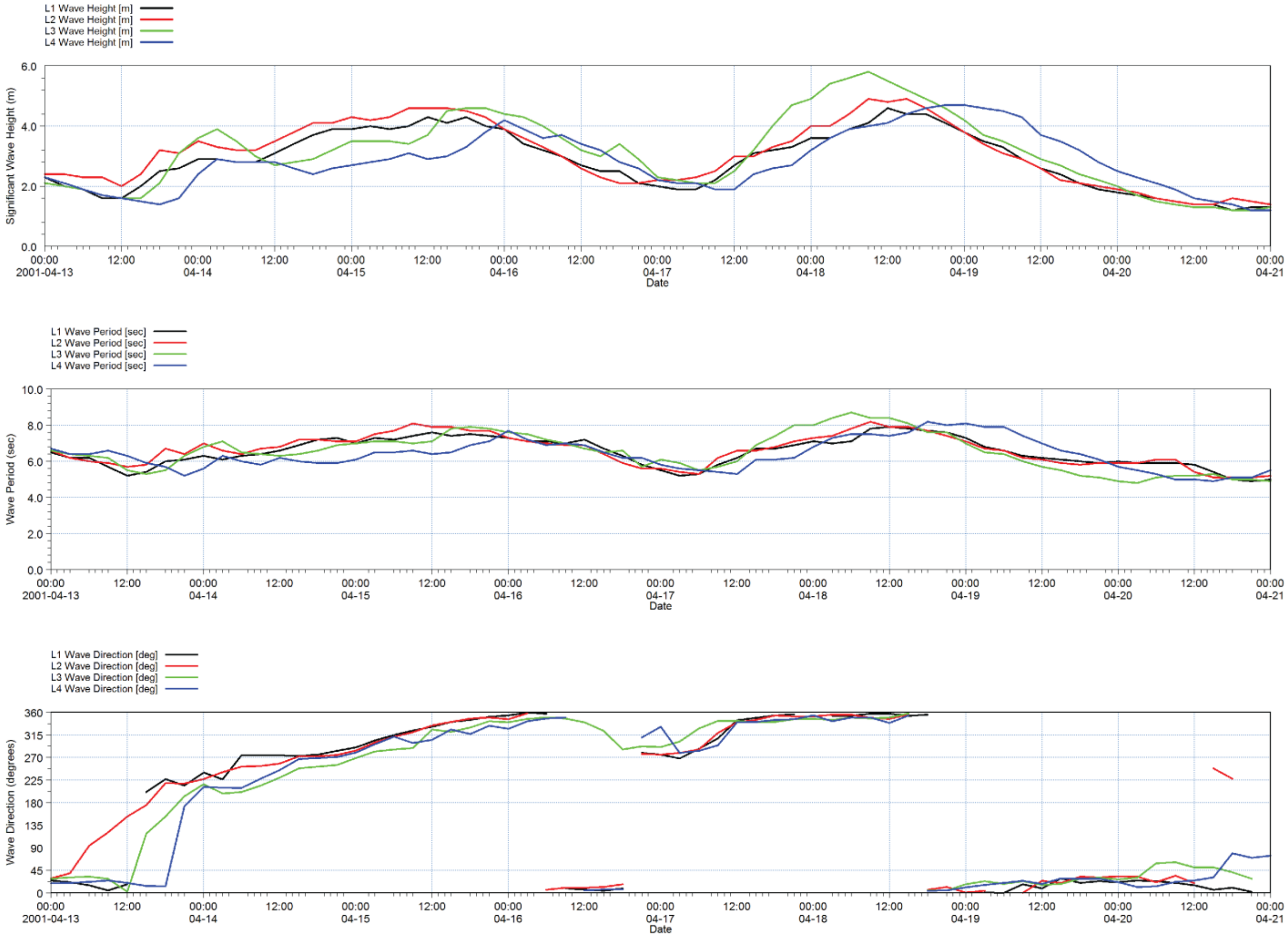
A summary of the model quality measures for these runs is shown in Table 4-7. Note that measurements of wave direction are not available at this site.

TABLE 4-7 MODEL QUALITY MEASURES AT DOUNREAY FOR APRIL 2001 RUNS (13 APRIL 00:00 – 16 APR 23:00).

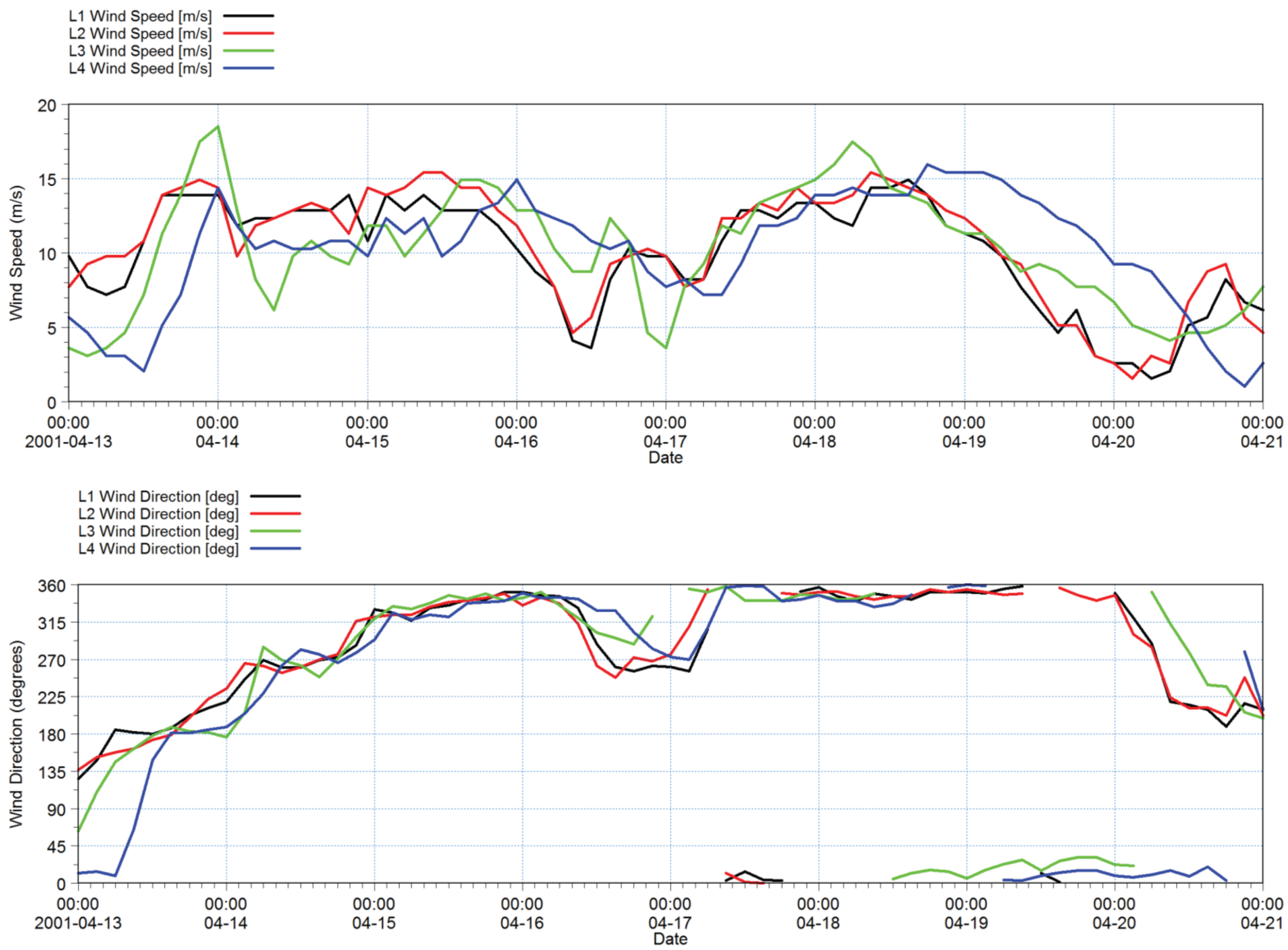
Simulation Quality indices	Run 2F 4-point wind + Komen wi + Komen wc	Run 2J Scaled 12km wind + Janssen wi + Janssen wc
Hm0: Mean error, bias (m)	-0.48	-0.56
Hm0: RMS error (m)	0.64	0.67
Hm0: SI (RMS/mean Hm0)	0.37	0.39
Hm0: Correlation coefficient	0.92	0.93
Tp: Mean error, bias (s)	-4.96	-4.67
Tp: RMS error (s)	5.22	4.83
Tp: SI (RMS/mean Tp)	0.53	0.49
Tp: Correlation coefficient	-0.28	-0.21

The modelled and measured wave conditions are shown in Figure 4-13a and Figure 4-13b for Run 2F (4-point wind data) and Run 2J (12km wind data) respectively. Table 4-7 shows a negative bias in the wave heights (that is, the modelled wave heights are generally lower than the measurements during the comparison period) of about 0.5m to 0.6m. Furthermore, the peak period is also significantly under-estimated (bias of about -5s). The under-estimation in the wave period comes from the specified offshore wave period (about 7s) as this site is an exposed site. With offshore wave period of about 7s, there is no mechanism in the wave model that can increase the wave period to 12s over the propagation distance. The fact that the offshore wave period is relatively short can partly explain the under-estimation of the wave height, since the effect of whitecapping dissipation is stronger for steep waves (which is the case here). Thus, this is likely the best comparison that can be obtained with the available offshore boundary wave conditions for this event.

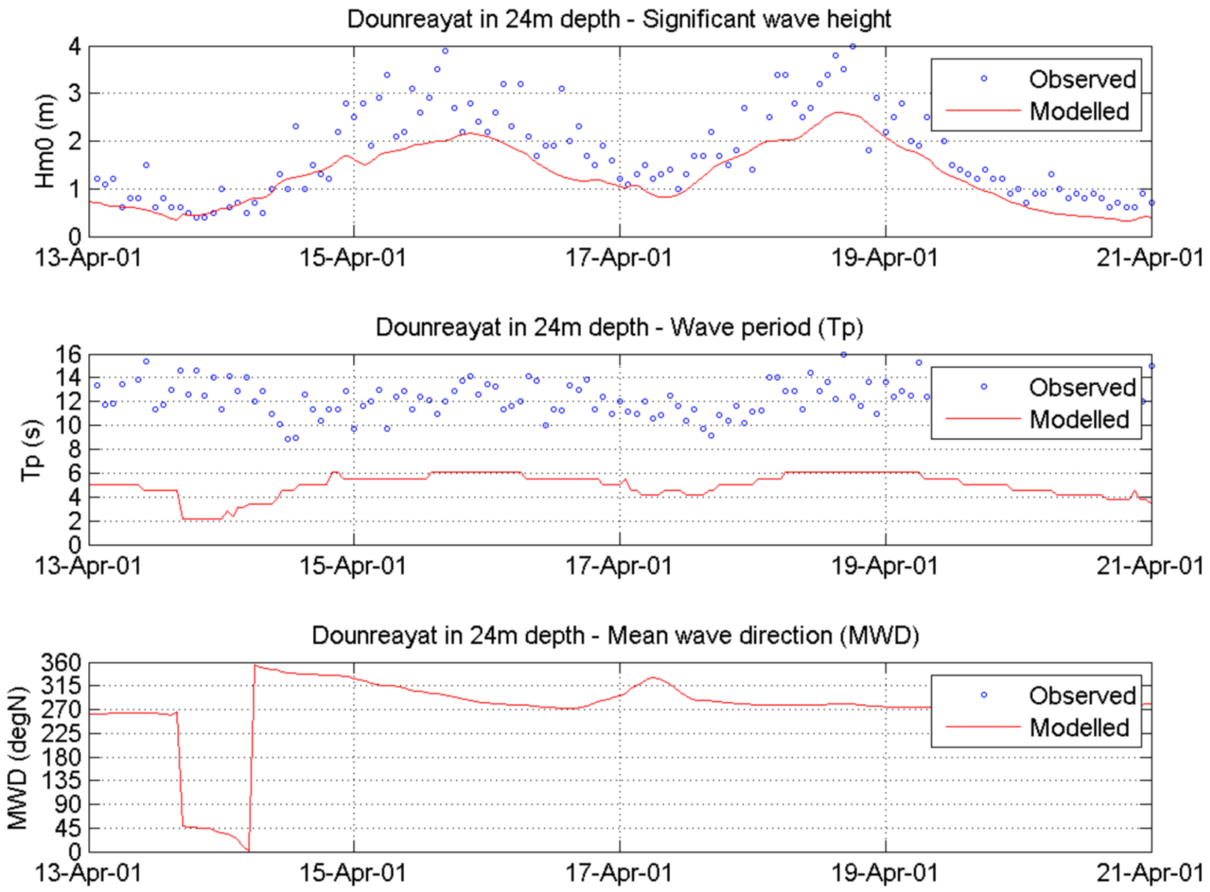
Figure 4-14 shows examples of two-dimensional contours of significant wave heights and wave direction pattern (scaled with wave height) at the peak of the storm. The left panel shows the result using the 4-point wind data, while the right panel shows the result using the scaled 12-km wind data.



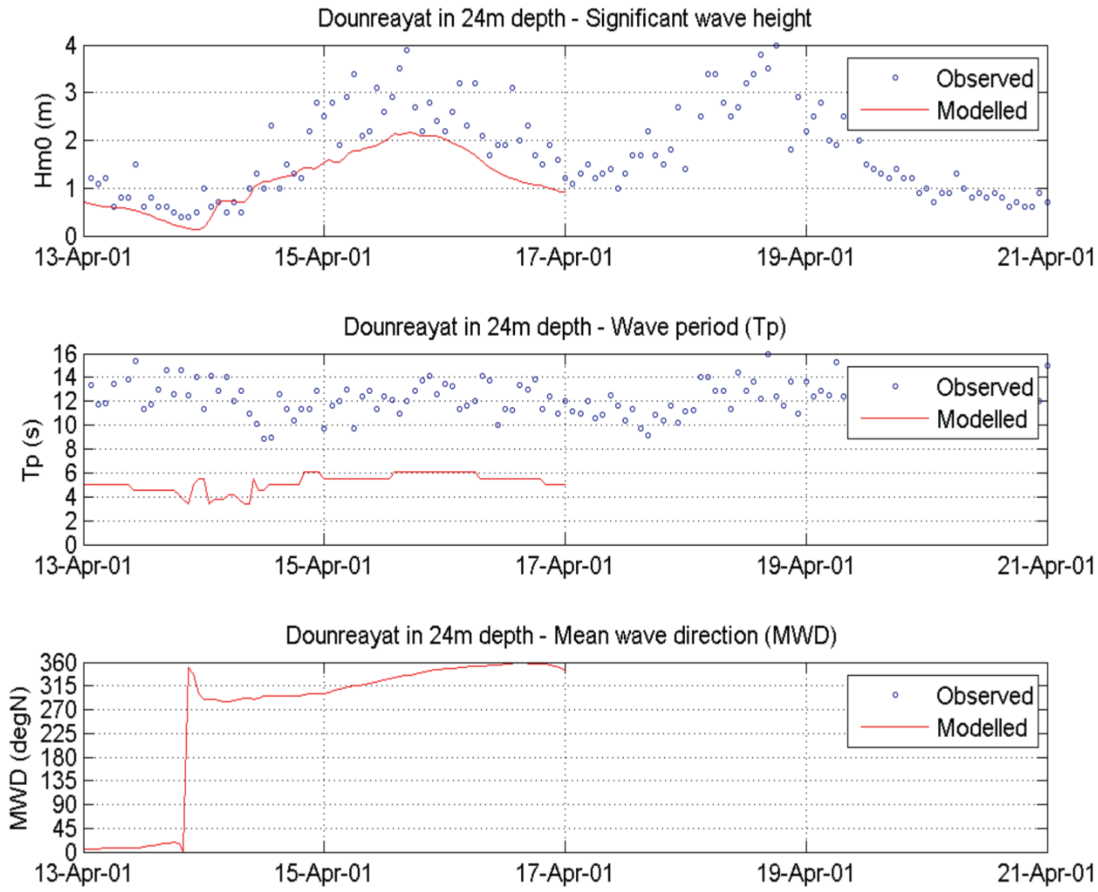
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-12a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wave conditions during April 2001. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



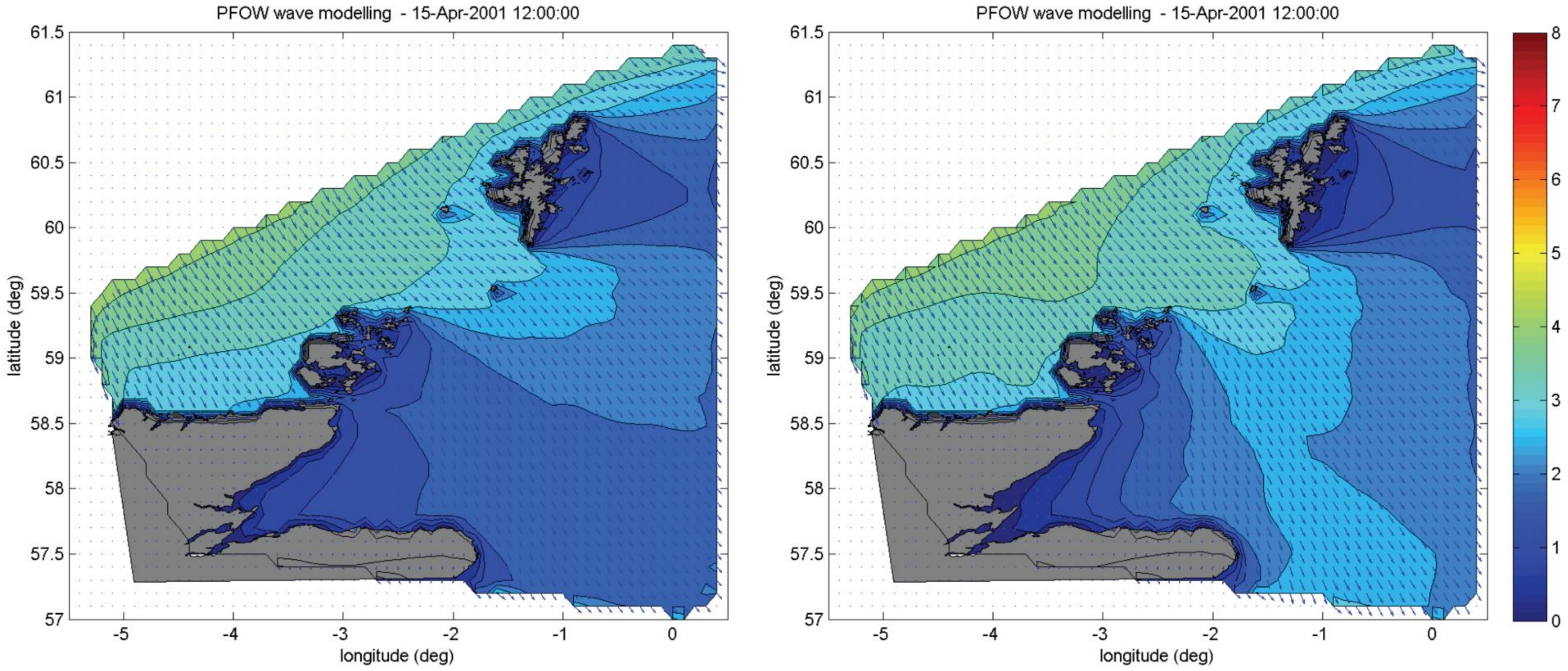
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-12b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wind conditions during April 2001. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-13a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions with measured data at Dounreayat (Wind forcing from 4-point data set)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-13b		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions with measured data at Dounreayat (UKMO 12-km wind field, wind speeds increased by 20%)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Wind forcing from 4-point dataset

Wind forcing from 12-km UKMO dataset

Client	Consulting Engineer	Project:	Figure Title:	Figure 4-14		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Contours of wave height and wave direction vectors scaled with Hm0 near the peak wave height of 15 Apr 2001. Left panel: Wind forcing from 4-point data; Right panel: Wind forcing from 12km wind dataset	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.3.6.3 Jan 2004 simulation – Holm Sound

A number of model runs were carried out to calibrate the wave model against measured data at Holm Sound. Results from two selected runs are presented in this Section, which illustrate the effects of input wind dataset, and model sensitivity to the wind input and whitecapping source term formulation. The model runs are carried out for the period 04-January 00:00 to 18-January 23:00, including a 24-hour model spin-up period. The selected model runs are:

- Run 3C: 4-point wind; Komen wind input; Komen whitecapping
- Run 3D: Scaled 12-km wind; Janssen wind input; Janssen whitecapping

Time series of wave conditions (during the simulated period) at the 4 UKMO points are shown Figure 4-15a, while the time series of wind conditions are shown in Figure 4-15b. The largest storm during the simulation period occurred on 08-09 January 2004. The maximum offshore wave height during the storm is about 8m, coming from SSE (at position P4/L4) and with wave period of 10secs. The corresponding wind speed is about 22m/s from S to SSE sector.

A summary of the model quality measures for these runs is shown in Table 4-8. The modelled and measured wave conditions are shown in Figure 4-16a and Figure 4-16b for Run 3B (4-point wind data) and Run 3D (scaled 12km-grid wind data) respectively.

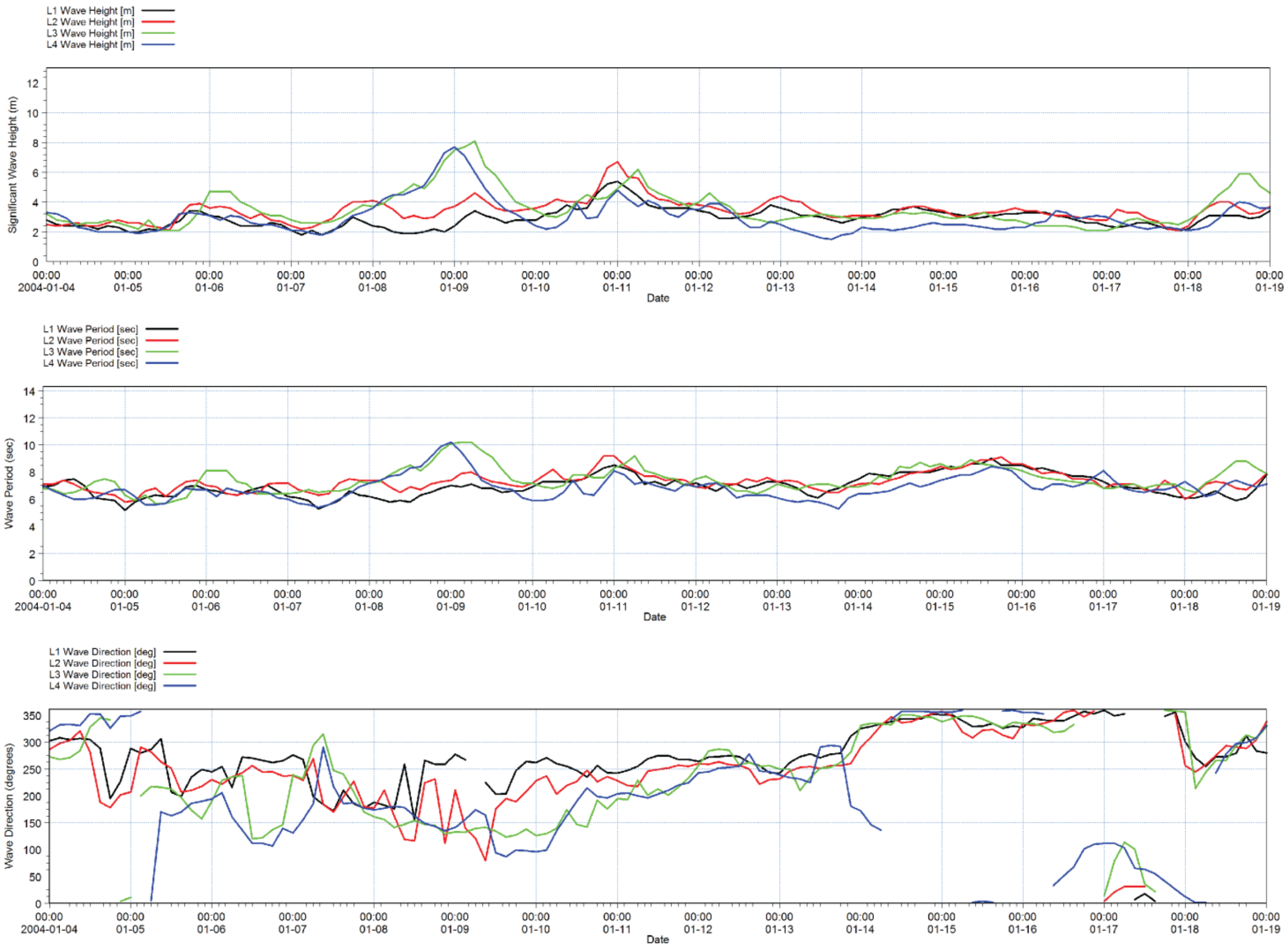
The observed peak significant wave height during the storm is about 4.0m, while the corresponding modelled wave height is about 3.8m (Run 3C) and 3.5m (Run 3D). The peak wave height occurs slightly later in the model forced with the 4-point wind data (Run 3C). This phase error is corrected in Run 3D with the use of the scaled 12km wind fields. Visual comparison between the modelled and measured data shows that the model prediction of the wave height, wave period and direction are significantly improved in Run 3D. This calibration is considered to be satisfactory.

TABLE 4-8 MODEL QUALITY MEASURES AT HOLM SOUND FOR JAN 2004 RUNS (05 JAN 00:00 – 18 JAN 23:00).

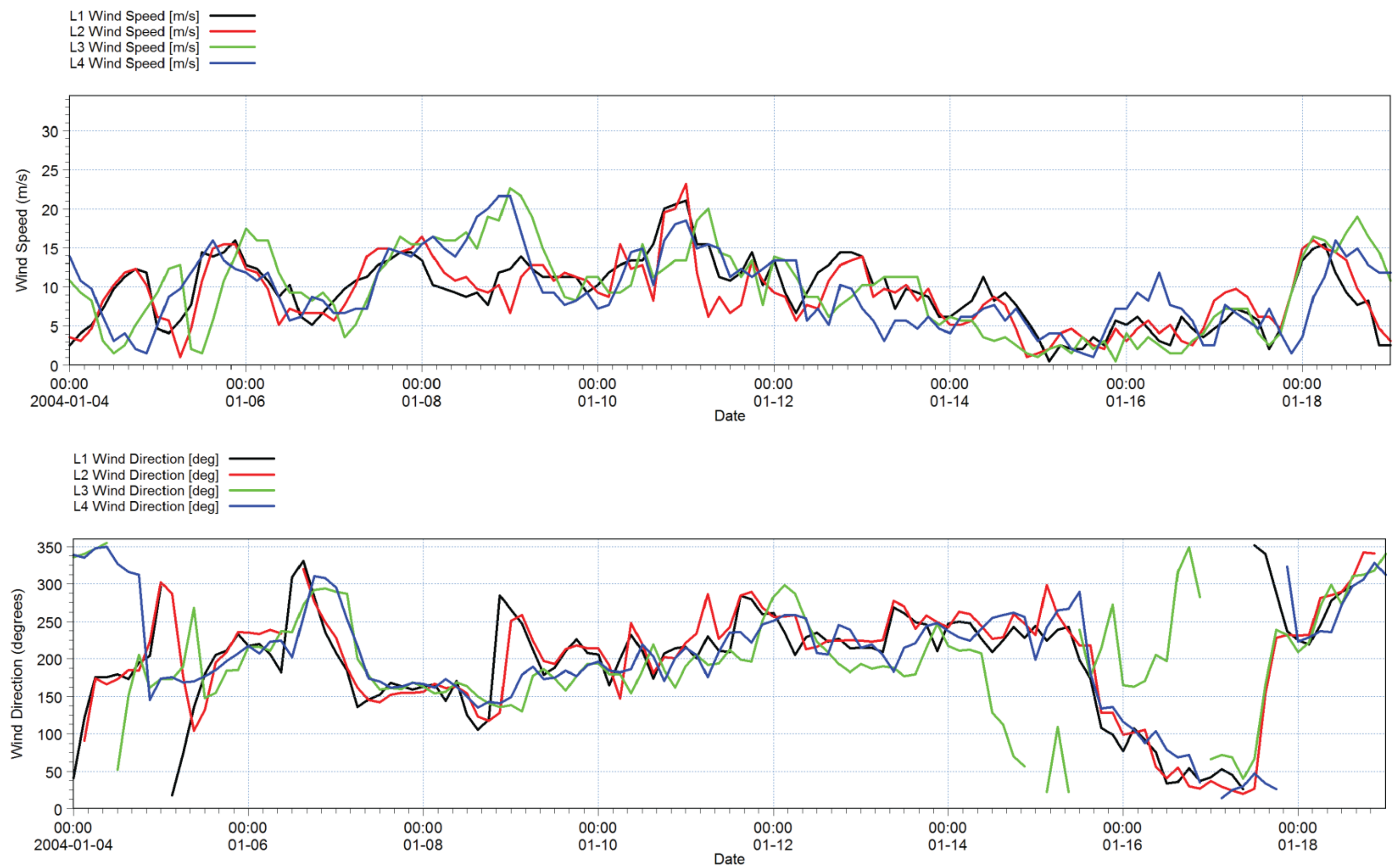
Simulation Quality indices	Run 3C 4-point wind + Komen wi + Komen wc	Run 3D** Scaled 12km wind + Janssen wi + Janssen wc
Hm0: Mean error, bias (m)	0.02	-0.10
Hm0: RMS error (m)	0.48	0.35
Hm0: SI (RMS/mean Hm0)	0.35	0.26
Hm0: Correlation coefficient	0.85	0.94
Tp: Mean error, bias (s)	1.71	1.75
Tp: RMS error (s)	2.35	2.36
Tp: SI (RMS/mean Tp)	0.47	0.48
Tp: Correlation coefficient	0.67	0.75
Dir: Mean error, bias (deg)	23.47	9.67
Dir: RMS error (deg)	41.77	24.66
Dir: SI (RMS/mean Dir)	0.31	0.18
Dir: Correlation coefficient	0.28	0.38

**Run 3C completed to 15 Jan 14:00, and indices calculated to for corresponding period.

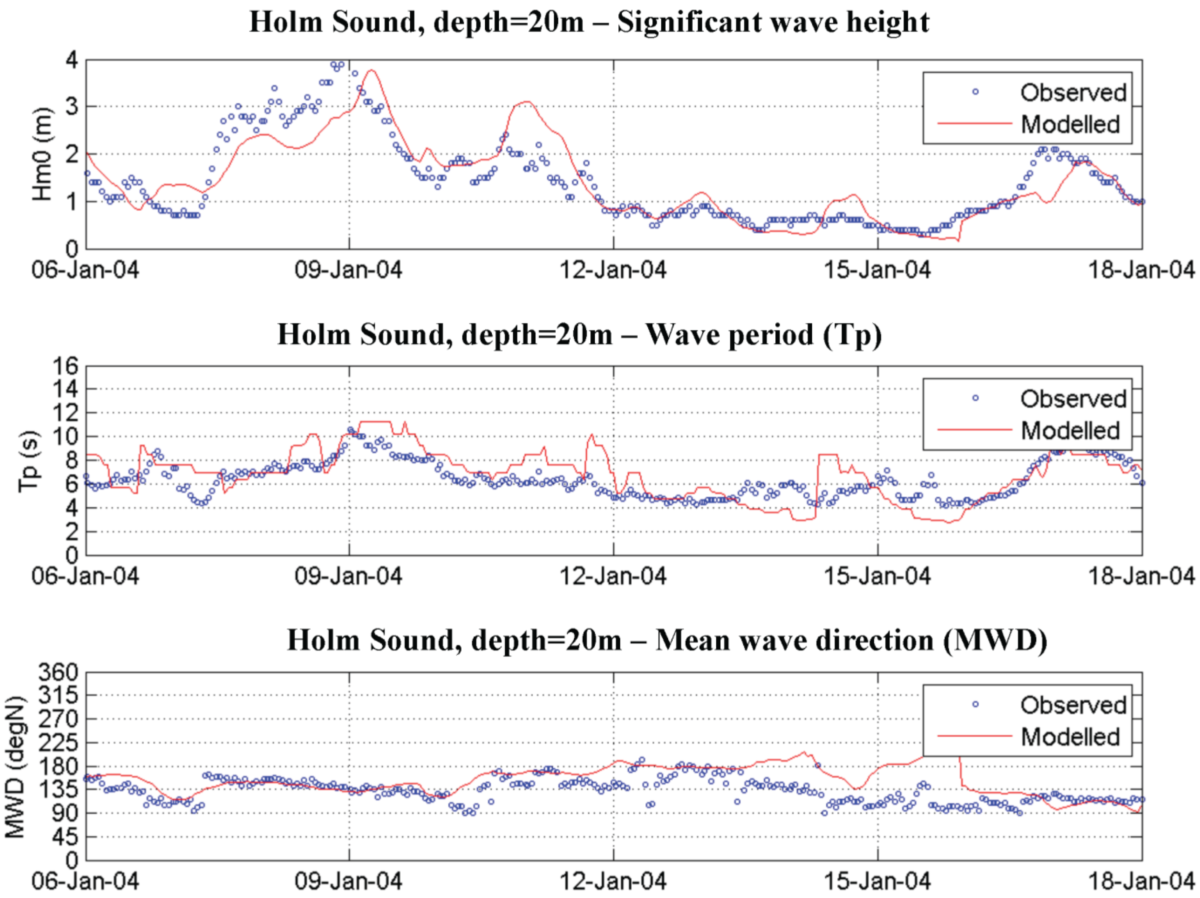
Figure 4-17 shows examples of two-dimensional contours of significant wave heights and wave direction pattern (scaled with wave height) at the peak of the storm. The left panel shows the result using the 4-point wind data, while the right panel shows the result using the scaled 12-km wind data.



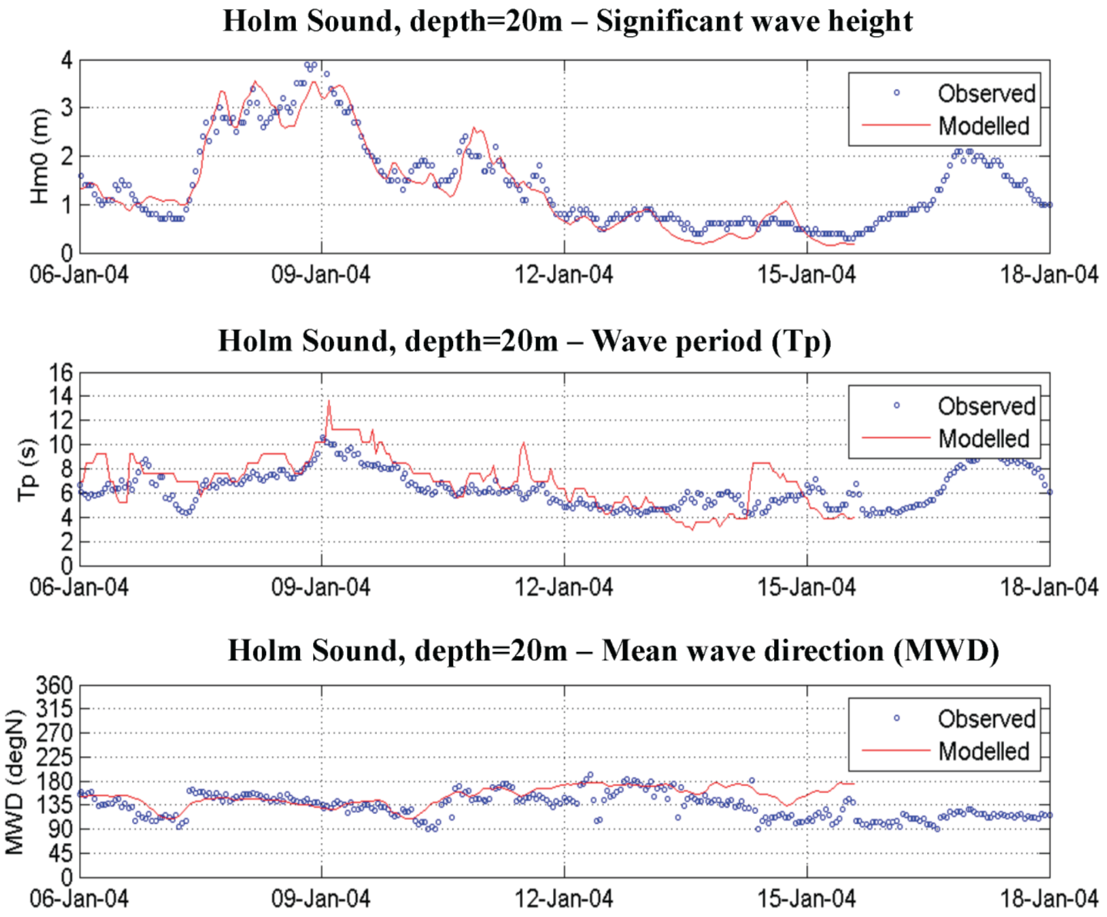
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-15a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wave conditions during January 2004. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



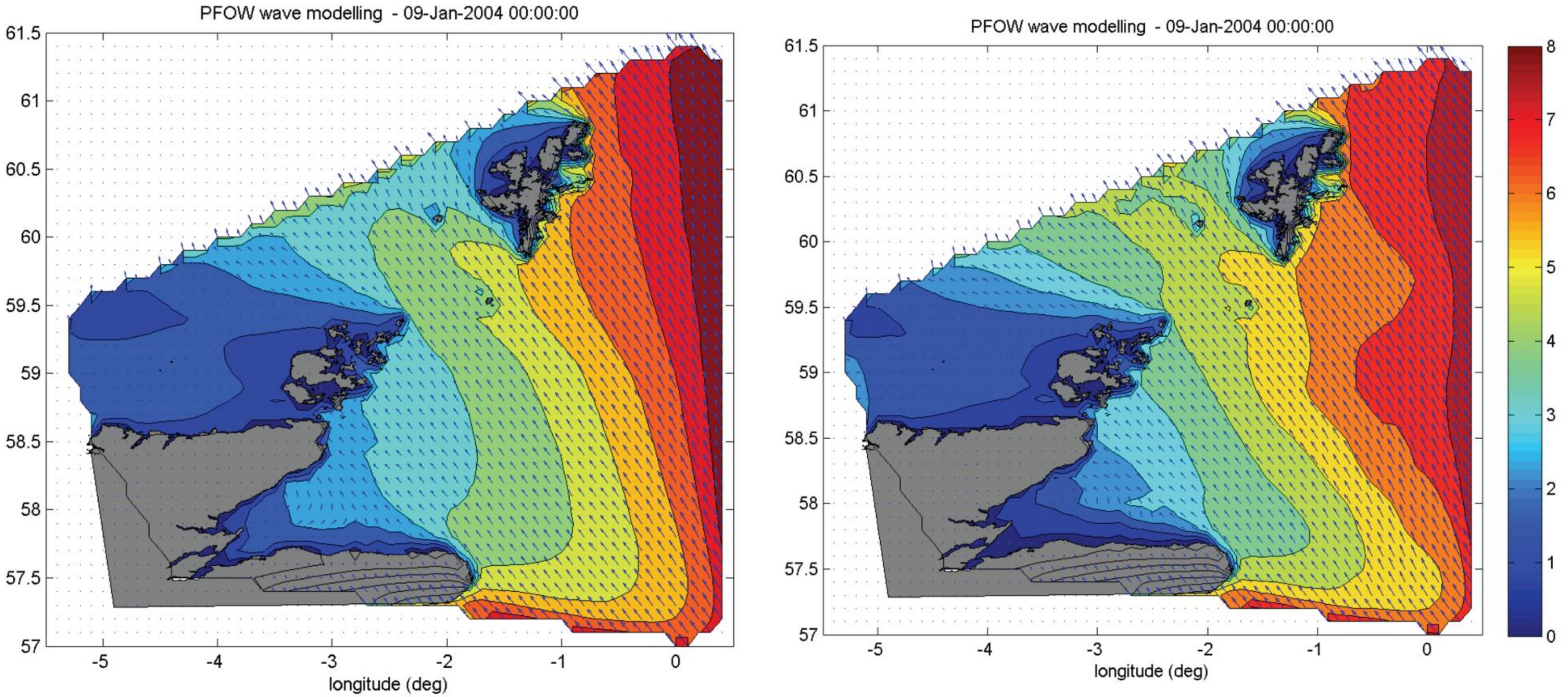
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-15b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Offshore wind conditions during January 2004. Note: L1-L4 are the same points as P1-P4 in Figure 4-4.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-16a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions (Run 3C) with measured data at HolmSound Orkney (UKMO 4-point dataset)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-16b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of modelled wave conditions (Run 3D) with measured data at HolmSound Orkney (UKMO 12-km wind field, wind speeds increased by 20%)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Wind forcing from 4-point dataset

Wind forcing from 12-km UKMO dataset

Client	Consulting Engineer	Project:	Figure Title:	Figure 4-17		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Contours of wave height and wave direction vectors scaled with Hm0 during the storm of 09 Jan 2004. Left panel: Wind forcing from 4-point data; Right panel: Wind forcing from 12km wind dataset.	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.3.7 Summary & Conclusions

A wave model for the Pentland Firth and Orkney Waters (PFOW) has been constructed using the FVCOM-SWAVE. The model has been calibrated using measured wave data at Scapa Flow, Dounreay and Holm Sound. The comparison between the modelled and measured wave data at Scapa Flow and Holm Sound are considered to be satisfactory. The correlation coefficient for wave height is above 0.85 at all three locations.

However, the model generally under-predicts wave heights at Dounreay. A close examination of the offshore wave conditions during April 2001 shows that the offshore wave periods are significantly lower than the measured wave periods at Dounreay. Assuming that the measured wave periods are correct, the limitation in the offshore wave data is a plausible explanation for the under-prediction at this site.

The calibration shows that the wind input and whitecapping source terms are best described using the Komen formulation if the 4-point wind data is used to force the model. The Janssen formulation was found to be better when using the high resolution wind data (12km wind data). Furthermore, the scaled 12-km wind data provides improved results compared to the measurements.

4.4 Wave model simulations

Deliverable CS 1(a) in the Invitation to Tender (ITT) requires a wave model to be setup and calibrated in order that seasonal conditions and specific periods of interest can be simulated. For this purpose the spectral wave model FVCOM-SWAVE has been used, and the model has been setup and calibrated as described in Section 4.3. Deliverable CS 1(a) also require that the model should deliver an assessment of the wave energy available for extraction.

Deliverable CS 1(b) requires that a year-long simulation using idealised forcing is undertaken for waves. For this simulation, a representative year was selected from analysis of the available boundary wave data (P1 to P4, see Figure 4-4). The representative year was selected using the methodology described in Section 4.4.1.

4.4.1 Selection of representative year

As stated above, one of the deliverables in CS 1(a) is that the model should deliver an assessment of the wave energy available for extraction.

The standard method of assessing wave energy resources is to carry out long term wave simulations (over several years) or use long term wave data available from reputable wave data supplier such as UK Meteorological Office. The long term wave data are used to determine available wave energy resources by determining the average annual, monthly and seasonal wave power (averaged over the number of years simulated) at all computational points in the model area. This approach was used in a number of previous studies (for instance, ABPmer(2008) to determine wave energy resources in UK waters; EMEC, 2009; WERATLAS, 2007, Wave Energy Centre, 2010). These studies typically cover a large area with fairly coarse model resolution, for instance, ABPmer(2008) used data from the Met Office UK Coastal Waters model with 12km resolution.

Recently, ABPmer(2012) used the same method to determine wave energy resources over the Pentland Firth and Orkney Waters Strategic Area (PFOWSA) by simulating wave conditions over a 20year period (1990-2009). However, the area of coverage of the PFOWSA model is small in comparison to the model area covered in the present study. Similarly, Neill et al (2014) carried out wave simulations over a 10 year period (2003 -2012) to assess wave energy resources over the PFOWSA area.

For this study, the area covered by the PFOW model is relatively large and the model spatial resolution is also quite high (0.25 km to 1.0 km in the Pentland Firth and Orkney Waters). This results in excessive computational resource requirements (4 days simulation per month, using 60 cores on the computer cluster at the Hartree centre [http://community.hartree.stfc.ac.uk/wiki/site/admin/Home.html]) which is considered impractical for carrying out long term simulations. An alternative approach was therefore devised with the aim of ensuring that a realistic measure of the average annual wave energy resources is derived in a way that is computationally practical. A representative year approach was devised, which is an extension of a method used by Johnson et al (2001) to select representative annual wave conditions for sediment transport studies.

The aim is to determine a ―representative year" from the available 12-year time series (2000-2011), such that the wave power determined from the selected year is broadly representative of the average available wave power over the 12-year period. The selected year is chosen to be broadly representative in terms of the annual, monthly and quarterly wave power and the directional distribution of the wave power. This method is referred to as the representative year approach, in contrast with the multiple year simulation approach used in previous studies.

The representative year has been determined using the wave data obtained from UK Met Office (UKMO) at four locations around the study area. The methodology outlined below has been used:

1. The time series of available wave power per metre of wave crest, P was calculated as:
   $$P = E*Cg, \qquad (4.1)$$
   where E = $\rho g\, H_{m0}^2/16$ is the wave energy, $C_g = C_g(T_e, h)$ is the wave group velocity calculated as a function of wave energy period ($T_e = m_{-1}/m_0$) and water depth (h), ρ is the density of seawater (1025 kg/m^3), g is acceleration due to gravity (9.81m/s). Wave energy period, T_e has been calculated as: T = Tp/1.2 (this assumption is reviewed in Section 5.3), Tp is the peak wave period and C_g is calculated from the linear wave dispersion relation. The units of P is in W/m crest.
2. The average annual wave power for each year was calculated along with the average annual wave power for all years. The years were then ranked based on their deviation from the average annual wave power for all years (Figure 4-18).
3. The average wave power for each month in each year was calculated as well as the average monthly wave power for the 12-year series. (For example, the average wave power for January was calculated for each year individually, then the average for all Januarys was calculated). The individual monthly averages were then ranked based on their deviation from the all-years average (Figure 4-19a). Similarly, the average quarterly wave power for each year was calculated and ranked based on their deviation from the overall average quarterly wave power (average for each quarter in the 12-yr time series). This is shown in Figure 4-19b.
4. The data was divided into 16 directional sectors (sector width of 22.5°), the process described above was repeated for the 16 sectors, i.e. the average wave power from each sector in each year was ranked against the average wave power from each sector for all years (Figure 4-20).

Ranking the years in terms of their deviation from the overall average provides an indication of which year falls closest to the average and hence a representative year. For the monthly and directional rankings, there are 12 and 16 values for each year respectively. This required simplification, therefore the ranks for each year were averaged and ranked from smallest to largest to give a single measure of fit for each year. The results of this analysis at L2 are shown in Figure 4-18 and a summary for all four locations is shown in Table 4-9.

TABLE 4-9 SUMMARY OF REPRESENTATIVE YEAR ANALYSIS RESULTS AT THE 4 WAVE DATA LOCATIONS

Location	Annual best fit			Monthly best fit			Directional best fit		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
L1	2000	2005	2004	2010	2005	2004	2004	2000	2009
L2	2005	2007	2000	2005	2010	2004	2005	2000	2004
L3	2005	2007	2000	2004	2005	2007	2004	2005	2001
L4	2002	2004	2005	2004	2003	2001	2004	2001	2005

Table 4-9 shows that: a) year 2005 is the most representative of the annual wave power at the 4 locations, while year 2000 is second; b) year 2004 is the most representative of monthly distribution of wave power, while year 2005 is a second; and c) year 2004 is the most representative of the directional distribution of annual wave power, while year 2005 is second. Based on these results, 2005 was selected as the representative year.

Therefore the wave energy resource throughout the model domain was determined using wave model results from 2005. The calculated mean monthly distribution of wave power for the representative year (2005) is compared with the mean monthly wave power for the entire record (2000 – 2011) at all the UKMO locations in Figure 4-19a. It is clear from this comparison that the monthly distribution of wave power in 2005 is different from the long term average. For instance, the wave power in Jan 2005 is significantly higher than the average for January, while the wave power for Dec 2005 is significantly lower than the average for December. In order to estimate the long term monthly average wave power from the 2005 simulation results, a scaling ratio (R) has been calculated at each UKMO station as:

R = Long term mean monthly wave power / mean monthly wave power for 2005

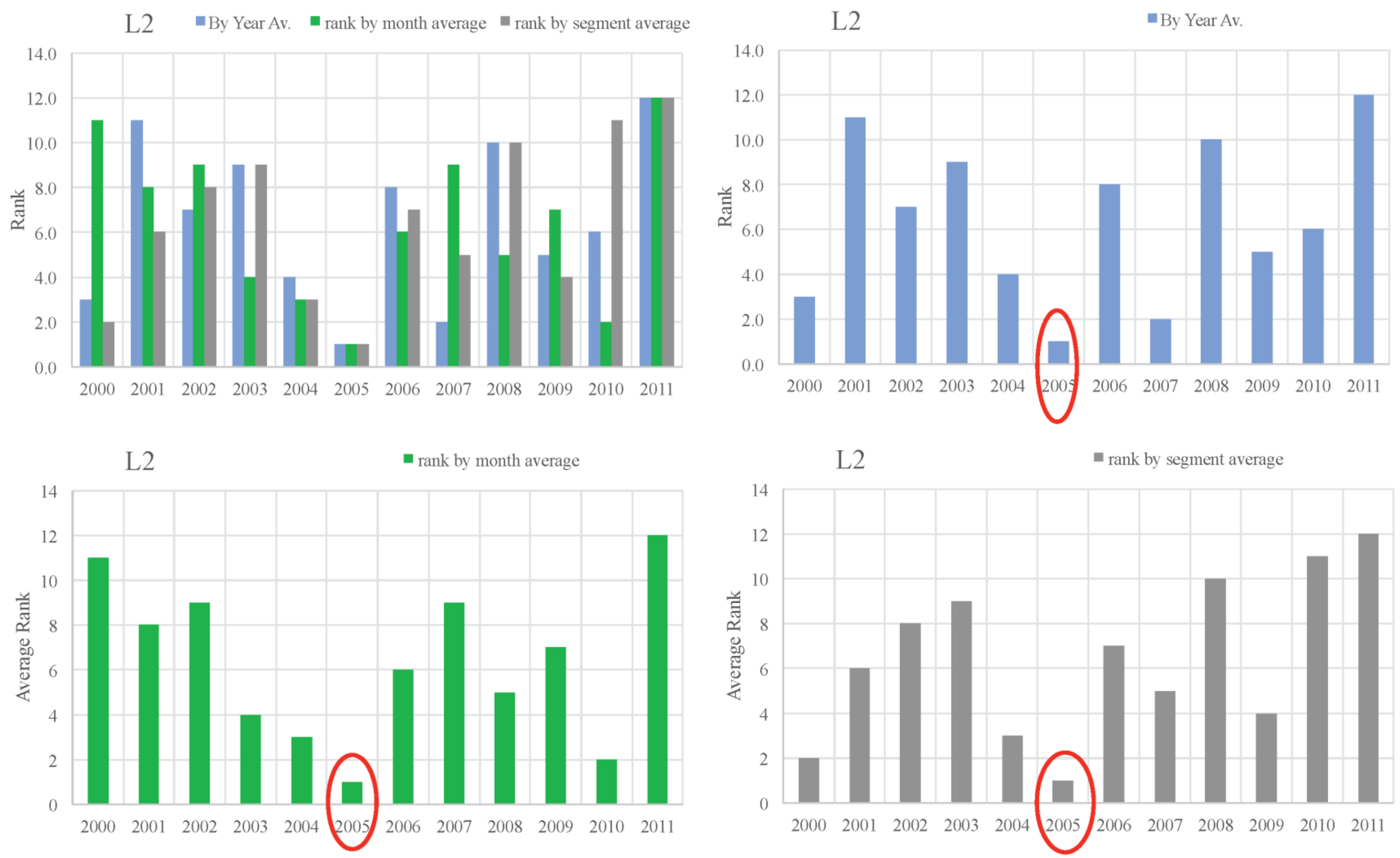
This ratio is averaged over all the four UKMO stations for each calendar month, and plotted in Figure 4-19b. The R values vary from 0.6 (August) to 1.4 (December), for a full list see Table 4-10.The calculated ratio is used to multiply the mean wave power calculated for each month in order to derive the best estimate of wave power for each individual month. Calculations show that the corresponding R for the entire year is approximately 1.0. Thus, the wave energy calculations for 2005 is the best estimate for the mean annual wave power.

TABLE 4-10 LIST OF R VALUES USED FOR EACH MONTH

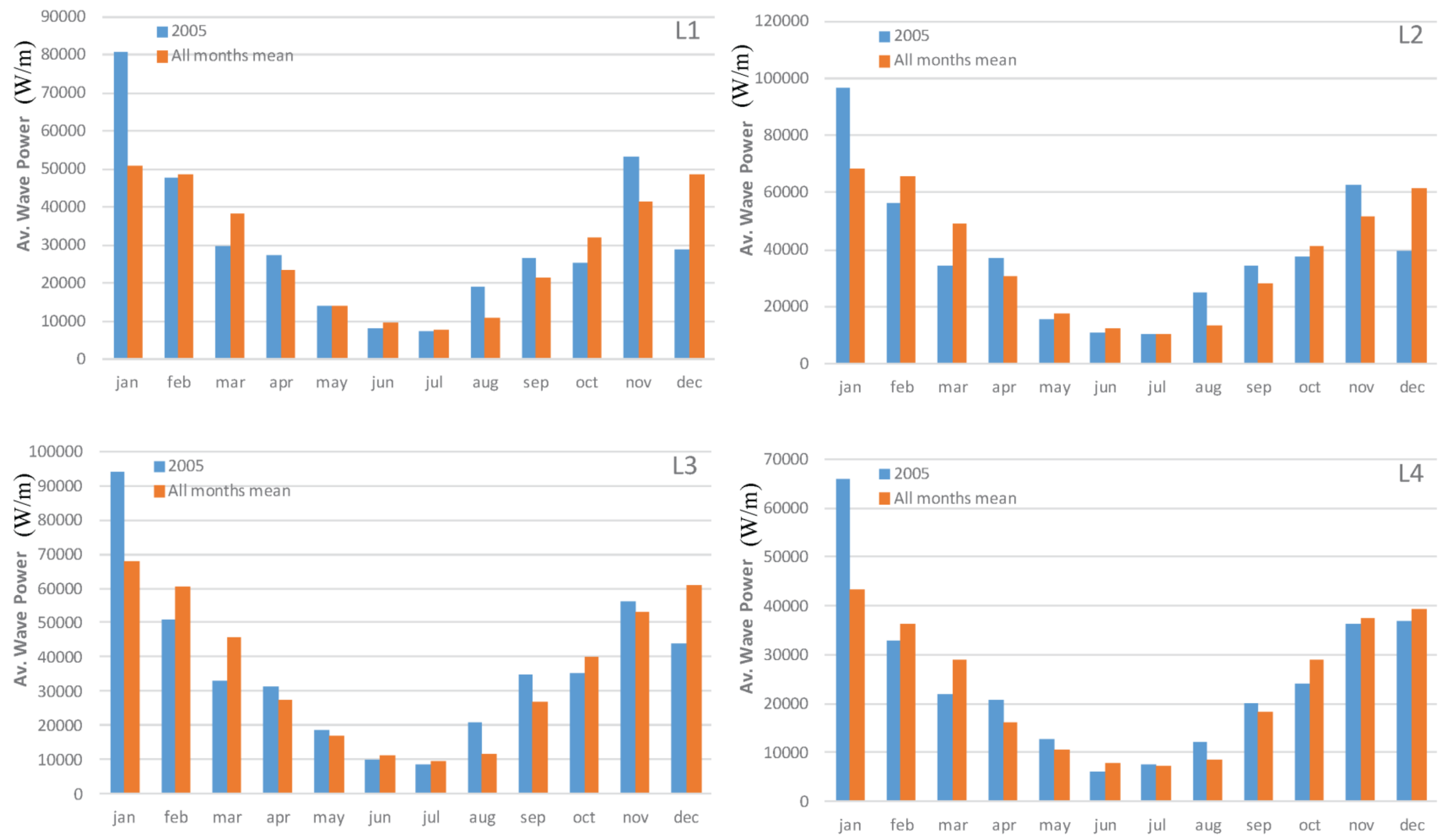
Month	R at the four Met office data locations				
	L1	L2	L3	L4	Average
January	0.63	0.71	0.72	0.66	0.68
February	1.02	1.17	1.19	1.11	1.12
March	1.28	1.42	1.38	1.33	1.35
April	0.86	0.83	0.88	0.78	0.84
May	1.01	1.14	0.91	0.84	0.97
June	1.18	1.16	1.13	1.29	1.19
July	1.05	1.00	1.14	0.96	1.04
August	0.57	0.54	0.55	0.69	0.59
September	0.81	0.81	0.77	0.90	0.82
October	1.27	1.10	1.14	1.21	1.18
November	0.77	0.83	0.94	1.03	0.89
December	1.68	1.55	1.39	1.07	1.42

The comparison of mean wave power on a quarterly basis is shown in Figure 4-20, which shows fairly good agreement between the 2005 estimate and the long term average at all UKMO stations. The comparison of the directional distribution of wave power is shown in Figure 4-21. This shows a fairly good agreement between the 2005 directional distribution and the long term average at L1 and L2, although the agreement is not as good at L3 and L4. However, given that most of the wave energy comes from the sector of directions from SW and North, the wave energy coming from L1 and L2 are the most important. Hence, this is considered to be acceptable.

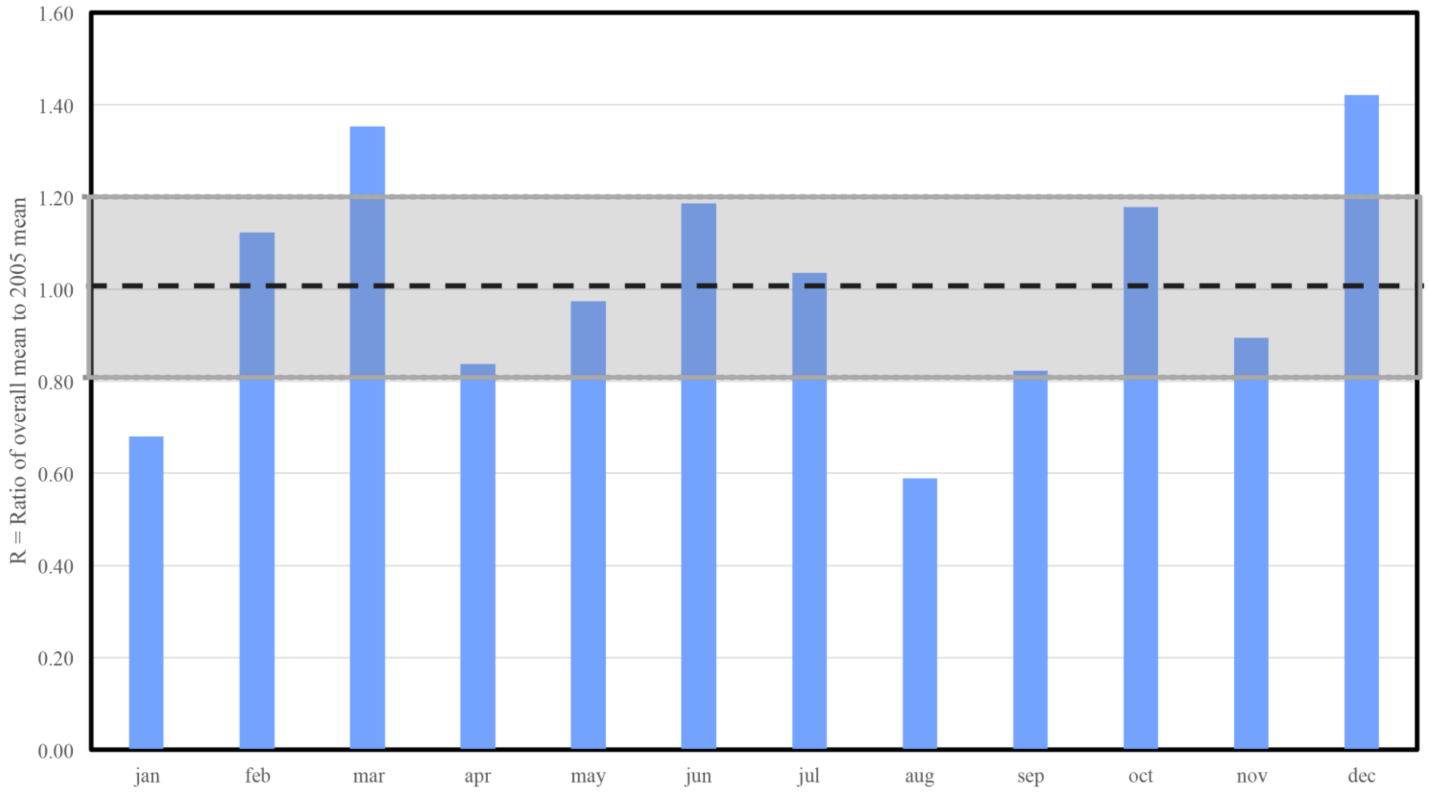
The wave model results for the simulated year is used to provide an estimate of the wave energy resources at the site. The estimated wave energy resources are subsequently compared with the results of previous studies.



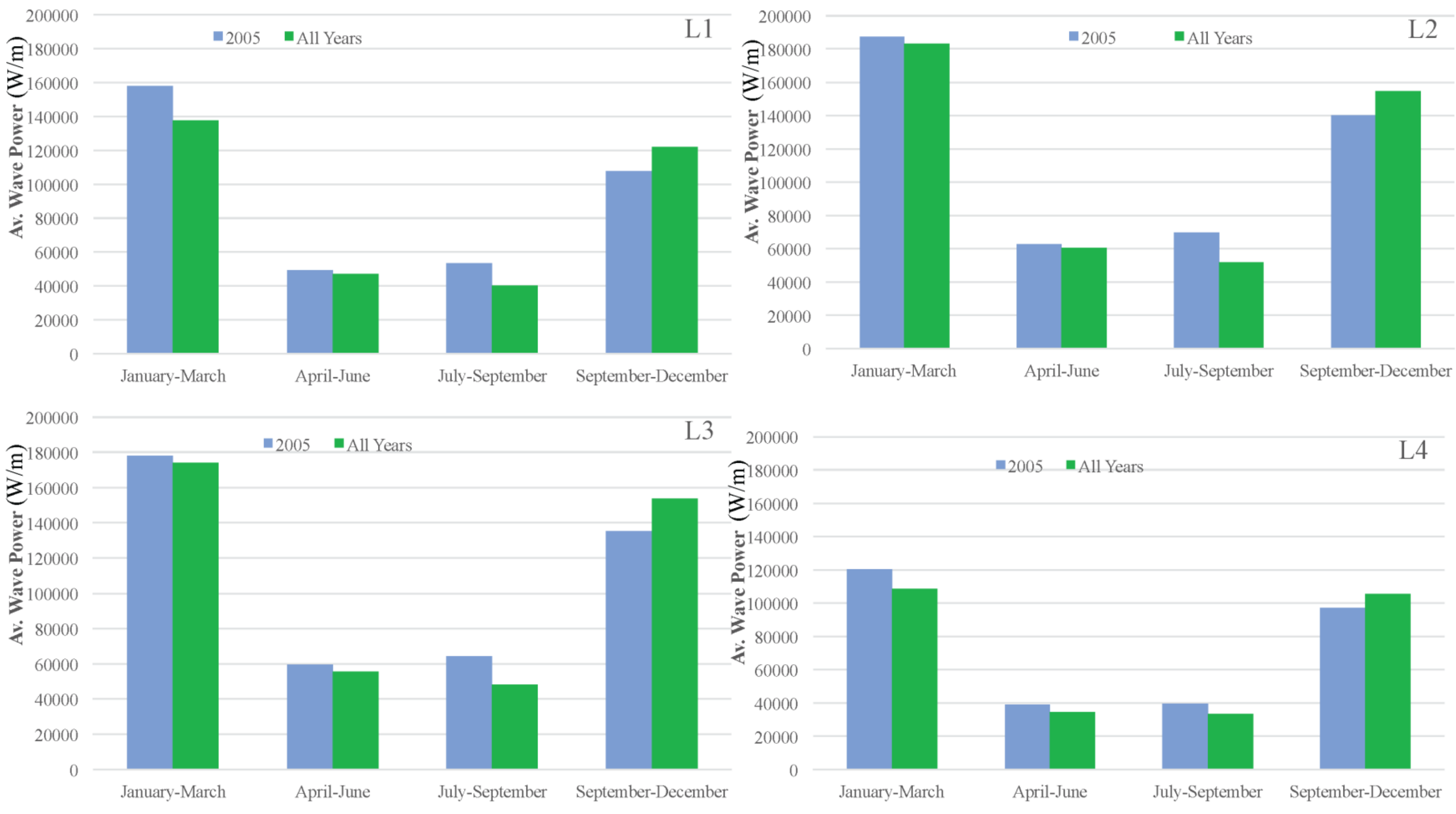
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-18		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Results of representative year analysis at L2	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



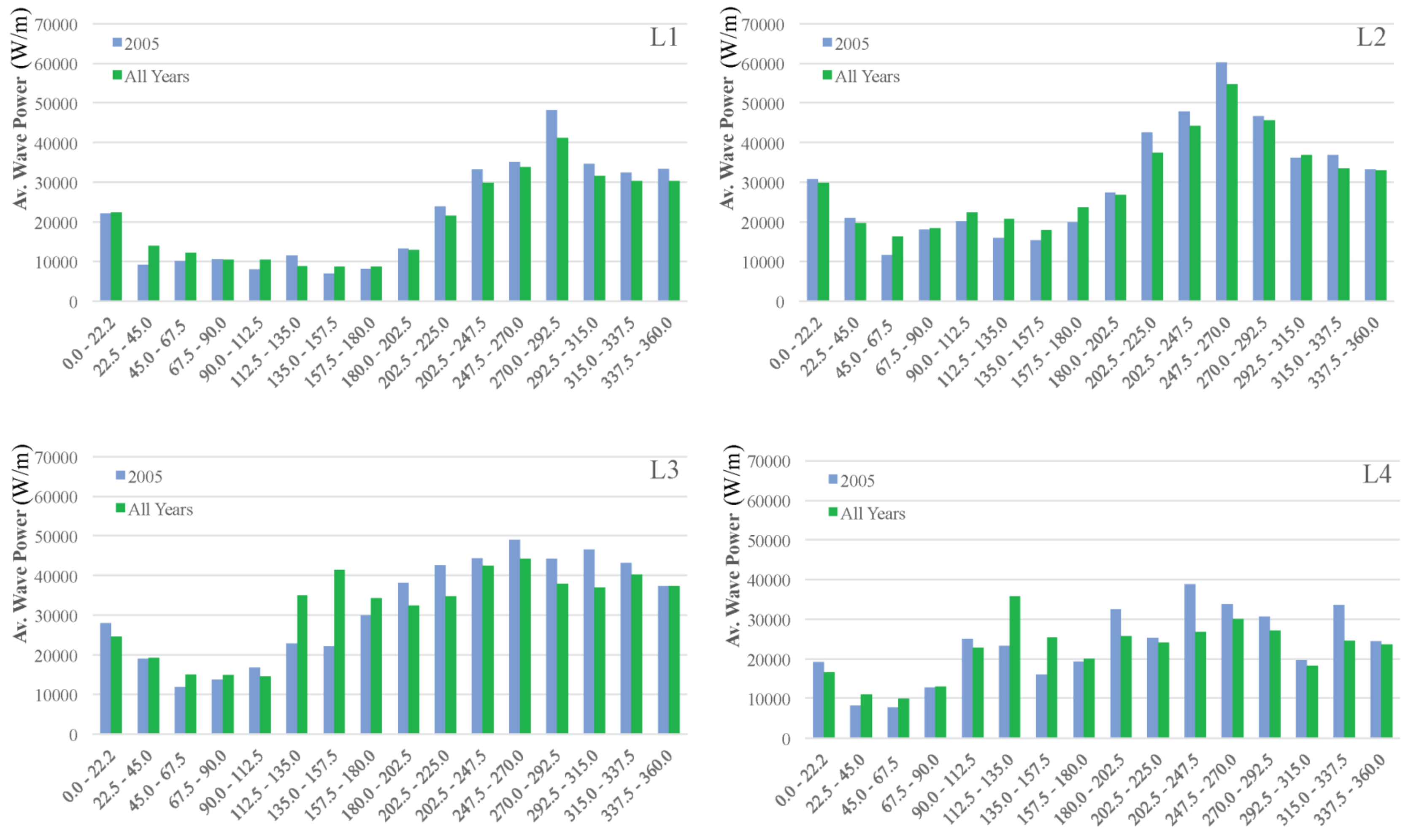
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-19a		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of monthly average wave power for 2005 with monthly average wave power over the 12-year period (2000-2011)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-19b		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Ratio of long-term mean monthly power (2000-2011) to mean monthly power for 2005 (averaged over all 4 UKMO locations).	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-20		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of quarterly average wave power for 2005 with quarterly average wave power over the 12-year period (2000-2011)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-21		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of directional average wave power for 2005 with directional average wave power over the 12-year period (2000-2011)	Checked ..	Scale Not to scale	Rev. 0
				Designed CS	Drawn	Date 26/02/2014

4.4.2 Model simulations for the representative year

The parameters used in the wave model simulation for the representative year are the same as those derived from the final calibration simulations. The model parameters are summarised in Table 4-11.

The model results over the entire study area were archived at hourly intervals for the simulated year. The outputs include: a) significant wave height, H_{m0}; b) peak wave period, T_p and c) mean wave direction. In addition, hourly wave data (mostly) including wave spectrum were output at selected locations as shown in Table 4-12. The only exception to hourly data at the selected stations is the first three months (January to March), where the data is output every 3-hours.

TABLE 4-11 WAVE MODEL SETUP PARAMETERS

Parameter	Value
Frequency grid:	JONSWAP shape, f_low= 0.05; f_high = 0.5, No of frequencies = 24
Direction grid:	Cos^5 spreading, D_low= 0; D_high = 360, No of discrete directions =24
Forcings:	Boundary waves: UKMO wave data at 4 locations (2005) Wind conditions: UKMO 12-km resolution wind data (2005). A multiplication factor of 1.2 was applied to the wind speeds.
Water level:	0.0m (i.e. MSL)
Model physics	Wind Generation: GEN=3, GROWTH= JANS, AGROW=F Bottom Friction: Jonswap formulation, Cfw=0.015, Cfc=0 Whitecapping: WCAP= Janssen Wave breaking: alpha=1, gamma=0.73 (Battjes & Janssen) Wave-wave interaction: Quadruplet wave interaction
Time steps:	Flow part ⇒ OFF in Waves ONLY run, but should be specified External timestep = 1s; ISPLIT= 6 Waves part ⇒ Propagation: NS_DELTC = 12.0s Source terms: DTMIN = 1.0, DTMAX = 12.0s
Others:	Minimum water depth = 1.0m Nautical=True PWTAIL=4 (Non-diagnostic high frequency tail)

TABLE 4-12 OUTPUT LOCATIONS FOR WAVE SPECTRUM

Location ID	Longitude (°E)	Latitude (°N)
WN1a	-4.290	58.620
WN2a	-3.434	59.051
WN2b	-2.911	59.470
WN3a	-1.374	59.796
WN3b	-1.410	60.008
Billia Croo East Buoy (2010-2012)	-3.391	58.971
Billia Croo Offshore	-3.431	58.981
Falls of Wareness	-2.820	59.140
West PF	-3.291	58.718
Mid PF	-3.089	58.715
East PF	-2.937	58.650
Costa Head	-3.280	59.210

The model results for the representative year were further processed to determine wave energy resources at the at the project site. These results are presented and discussed in Section 5.3. Furthermore, the influence of wave-current interaction on the wave energy resources in the PFOW area has been assessed and discussed in Section 5.3.

4.5 Summary and Further work

A wave model has been developed and calibrated against measured data at 3 locations in the model area. The wave model calibration achieved a high degree of correlation (> 0.85) at the three measurement stations, which is considered satisfactory. Further improvements can be made in subsequent work (outside of the present study) to reduce the small negative bias in wave height predictions. Some suggestions to investigate include: a) increasing the 12km winds by a factor of 1.3 to 1.4 to determine the optimal scaling factor; b) reducing the rate of whitecapping dissipation; c) use of spectral data from a larger FVCOM SWAVE model or other similar models to investigate the impact of mixed sea and swell and d) use of additional boundary data points to better describe the boundary wave conditions.

Analysis of wave energy flux (wave power) at the four boundary data locations has been used to select a representative wave year. The representative year has been selected as Year 2005. And wave simulations have been carried out for the representative year. The results of the representative year simulations has been used in Section 5.3 to assess wave energy resources in the PFOW area.

5 Marine Energy Resources

5.1 Introduction

According to the Invitation to Tender (ITT) Deliverable CS 1(b) requires that a one-year simulation using idealized forcing is undertaken for waves. As shown in the previous section, the year 2005 has been chosen as the representative year. The results from the simulation of the representative year (2005) are used to map the available wave energy resources in the Pentland Firth and Orkney waters (PFOW). In addition, the tidal energy resources have been calculated. Mean neap and spring tidal range and mean neap and spring peak currents were calculated from the M2 and S2 tidal constituents. Tidal power density was calculated using the annual results from the climatological simulation.

5.2 Tidal energy resources

There are two main approaches to estimating tidal energy resources – either to select a representative tidal period (typically a —mean” spring tide) to analyse, or to perform harmonic analysis on a longer time series and use the constituents derived to compute representative values. The former approach is outlined in the EMEC standards document —Assessment of Tidal Energy Resource” (www.emec.org.uk), whilst the latter approach was used for the ABPMer / NOC Atlas of Marine Energy Resources (www.renewables-atlas.info). The second approach, performing harmonic analysis of a longer time series was chosen in this study.

The PFOW model was run for a whole year with boundary conditions taken from the shelf model climatology run. The results from this run were then analysed. The MATLAB software package T_TIDE was used to analyse time series to obtain harmonic constituents.

5.2.1 Mean Spring / Neap Tidal Range

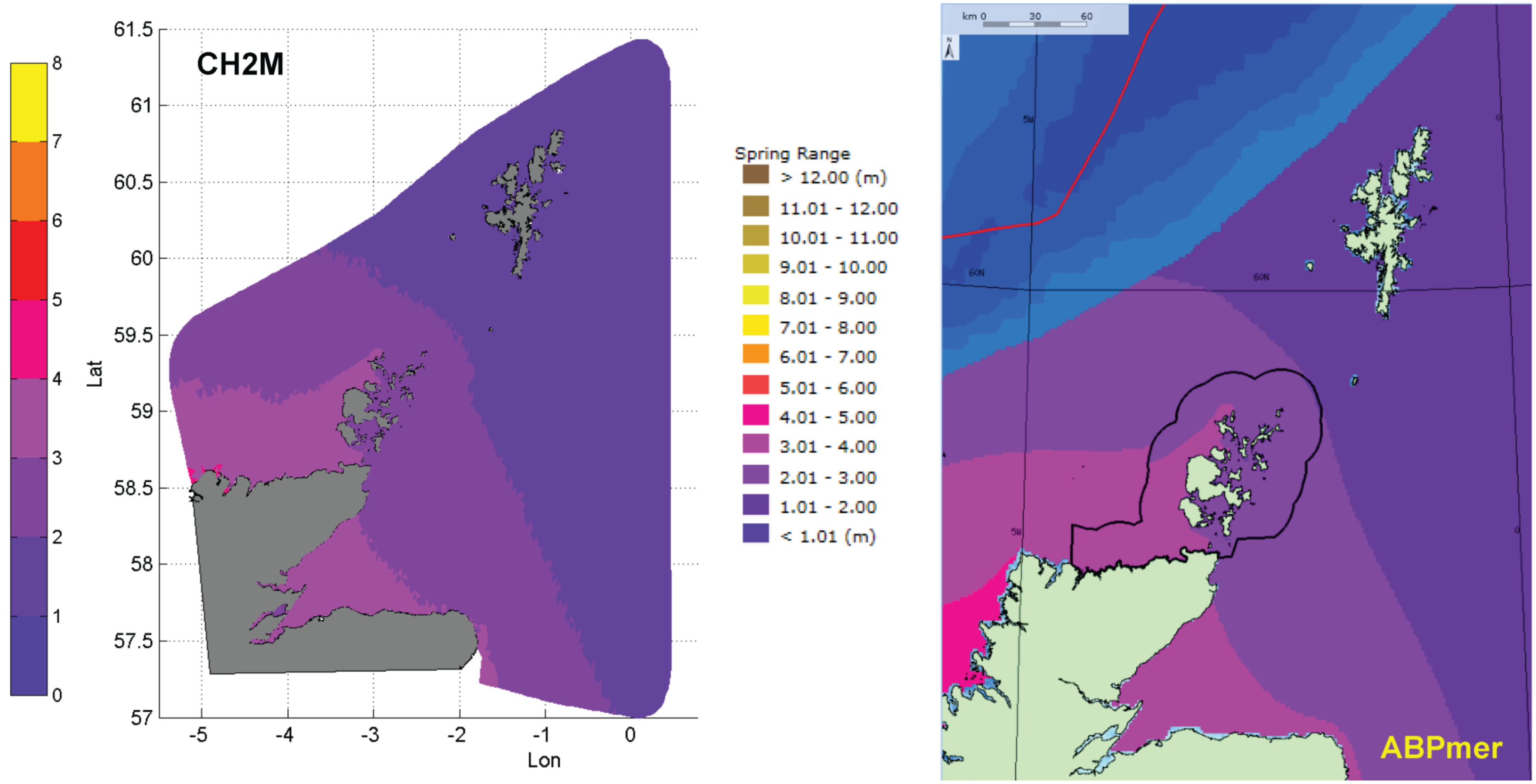
Mean spring tidal ranges have been computed directly from the two principal semi-diurnal components M_2 and S_2 based on the following equations from Pugh (1987):

mean high-water springs $= Z_0 + (H_{M2} + H_{S2})$
mean low-water springs $= Z_0 - (H_{M2} + H_{S2})$
spring tidal range = mean high-water springs - mean low-water springs

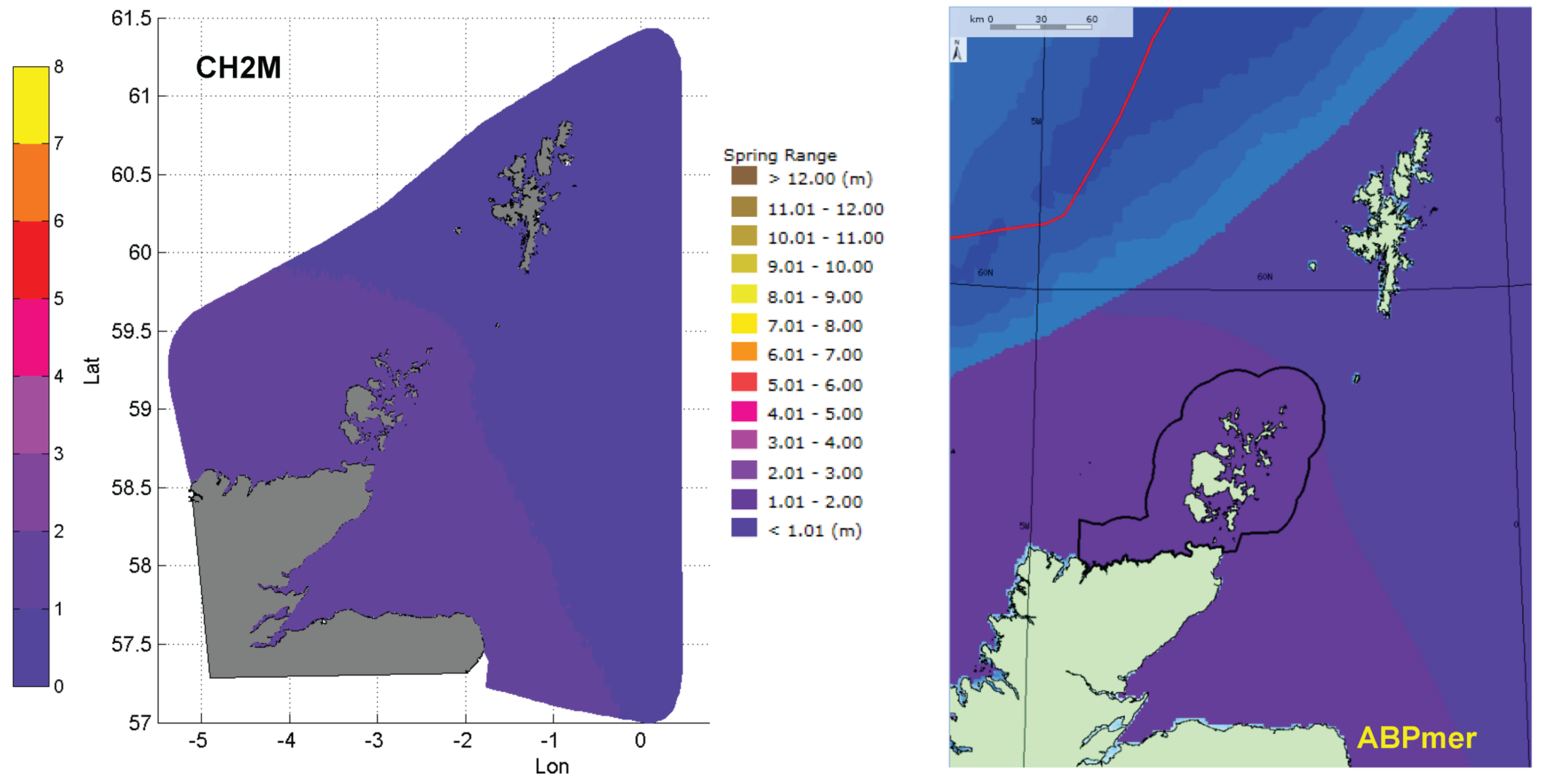
Values for these constituents were obtained from a harmonic analysis of 60 days‘ worth of data from the PFOW climatology run. These harmonic components control the timing of the spring-neap cycle, and their combination is considered to give a good measure of average spring (and neap) tides. The data was also used to calculate the mean neap tidal range as:

mean high-water neaps = $Z_0 + (H_{M2} - H_{S2})$
mean low-water neaps = $Z_0 - (H_{M2} - H_{S2})$
neap tidal range = mean high-water neaps - mean low-water neaps

A map of the mean spring results are shown, along with the equivalent tidal range from the ABPMer / NOC Atlas of Marine Energy Resources (http://www.renewables-atlas.info/), in Figure 5-1. The corresponding plots for mean neap tidal range are shown in Figure 5-2. There are some small variations in spring tidal range between the ABPMer/NOC Atlas and the CH2MHILL data sets, the reduction in tidal range with distance from the mainland occurs sooner in the CH2MHILL data along the east coast; although it should be noted that the Lochs within the Moray Firth are resolved and included within the PFOW model, but do not appear to be resolved within the ABPMer / NOC Atlas results. Overall the agreement between the two data sets is good. The comparison of neap tides shows very good agreement between the two data sets.



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-1		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of Mean Spring Tidal range calculated from FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-2		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of Mean Neap Tidal range calculated from FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014

5.2.2 Mean Spring / Neap Currents

Mean peak current speeds have been calculated from a harmonic analysis of 60 days of tidal velocities, from the PFOW climatology run. In line with the methodology used for the ABPMer / NOC Atlas, a mid-depth velocity was used for the calculations. The east and west components of velocity were analysed using T_TIDE to give the M_2 and S_2 amplitudes and phases. These were in turn analysed to give the semi-major axis amplitudes for each ellipse. The mean peak spring current was then computed as:

mean peak spring current = amplitude semi-major axis M_2 + amplitude semi-major axis S_2

The mean neap spring current was computed as:

mean peak neap current = amplitude semi-major axis M_2 - amplitude semi-major axis S_2

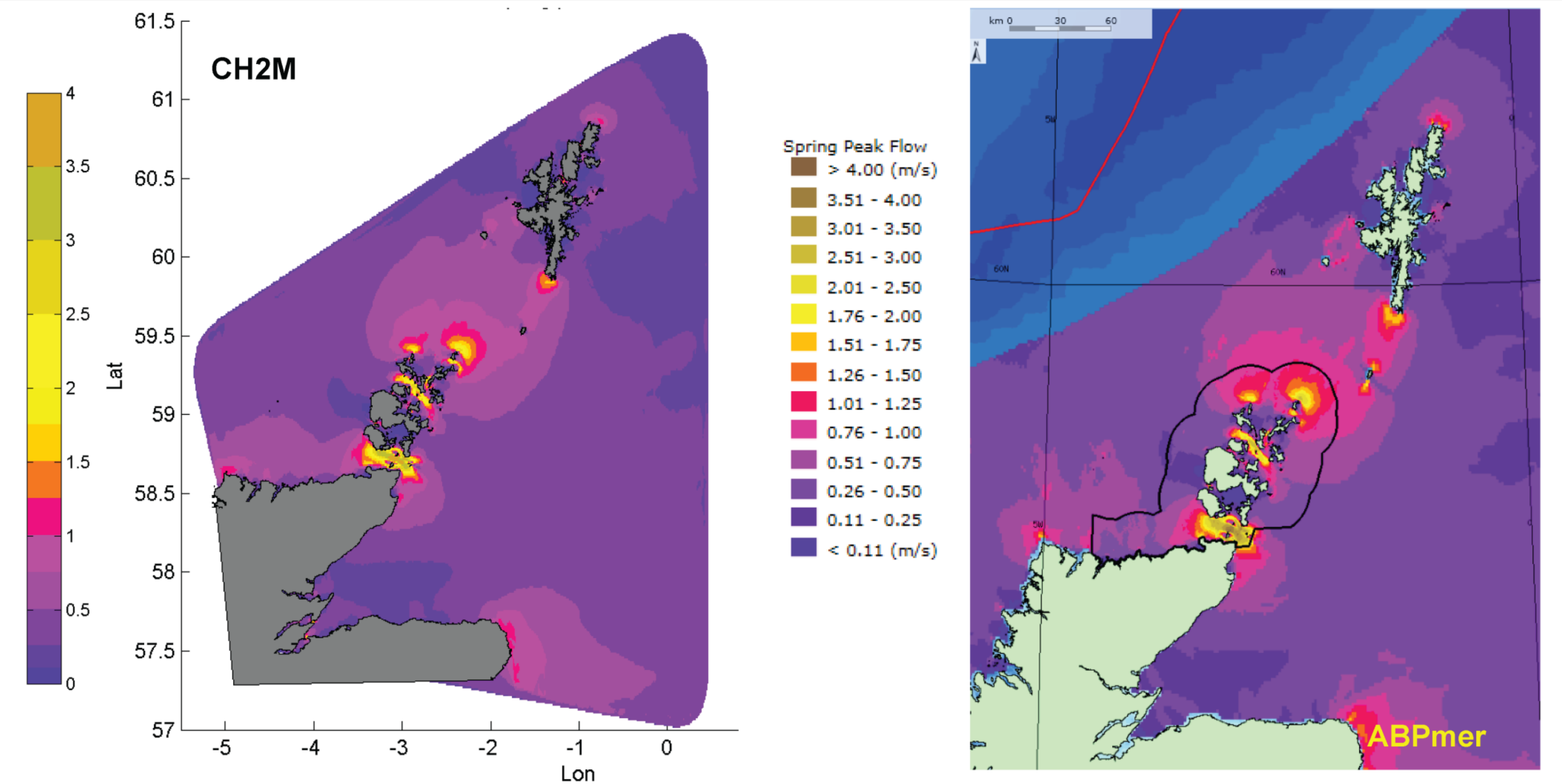
A map of the results for mean spring current is shown, along with the equivalent peak currents from the ABPMer / NOC Atlas of Marine Energy Resources, in Figure 5-3. Corresponding plots for the mean neap current are shown in Figure 5-4. The comparison of peak flows show good agreement between the data sets. Spatial variations are consistent between the two data sets for both the spring and neap tides, however the CH2MHILL data gives lower values of peak flow velocities at some locations, i.e. Fair isle (between Orkney and Shetland) and the north east corner of the mainland.

5.2.3 Mean Tidal Stream Power Density

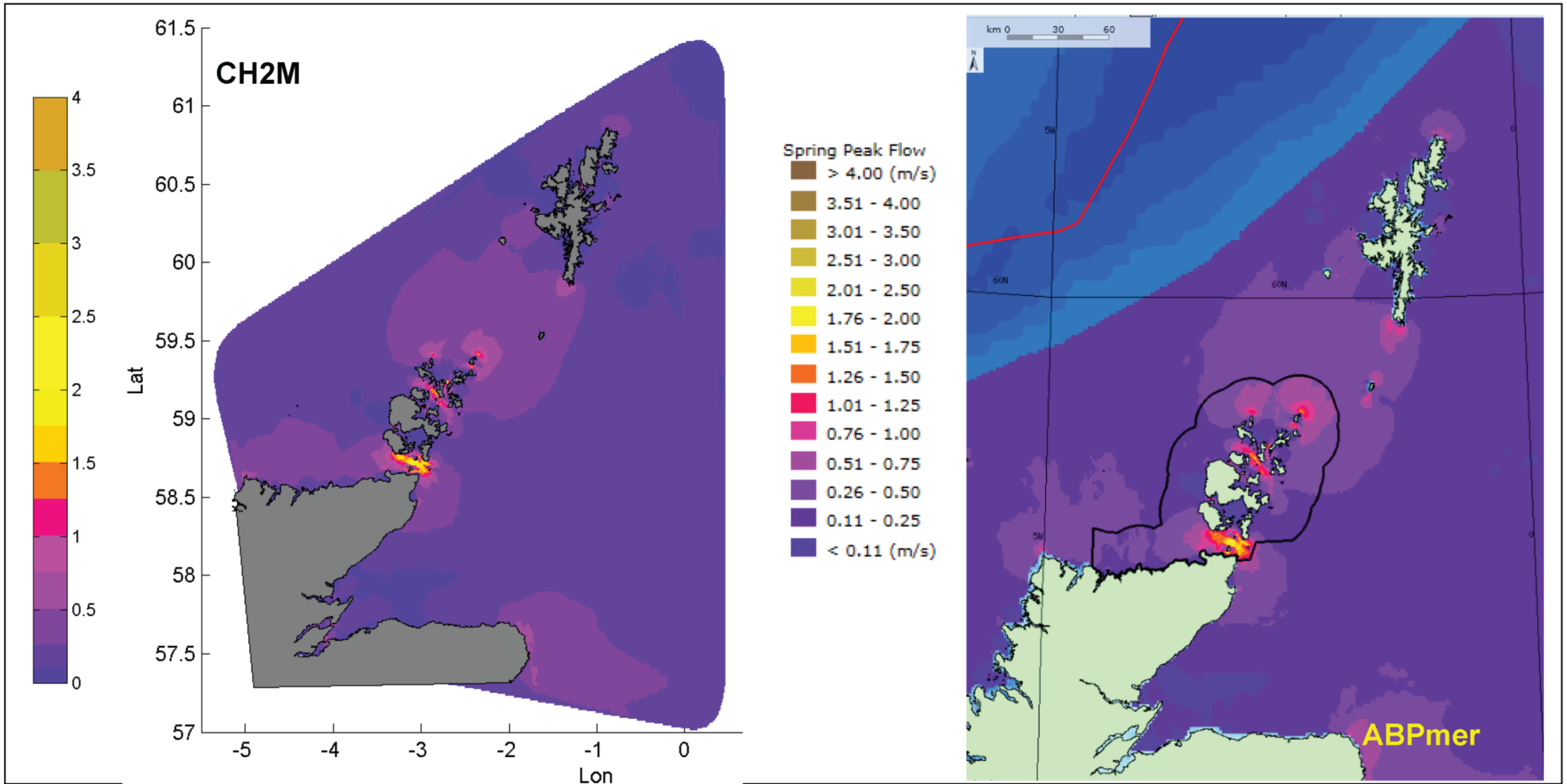
The mean tidal stream power density (denoted as P_{TS}) is the kinetic energy in the tidal flows (per unit cross-sectional area) averaged over the time period, which in this exercise was 365 days of the PFOW climatology run. A mid-depth velocity was used as in the previous section, with the mean power density being given by:

$$\overline{P_{TS}} = 0.5 \times \rho \times \overline{U^3}$$

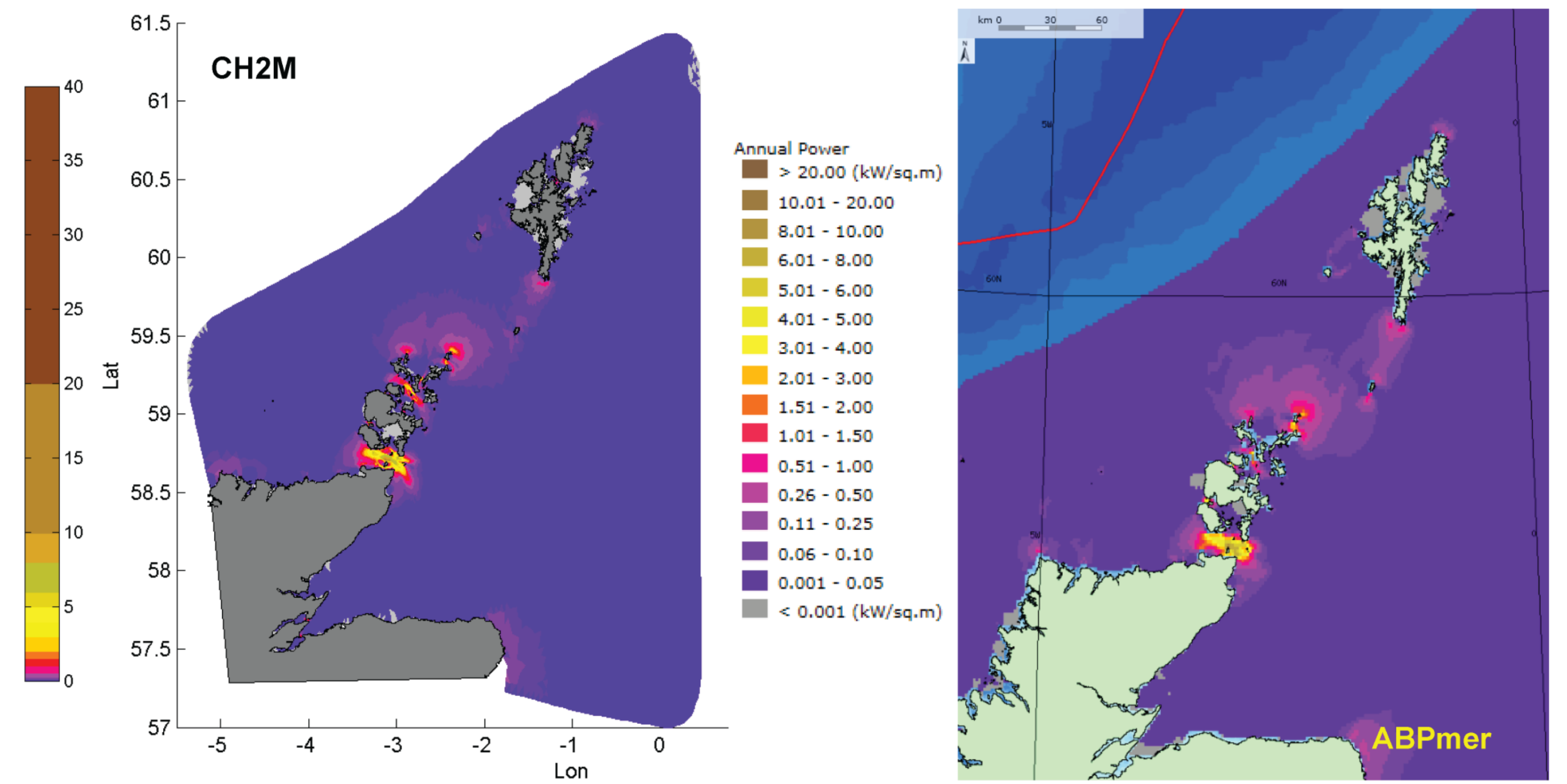
Where U is the mid-depth current speed, ρ is density taken as 1027 kg/m^3 and the overbar sign denotes averaging over the entire year. A map of the results is shown, along with the equivalent tidal power from the ABPMer / NOC Atlas of Marine Energy Resources, in Figure 5-5. As with the spring and neap peak flows the spatial variations in tidal stream power are consistent between the two data sets but the CH2MHILL data gives lower values at some locations.



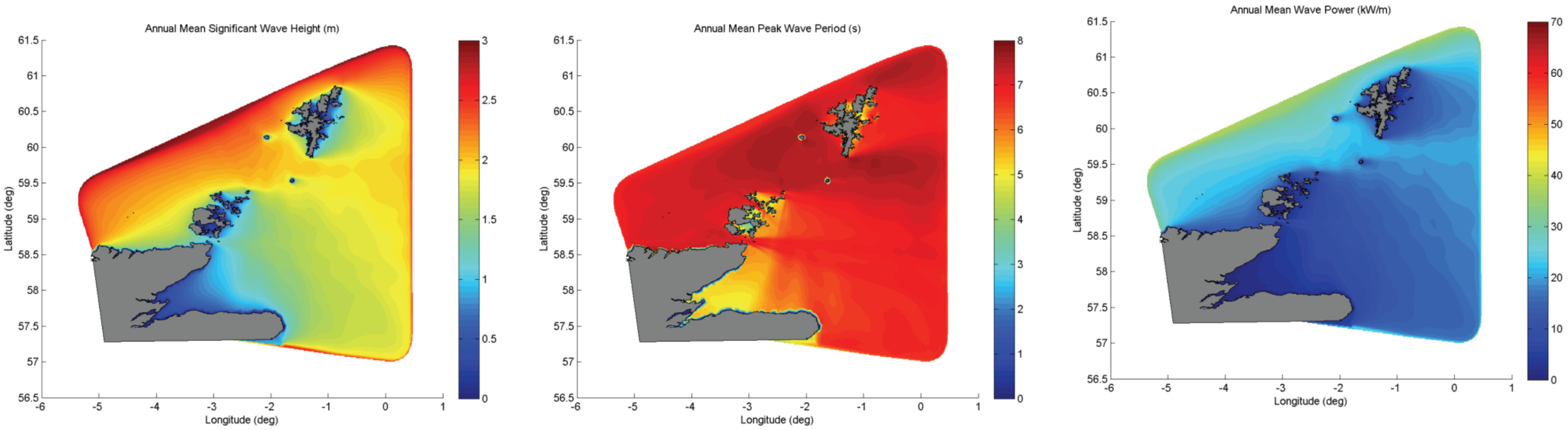
Client	Consulting Engineer	Project:	Figure Title:	Figure 5-3		
Marine Scotland	ch2m:	Pentland Firth and Orkney Waters Model	Comparison of Mean Spring Peak Currents calculated from FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-4		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of Mean Neap Peak Currents calculated from FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-5		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Comparison of Tidal Power calculated from FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014



Annual mean significant wave height (m) | Annual mean peak wave period (s) | Annual mean wave power (kW/m)

Client	Consulting Engineer	Project:	Figure Title:	Figure 5-6		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Mean annual wave height (m), wave period and wave power in the PFOW model area. Results from the 2005 model run.	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014

5.3 Wave energy resources

The model results from the wave simulations for the representative year described in Section 4 were processed to determine maps of the following wave energy parameters at the project site:

- Mean annual parameters
  - Mean annual significant wave height, H_{m0} (m)
  - Mean annual peak wave period, T_p (s)
  - Mean annual wave power, P (kW/m)
- Mean seasonal wave power, P (kW/m)
- Mean monthly wave power, P (kW/m)

The mean annual parameters are shown in Figure 5-6. As discussed in Section 4.4.1, the mean monthly wave power has been determined by scaling the wave power results calculated for the each month in 2005 with the corresponding R value to determine the long term monthly wave power. The maps showing the wave energy parameters are shown in Appendix E (E1 –E5). The results from this study are compared with previous studies in Section 5.3.3 (ABPmer, 2008 and 2012) and 5.3.4 (Neill et al, 2014).

In addition to the wave power maps, the following wave energy parameters were calculated at selected stations (see Table 4-12 for a list of the stations) and presented in Appendix E (Figure E5-E16).

- Annual wave power weighted rose
- Annual wave power exceedance curve
- Monthly distribution of wave power
- Scatter plot of Hm0-Te

Wave power is not one of the output parameters from FVCOM-SWAVE model. Hence, this parameter needs to be calculated separately. Matlab scripts were developed to carry out these calculations. There are two methods to calculate wave power namely: 1) the direct method using wave spectra and 2) the approximate method using wave parameters. These methods are described in Section 5.3.1 and 5.3.2. In FVCOM-SWAVE, wave spectra is not output over the entire model domain. Hence, only the approximate method can be used to output the wave power over the domain. However, it is possible to output the frequency spectrum at specific points in the model area, which can in turn be used to determine the wave power at those points.

5.3.1 Calculation of wave power from wave spectrum

The omni-directional wave power, P (W/m) can be calculated from the wave spectrum using (EMEC, 2009):

$$P = \int \rho g \, S(f) \, C_g(f,h) \, df \qquad (5\text{-}1)$$

In Eq 5-1, ρ is the density of seawater (1025 kg/m^3), g is acceleration due to gravity (9.81m/s), S is the energy spectral density (as a function of frequency, f), C_g is the wave group velocity (calculated using the linear wave dispersion equation. Given the frequency, f_i and spectral density, S_i at N discrete frequency points, Eq 5.1 can be expressed in discrete form to calculate wave power as shown below:

$$P = \sum_{i=1}^{N-1} \rho * g * S\left(f_{i+1/2}\right) * C_g\left(f_{i+1/2}, h\right) * (f_{i+1} - f_i) \qquad (5\text{-}2)$$

$$f_{i+1/2} = 0.5 * (f_{i+1} + f_i),$$

$$S(f_{i+1/2}) = 0.5 * [S(f_{i+1}) + S(f_i)]$$

C_g is calculated using frequency $f_{i+1/2}$ and water depth, h.

In addition to calculating the wave power, the spectral data can also be used to determine the appropriate relationship between the peak period and other integral wave periods, T_{-10} (=m_{-1}/m_0), T_{01} (=m_0/m_1) and T_{02} (=sqrt(m_0/m_2). T_{-10} is the wave energy period (T_e) used in the calculation of wave energy from wave parameters, T_{01} is sometimes called the mean wave period, while T_{02} is the approximately the zero-crossing wave period (T_z). The nth moment of the spectrum is:

$$m_n = \int f^n \, S(f) \, df \qquad (5\text{-}3)$$

And in discrete form:

$$m_n = \sum_{i=1}^{N-1} f_{i+1/2}^n * S\left(f_{i+1/2}\right) * (f_{i+1} - f_i) \qquad (5\text{-}4)$$

5.3.2 Calculation of wave power from parameters

The omni-directional wave power can be calculated using integral wave output parameters (H_{m0} and T_e) as shown below:

$$P = \rho g \frac{H_{m0}^2}{16} C_g(T_e, h) \qquad (5\text{-}5)$$

where H_{m0} is the significant wave height, C_g is the wave group velocity (calculated as a function of wave energy period, T_e and water depth, h).

In deep water (water depth > $L_0/2$, where L_0 is deep water wave length) Eq. 5.5 can be further simplified to:

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \qquad (5\text{-}6)$$

As the bathymetry in the study area includes shallow to transitional water depths, Eq 5-5 was used to calculate the wave power over the entire model area.

FVCOM-SWAVE outputs the peak wave period, but does not output the wave energy period T_e. In order to determine T_e, the spectral output data at the selected stations were analysed to determine the moments of the spectrum and spectrally derived wave periods T_e, T_{01} and T_{02} as described in Section 5.3.1. Furthermore, the ratios T_p/T_e, T_p/T_{01}, T_p/T_{02} were calculated at every output time step (typically 1-hour) and averaged over the entire year (see Table 5-1). At the exposed locations, T_p/T_e vary from 1.13 to 1.17 with an average of 1.14. The corresponding average T_p/T_{01} and T_p/T_{02} is 1.26 and 1.34. These ratios correspond approximately to a JONSWAP spectral shape with peakedness parameter of 1.9. The wave energy period T_e used in the power calculations is calculated from the calculated peak periods (T_p) using the average ratio T_p/T_e = 1.14. Table 5.2 shows a comparison of the empirically derived ratios used in this study with those used in previous wave power studies at the project site.

TABLE 5-1 SPECTRALLY DERIVED WAVE PERIOD RATIOS AT THE OUTPUT LOCATIONS (EACH RATIO IS AVERAGED OVER SIMULATED YEAR).

Location ID	T_p/T_e	T_p/T_{01}	T_p/T_{02}
WN1a	1.15	1.26	1.34
WN2a	1.13	1.25	1.32
WN2b	1.15	1.27	1.35
WN3a	1.16	1.28	1.37
WN3b	1.17	1.31	1.39
Billia Croo East buoy	1.13	1.24	1.31
Billia Croo Offshore	1.13	1.24	1.31
Costa Head	1.14	1.25	1.33
Average	**1.14**	**1.26**	**1.34**
Falls of Wareness	1.20	1.35	1.45
West PF	1.16	1.30	1.38
Mid PF	1.15	1.28	1.36
East PF	1.21	1.37	1.47

TABLE 5-2 EMPIRICALLY DERIVED PERIOD RATIOS

Location ID	Empirical ratios	Remarks
ABPmer(2008)	$T_e/T_z = T_e/T_{02}$ =1.05 – 1.14 (mostly 1.14)	
ABPmer(2012)	$T_e/T_m = T_e/T_{01}$ = 1.19	
Present study	T_p/T_e = 1.14; (T_e/T_{01}=1.26/1.14=1.11) (T_e/T_{02} = 1.34/1.14=1.18)	• For the same T_{01}, wave energy period in the present study is about 7% **lower** than ABPmer(2012). • For the same T_{02}, wave energy period in the present study is about 4% **higher** than ABPmer(2008).

5.3.3 Comparison with ABPmer results

The results from this study are compared with results from ABPmer (2008, 2012) in Appendix E (Figure E-17 to Figure E-22). The ABPmer (2008) study was used to develop a wave and tidal energy Atlas UK waters. The ABPmer (2012) study supplements this study with a high resolution model of the PFOWSA. In the present report, the ABPmer (2012) PFOWSA results is referenced as ABPmer(PFOW), while the original study for the UK Atlas is referenced as ABPmer(Shelf). In order to better illustrate the differences between the present study and ABPmer studies, the wave height and wave power are also compared at selected locations (see Table 4-10 for a list of selected locations).

The comparison plots in Appendix E show the following features:

- Model bathymetry – The main bathymetry features in both models are broadly similar (Figure E-17). The present model shows more detailed features than the 12km grid bathymetry used in ABPmer (2008). For example, the depths in the 12km grid tend to be deeper near the coast. This is expected, since the 12km grid model does not resolve the variation in the water depths close to the coast. The consequence of the increased depths in the 12km grid model is that the wave height and wave group velocity are likely to be overestimated near the coast, so that the corresponding wave power is also likely to be high.

We were not able to access plots of the PFOWSA area bathymetry used in ABPmer (2012), and therefore unable to compare with the high resolution bathymetry used in the present study.

- Wave height – The spatial distribution of the mean annual significant wave height is broadly similar for the two model results. The wave heights are higher on the western side (North Atlantic side) and lower in the lee of Orkney, Shetland, the Pentland Firth and the Moray Firth. The mean annual wave height is lower (about 0.3m) in the present model compared to the ABPmer (Shelf) results, and about 0.5m lower compared to the ABPmer (PFOW) results.

Figures E-18 and E-19 show that the ABPmer (PFOW) results are higher compared with the ABPmer (Shelf) results. The reasons for this are unclear. Possible reasons include: a) use of boundary wave data from a model that is different from the Met Office UK Waters model in the ABPmer(PFOW) model; b) Rougher wave conditions in the additional period outside of June 2000-May 2007 used in the original study; and c) differences in the model resolution and model setup. The boundary conditions for this study was obtained from the Met Office wave data, which was used in the ABPmer (2008) study. It is therefore considered prudent to focus only on comparing the present results with the ABPmer (2008 results).

We conclude that the present model provides a reasonably accurate representation of the wave height variation in the study area, as this is based on a larger high resolution model that has been calibrated and validated for this model area.

- Wave period – The mean annual peak wave period in the present model is generally lower (about 2secs) compared to the ABPmer (2008) results. The reason for this is unclear. Possible reasons are: a) the influence of swell wave conditions at the boundary of the present model. In the present model, wave parameters have been specified at the model boundary and a JONSWAP spectral shape prescribed. Such a spectral shape will not include the effect of mixed wind sea and swell waves correctly, and may lead to smaller peak wave period. However, this is the best approximation that can be made within the framework of the present study, as only the wave parameters were available as offshore boundary data; b) the method of calculation of peak period (T_p) from the spectral data. The peak period T_p is defined as the wave period corresponding to the maximum spectral energy density in the wave spectrum. However, given the discrete frequencies that are used in numerical models, calculation of peak period using the direct search method means that the output peak period will have some granularity (as it can only be found at the different discrete periods). This is the method used in FVCOM-SWAVE. However, alternative methods exist to improve the accuracy of determining $T_{p.}$ For instance, by fitting a quadratic to the 3 values around the peak spectral density (as used in MIKE 21 SW). The method used in the Met Office Coastal wave model used in the ABPmer(2008) study is not known to us at this time.
- Wave power – The mean annual wave power in the present model is generally similar or lower to the ABPmer (Shelf) results. This is probably due to the differences discussed above (bathymetry, model resolution and effect of swell waves). In the present study, the bathymetry has been compiled from the best available data sources (see Section 2.2), and the mesh resolution is significantly improved compared to previous models. As the boundary data was specified with wave parameters (as opposed to wave spectrum), it is likely that the effect of swell waves may not be well represented. Even with this limitation, the wave model was successfully calibrated against measured wave heights at 3 different locations.

5.3.4 Comparison with results from Neill et al (2014)

The results from this study are compared with results from Neill et al (2014) in Appendix E (Figure E-23 to Figure E-25). Neill et al (2014) used the SWAN (Simulating WAves Nearshore) wave model with a high resolution grid (approximately 434m grid resolution) over the Pentland Firth and Orkneys Waters to quantify the Orkney wave power resource over a ten year period (2003 – 2012). The wave model validation results achieved by Neill et al (2014) is reproduced in Figure E-23, and shows that the model is adequately validated.

The comparison plots in Appendix E show the following features:

- Monthly wave power – The variation of mean monthly wave power developed in the present model is generally similar to the results of Neill et al (2014), see Figure E-24. The wave power is typically maximum in January and gradually reduces through April. Between May and August, the wave power is generally low, and starts increasing gradually again in September through December. The calculated wave power in the present model is however higher (visually estimated as about 25% higher) than the results of Neill et al (2014).
- Annual wave power - The spatial variation of the mean annual wave power developed in the present model is similar to the results of Neill et al (2014). This indicates that most of the wave power resource are on the western and northern coasts (and offshore areas) of Orkneys. However, the calculated wave power in the present model is higher (visually estimated as about 25% higher) than Neill et al (2014). Furthermore, the penetration of wave energy through the Pentland Firth does not appear to be reproduced to the same extent in the Neill et al model.

It is interesting to see that the key features of the annual and monthly wave power resource are similar in both models. However, there are differences in the level of the wave power resources. Neill et al estimated the uncertainty in their calculated mean annual wave power resources to be in the order of 15 to 20%, west of the Orkneys. Addition of the uncertainty estimate to their calculated wave power resources will bring their results closer to the results from the present study.

5.3.5 Influence of wave-current interaction

The influence of wave-current interaction can be conveniently separated into two categories – namely, 1) effect on currents on waves as summarised in Table 5-3, and 2) effect of waves on currents summarised in Table 5-3.

TABLE 5-3 EFFECT OF CURRENTS ON WAVES

Process	Effect	Modelled in FVCOM (Y/N)
Tide levels	• Changes to wave refraction and shoaling in shallow and intermediate water depths • Changes the depth limited wave condition in shallow water	Y – Included in wave action equation solved.
Current speeds	• Current refraction (Doppler effect) • Wave steepening & lengthening due to opposing and following currents	Y – Included in wave action equation solved.

TABLE 5-4 EFFECT OF WAVES ON CURRENTS

Process	Effect	Modelled in FVCOM (Y/N)
Wave boundary layer	Increased bottom friction by mean flow	N
Stokes drift	Modification of currents in the top layers due to wave orbital velocities.	N
Radiation stresses	Breaking waves driven currents in the surf zone. (This requires that the zone of wave breaking should be resolved, typically with mesh resolution in the order of 5 to 10m, which is not realistic for this study).	Y (depends on mesh resolution)
Mixing due to surface waves	Changes to turbulent mixing due to surface waves	Y -parameterised in 2.5 MY model

In the present study, the influence of wave-current interaction on wave parameters and wave energy resources in the PFOW area has been assessed. The assessment was carried out by running two sets of simulations, namely: 1) waves only runs (with and without wind forcing) and 2) coupled wave and flow model simulation as summarised in Table 5-5. The model setup parameters for the runs are summarised in Table 5-6. These simulations were carried out using the wave model mesh, which is different (coarser) from the mesh used for the hydrodynamic simulations in Section 3.2.1. Thus, a tides only simulation was also carried out to ensure that the modelled tides using this mesh is also good.

TABLE 5-5 SIMULATIONS CARRIED OUT TO ASSESS EFFECT OF WAVE-CURRENT INTERACTION

RunID	Description	Simulation period	Remarks
co00	Tide only simulation, no waves	10 days 1/May/09 0100 to 11/May/09 0100	Check tide levels and current speeds are reasonable when compared to measured data & previous flow model calibration.
wo01	Waves only simulation	48h 1/May/09 0100 to 3/May/09 0100	Baseline run, no wind forcing
wo02	Waves only simulation + wind	48h	Baseline run + wind forcing
wc01	Waves + tides	48h	Assess influence of wave-current interaction by comparison with Run wo01
wc02	Waves + tides + wind	48h	Assess influence of wave-current interaction by comparison with Run wo02
wc03	Waves + tides + wind + surface wave mixing ON.	48h	Assess influence of wave-current interaction by comparison with Run wo02

TABLE 5-6 MODEL SETUP PARAMETERS

Parameter	Value
Mesh:	23,508 nodes; 41,666 cells; spherical co-ordinates (lon/lat); 4 sigma levels
Time steps:	EXTSTEP_SECONDS=0.5 , ISPLIT= 3
Forcing:	Elevation forcing + nesting data (from AMM model); Sensitivity to constant wind forcing (U10 = 10m/s, Udir = 270degN); HEATING, PRECIPITATION, AIRPRESSURE = F
Turbulence physics	Mixing: Smagorinsky+MY2.5; Sensitivity to surface wave mixing for coupled runs; Bottom roughness: z0 = 0.1m TS off;
Wave model setup parameters:	Boundary data: Hm0=2m, Tp=10s, MWD=270degN Wind forcing: U10 = 10m/s, Udir=270degN Other parameters as in final calibrated model setup (see Section 4).

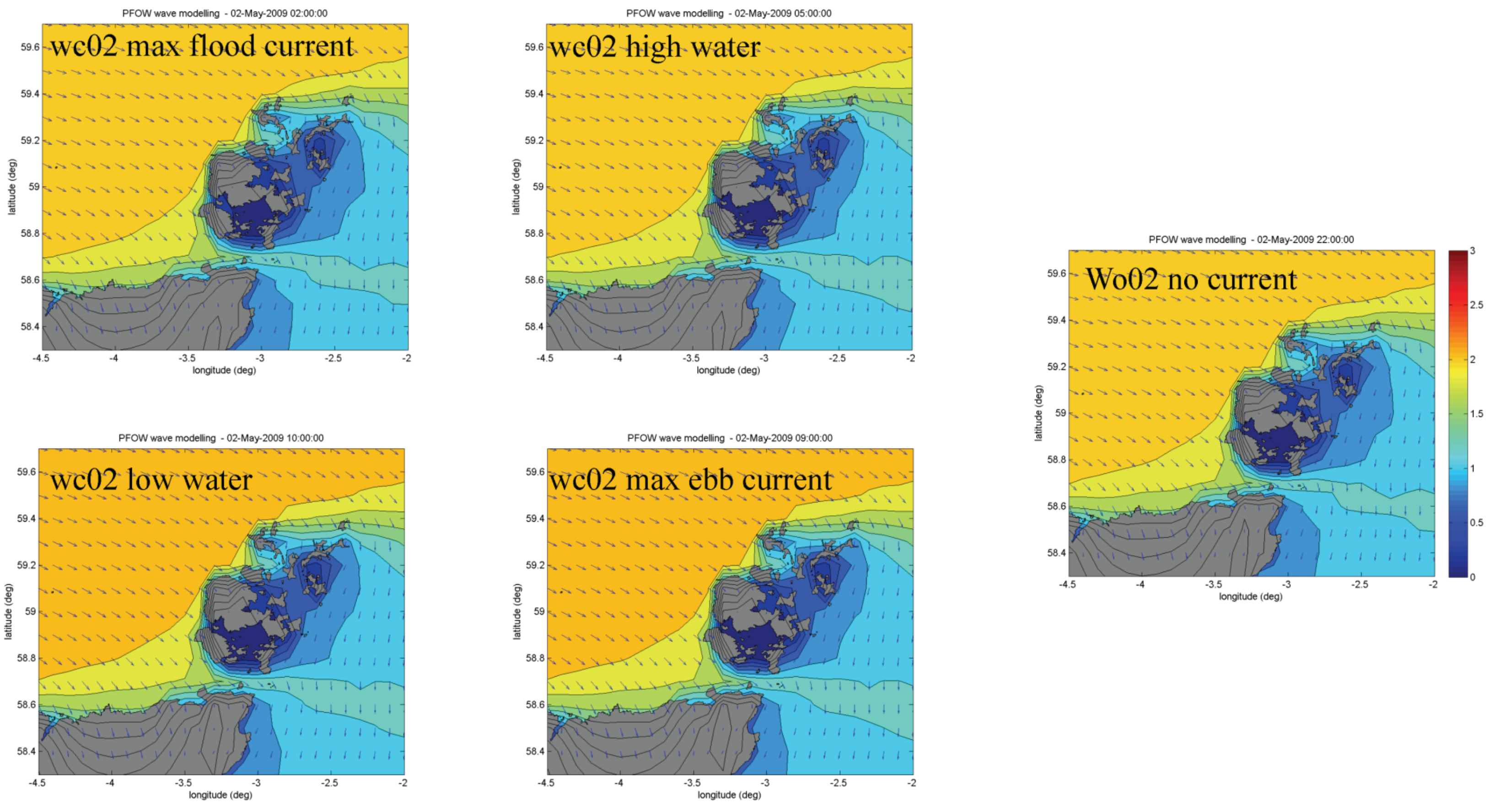
The detailed model results are shown in Appendix E (Figure E-26 to Figure E-30), while the key results are shown in Figure 5-7 and Figure 5-8. Figure E-26 shows that the tide is well predicted by the model (Figure E-26), while Figure E-27 show that the maximum currents in the area are attained in the Pentland Firth. The main result from the investigation is that the effect of wave current interaction on the wave parameters is small (< 0.1m for wave height and 2 to 4 deg for wave direction). Similarly, the effect on wave power is small, but localised changes of up to 10% in wave power was found at a few locations. Furthermore, the effect of increased turbulent mixing due to surface waves is not noticeable in the calculated depth-averaged current speeds or water levels. However, the absence of any noticeable effect may be due to the limited number of vertical sigma-levels used in this assessment.

Other investigators have also reported that the effect of wave-current interaction on the calculated wave energy resource is small. For example, Hashemi et al (2014) carried out a study to investigate the impact of wave-current interaction on the NW European shelf seas. They carried out model simulations for January 2005 using a decoupled SWAN model, a one-way coupled model (in which calculated water levels and currents from a separate model are introduced into SWAN) and a fully coupled wave-current model using a model called COAWST. They concluded that the decoupled SWAN model, one-way coupled model, and the COAWST model seem to produce very similar results. However, they also observed that the impact in some specific regions (e.g. Orkney) can reach 10% of the resource.

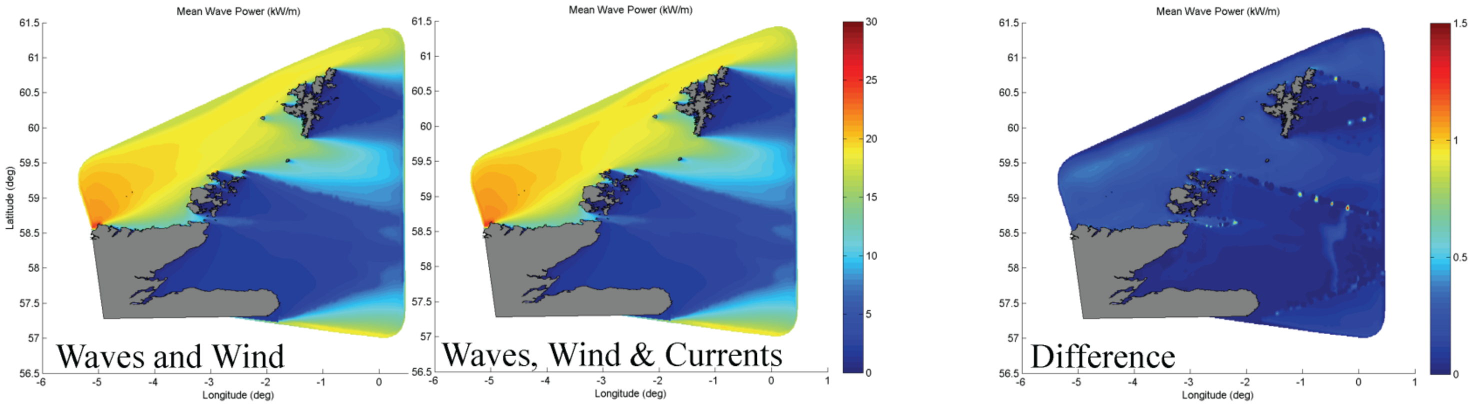
Wolf et al (2006) also investigated the influence of wave-current interaction in Liverpool bay. They carried out a wave model hindcast for 26 January – 7 February 2003, using the coupled POLCOMS-WAM model, forced by Met Office mesoscale model winds. They also obtained buoy and ADCP observations for the same period. They concluded that the general agreement between model and measurements is very good. However, they observed marked tidal modulations of the wave height especially, and to a lesser extent the wave period, that are not captured by the coupled model. They found only slight differences between the uncoupled and coupled model runs for Liverpool bay.

The conclusion from the present study is however different from ABPmer (2012) who also studied the impact of wave-current interaction on wave parameters and wave energy resources in the PFOWSA. The ABPmer (2012) study was carried out by determining the difference in wave conditions for a waves-only run, and a simulation using one-way coupling (pre-calculated ebb and flood pattern of mean spring tidal currents used as input to the wave model). They found that the effect of wave -current interaction is quite significant. ABPmer calculated that the changes in Hm0 for ebb and flood flow are well above 20% at a number of locations including the Pentland Firth. However, they also observed that the large changes are mostly in areas where the baseline wave conditions is typically low. It is also important to note that they found little impact of wave-current interaction in the western part of the Orkneys where the wave energy resource is high.

In summary, the assessment of wave-current interaction on wave energy resources carried out in this study shows that the effect is generally small, but localised changes of up to 10% in wave power can be seen at some locations.



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-7		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Simulated wave conditions at different stages of the tide in the coupled waves+tides simulation. Shaded contours are Hm0, vectors are wave direction directions scaled with Hm0	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-8		
Marine Scotland	ch2m	Pentland Firth and Orkney Waters Model	Wave power (kW/m) averaged over the last 36 hours of the 48h simulation (left & middle). Right panel: Difference between left and middle plots.	Checked ..	Scale Not to scale	Rev. 0
				Designed CSS	Drawn	Date 02/06/2014

5.4 Approaches for assessing impacts of extracting energy

The energy available from currents and waves throughout the PFOW area without any energy extracting devices have been determined in the preceding sections. However the future use of the hydrodynamic and wave models will entail the determination of the impact from the extraction of tidal and wave energy from the system. If the flow or wave extracting device can be represented adequately in the numerical models, the impact of the device can be determined by post-processing of the model results to determine differences with the baseline conditions for a range of parameters. Thus, in this section, we focus on how the devices can be incorporated within the FVCOM model so that the impact of extraction of energy can be assessed.

5.4.1 Representation of flow energy devices in FVCOM

The ongoing Terawatt Project produced a report by Baston, Waldman and Side (2014) entitled —Modelling energy extraction in tidal flows”. This position paper presents approaches used by a range of organisations and numerical models, to simulate the energy removed by energy extraction devices and the effect upon the surrounding hydrodynamics. The information contained within the Terawatt position paper should be read with this report, as the Terawatt project is an ongoing project which extends beyond the duration of the present study. This paper also goes into much more detail than can be included in this section of this report.

5.4.1.1 Scale of representation

Simulating the accurate shape and dynamics of a tidal energy device and its effect upon the immediate surrounding water body could only be simulated accurately using Computational Fluid Dynamic (CFD) models. These are costly in terms of time and would only allow the structure to be simulated and not the wider regional area surrounding it which is usually the reason to simulate the devices. This is the reason why representation of tidal energy devices, assumed here to be turbines, are often represented as supra or sub-grid scale devices using 2D or 3D hydrodynamic models. Supra scale meaning that each device is resolved in one or more model elements (but not in the detail that a CFD model could do) whereas the sub-grid scale means that a device or number of devices are included within a model element that is larger than the device(s).

A tidal energy device will generally consist of rotating blades as well as a mounting structure (if mounted onto the bed) both of which can have an effect upon the water flowing past. There are the drag forces from the whole structure as well as the lift/rotational forces from the turbine blades which extract the energy from the water flowing by. Additional turbulence is also created from the structure and the revolving blades which can cause further mixing in the water column. The additional mixing may not be important for 2D model, but could be for a 3D model if the vertical structure is important.

Another factor to consider is the interaction between multiple devices deployed in an array. Representing a number of devices within one grid element, may allow for the representation of the effects from the drag and the energy extraction, but will not be able to simulate the hydrodynamic interaction between the structures. For example an acceleration of water may occur between two closely located devices creating faster flowing water downstream, likewise a shadow zone of slower, more turbulent water is likely to extend downstream of a turbine, which in turn could affect a turbine downstream.

In the current PFOW model the model elements within the Pentland Firth have, in general, dimensions of the order of 100m or more. It would be possible to refine the model mesh further around an array of devices in order to resolve the overall dimensions of each individual device, however this will have an impact upon the timestep used and would slow the model down.

The alternative approach is to use a subgrid scale representation. In this approach the energy extraction and drag forces for each device are parameterised within an element that is larger than the device itself, in fact this representation may include more than one device although the hydrodynamic interaction is then affected.

What would be preferable would be a mixture of both approaches with one device per model element, thus the resolution of the model is driven by the distance apart of the devices rather than the device size itself. This approach would then be able to include to some extent, the hydrodynamic interaction between the devices. If devices are close together however, then this approach may prove too costly in terms of increases to simulation time.

5.4.2.1 Representation of energy extraction

In 2D models, a structure such as a turbine and the support is often represented by considering the drag/lift forces as an increase in the local bed roughness, such structures are often parametrised as a pier. This allows for sub-grid scale structures to be represented by models with resolutions greater than the dimension of the structure itself. However as the turbine and structure will affect the flow in only part of the water column then the 2D approach is not entirely valid as the assumed model velocity profile will not be correct following the inclusion of the device.

Models such as MIKE3 can include structures by including the drag, and for turbines the lift forces also.

An alternative approach has been presented, Yang et. al. (2013) where a momentum sink was included in the underlying model equations (using FVCOM) to take into account drag of the supporting structure and the turbine blades, as well as the thrust from the turbine blades. This approach seems a sensible approach requiring a number of parameters to define the coefficients of drag and thrust. As given in Yang et. al. (2013), the momentum sink rate due to tidal energy extraction by tidal turbines can be defined generally as:-

$$\overrightarrow{F^M} = \frac{1}{2} \cdot \frac{C_e A}{V_c} \cdot |\overrightarrow{u}|\vec{u}$$

Where $\overrightarrow{F^M}$ is the momentum sink rate from a control volume, V_c by tidal turbines

C_e is the momentum extraction coefficient

A is the flow facing area of the turbines, or turbine swept area

and, $\vec{u}$ is the velocity vector.

Yang, et al., goes on to further break down the momentum sink rate by subdividing a tidal turbine unit into three energy dissipative parts:-

1) turbine blades

2) turbine supporting poles

3) turbine foundation

Giving:-

$$\overrightarrow{F^M} = \frac{1}{2V_c}\left[(C_T + C_b)A_b + C_pA_p + C_fA_f\right] |\vec{u}|\vec{u}$$

Where

C_T is the turbine thrust coefficient for the amount of thrust exerted on a fluid, C_b, C_p and C_f are drag coefficients due to the physical structure of turbine blades, supporting poles and foundation. The area $A_b$is the flow-facing area swept by the turbine, A_p and A_f are the total flow-facing areas of the supporting poles and foundation respectively. This general approach has also been implemented (with small changes) by Rory O'Hara-Murray of MSS (personal communication and presentation at UK FVCOM user group meeting).

5.4.2 Representation of wave energy devices in FVCOM

As part of the ongoing TeraWatt project, MacIver et al (2013) produced a comprehensive position paper that summarise various approaches of representing wave energy extraction in regional scale numerical models. They considered spectral wave models and Boussinesq wave models as best suited for regional scale hydrodynamic models considering the environmental impact of arrays of wave energy converters, where domains can extend up to several tens of kilometres. Potential flow or CFD models were considered more appropriate in the immediate vicinity of devices.

FVCOM wave model (FVCOM-SWAVE) is a spectral wave model. The approaches for representing the devices in spectral models presented in MacIver et al (2013) are discussed below in relation to FVCOM.

The representation of wave energy converters in spectral models, either individually or as an array, can be achieved *only through accounting for their influence on the wave energy density spectrum*. Specifically phase-dependent effects cannot be accounted for directly, although certain effects, e.g. diffraction, can be modelled approximately. Furthermore, spectral wave models do not account for the scattering or radiating of energy by the wave energy converters.

Diffraction of wave energy is represented in spectral wave models (including FVCOM-SWAVE) using an approximate phase-decoupled refraction-diffraction formulation. Thus, the effects are not well reproduced in the immediate vicinity of a structure (i.e. within a few wavelengths). The diffraction option can be switched on in the INPUT file for FVCOM-SWAVE. However, this option has not been tested in this project.

5.4.2.1 Supra-Grid representation

In the supra-grid representation, each individual device within the array is resolved in the model, and a sufficient number of cells (at least 5 cells) are used to resolve the spaces within the individual devices. An explicit frequency dependent transmission coefficient is specified at each device (Foley et al, 2012). This ensures that the model can represent the effect of wave energy extraction for different frequencies at each device.

It is possible to resolve individual devices in the FVCOM SWAVE model (at mesh generation stage), hence this method can be used in principle. However, there is presently no facility to specify a frequency dependent transmission coefficient in FVCOM. The only alternative is to model the devices as small islands, with the surface of each island taken as an absorbing layer. This will however not model the wave energy extraction at the devices correctly.

5.4.2.2 Subgrid representation

In the subgrid representation, the energy absorption characteristics of individual device is represented as a point source [or sink] of energy at a computational node by including an additional frequency and directionally dependent source term (S_{wec}) in the governing equation (Silverthorne & Folley 2011, Weywada, Child & Cruz 2012, Greenwood, Christie & Venugopal 2013).

$$S_{wec} = c_g \, C(f,\theta) \, E(f,\theta)$$

where c_g is wave group velocity, $C(f,\theta)$ is a frequency and directionally dependent coefficient for the wave energy device.

The source term, S_{wec} is not implemented yet in FVCOM. Hence, it is presently not possible to use this method in FVCOM without significant additional coding.

6 Summary and Conclusions

6.1 Introduction

The aim of this report is to describe the setting up, calibration and application of a three dimensional hydrodynamic and a wave model of the Pentland Firth and Orkney Waters (PFOW). These models have been developed so that they can become community models for further development and application by Marine Scotland and other partners. In the present study, the models have been calibrated against available data; they have been used to simulate one full year (hydrodynamic model run for a full year with climatological forcing, while the wave model is run for a representative year) and they have been used to provide estimates of tidal and wave energy resources in the PFOW.

The FVCOM model has been used for this study for both the hydrodynamic and wave models. This model was chosen because of its capabilities as well as it being freely available, which then fulfils the aim for them to become community models.

Due to the exposed nature of the area around the north of Scotland and the Orkney Waters this is an ideal area for wave energy extraction. Similarly due to the nature of the high current speeds flowing through the Pentland Firth and the islands that make up the Orkneys, a lot of focus has been put on the potential for energy extraction from these strong currents. These models provide estimates of the energy available from these two sources as well as a means to determine the net effect of future deployments of such devices.

6.2 Hydrodynamic model

The PFOW hydrodynamic model was setup using bathymetry taken from a number of sources, from the freely available but coarser EMODnet/NOOS data, to the UKHO and Marine Scotland higher resolution datasets. Where data from these sources was not readily available, Admiralty Charts were digitised (with permission from the Hydrographic office) to fill in any gaps. All bathymetry was reduced to mean sea level as the common datum.

The model mesh was initially setup using the mesh generator which forms part of the MIKE by DHI suite, although this was later converted into an SMS format mesh so that the quality of the mesh could be adjusted to fit in with the requirements of FVCOM. The mesh used spherical coordinate system (latitude and longitude). The model was run with 10 vertical sigma layers.

An analysis of the data available for forcing the hydrodynamic (HD) model provided three main periods for calibration and validation. These were in 2001, 2009 and 2012 which aligned with suitable data for comparison. The simulation in 2001 was aimed at calibrating the hydrodynamic part of the model, whereas the 2009 was for comparison of the baroclinic version of the model with all forcing/inputs available. Datasets existed for calibration and validation of the model in the form of timeseries of water levels and current speeds as well as transects recording currents across either end of the Pentland Firth. Additionally temperature and salinity profiles were available for comparisons with the model.

Boundary conditions for water levels, depth-averaged currents, temperature and salinity were taken from the Atlantic Margin Model (AMM) developed by NOC-L. Water levels and currents were provided at hourly intervals, whereas the temperature and salinity were provided at daily intervals for each of the 40 layers in the AMM. Meteorological forcing was provided by NOC-L and derived from the Met Office model. The heating input was calculated internally by FVCOM rather than provided externally. This was found to provide the best results for sea surface temperature. River flow data was provided by CEH from their Grid to Grid model. Salinity was set at 0 psu, and temperature at 7 degrees Celsius which was felt appropriate for the observed sea water temperatures.

The model was initially driven by water level boundaries alone, however it proved to be very difficult to get a stable model when temperature and salinity were included as well as the 10 layers required. After experimentation, a nested boundary approach was used which applies current speed at the boundaries in addition to the water level, temperature and salinity, this proved to make the model much more stable and usable.

Comparisons between the model results and measurements of water level and current speeds showed generally good agreement. Comparisons of the 10 layer baroclinic model showed that salinity comparisons with data were generally within the 1 psu in line with our target. Temperature was within 1 degree Celsius, although our target was to be within 0.5 degrees, however much of this difference was due to the AMM derived boundary conditions which also exhibit temperatures that are too high.

One requirement of this study was to produce a one-year climatic run based upon climatological forcing to represent a typical annual cycle. Mean boundary forcing for water levels (mean yearly tides), currents, temperature and salinity were taken from the Scottish Waters Shelf Model climatology results. An efficient method was developed to interpolate the forcing data onto the nested boundary nodes and elements. River climatology was also provided by CEH and used for this study following analysis by NOC-L. Meteorological forcing was derived by NOC-L from ECMWF (ERA-Interim) data to provide monthly mean wind-stress, pressures, heating and evaporation minus precipitation from the period 1981-2010.

Average monthly temperature and salinity simulated by the model were compared against sea surface temperature and salinity climatological datasets and residual currents for the months of February and August; the results compared well with this data.

6.3 Wave model

The objective for the wave model was to construct a calibrated and validated wave model for the Pentland Firth and Orkney Waters, and subsequently use the model to carry out simulation for an idealised year and determine wave energy resources. After discussion with Marine Scotland and analysis of available data, it was decided that a representative year approach should be used for the idealised year.

The model mesh was derived from the one used for the hydrodynamic model, although the resolution was reduced in order to bring model run times to practical limits. Boundary wave data at four locations were obtained from the UK Met Office wave models for the period 2000-2012 whilst wind data was obtained from the UK Met Office forecast models that had been archived at NOC-L.

The wave model was calibrated against measured wave data at Scapa Flow, Dounreay and Holm Sound; the model results are satisfactory at Scapa Flow and Holm Sound, but generally under-predicts wave height at Dounreay (negative bias). At all three locations, the correlation is greater than 0.85. Suggestions are made in the summary and further work section on how to reduce the negative bias and improve the correlation.

Analysis of wave energy flux was used to determine a representative year (2005) upon which wave simulation for the entire year were carried out. The results from this simulation were used to calculate wave power and compared against results from previous studies. Additionally the effect of wave-current interaction was also assessed which showed that the effect accounted for less than 10% effect upon the wave height.

Suggestions are also included in this report on how to include energy extraction devices (waves and currents) into the FVCOM model.

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