The Scottish Shelf Model.
Part 1: Shelf-Wide Domain

Scottish Marine and Freshwater Science Vol 7 No 3

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The Scottish Shelf Model. Part 1: Shelf-wide domain

Marine Scotland

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The Scottish Shelf Model: Part 1: Shelf-wide domain

Marine Scotland

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1.5	5/09/2014	Climatology	Judith Wolf, Hannah Buckland		
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1.8	12/09/2015	Final Report	Judith Wolf Caroline Stuiver	Hakeem Johnson	John Debenham

The Scottish Shelf Model. Part 1: Shelf-wide domain.

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The FVCOM model has been developed by the Marine Ecosystem Dynamics Modeling Laboratory 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 Lucy Bricheno and Hedong Liu (NOC-L).

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.

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
ADCP	Acoustic Doppler Current Profiler
AMM	Atlantic Margin Model
ASCII	American Standard Code for Information Interchange
BADC	British Atmospheric Data Centre
BODC	British Oceanographic Data Centre
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CEH	Centre for Ecology and Hydrology
CS3, CS3X	Continental Shelf model 3 (1/6°x 1/9°) and extended
CTD	Conductivity, Temperature and Depth instrument
DHI	Danish Hydraulic Institute
DTM	Digital Terrain Model
ECMWF	European Centre for Medium range Weather Forecasting
EMODNet	European Marine Observation and Data Network
ERA40, ERA-Interim	ECMWF re-analysis of the global atmosphere and surface conditions for 45-years, 1957-2002; ERA-Interim extends this for 1989-present
FVCOM	Finite Volume Community Ocean Model
G2G	CEH Grid-to-Grid hydrological model
GEBCO	General Bathymetric Chart of the Oceans

Abbreviation	Meaning
GSHHS	Global Self-consistent, Hierarchical, High-resolution Shoreline
ICES	International Council for the Exploration of the Sea
MGGD	Marine Geology and Geophysics Division
MHW	Mean High Water
MHWS	Mean High Water Spring
MS	Marine Scotland
MSL	Mean sea level
NAE	Met Office North Atlantic European model
NGDC	National Geophysical Data Centre
NOAA	US National Oceanic and Atmospheric Administration
NOC-L	National Oceanography Centre – Liverpool
NODB	National Oceanographic Database
NTSLF	National Tide and Sea Level Facility
NWP	Numerical Weather Prediction
ODYSSEA	Ocean Data analYsis System for SEA
OS	Ordnance Survey
POLCOMS	Proudman Oceanographic Laboratory Coastal Ocean Modelling System
PFOW	Pentland Firth and Orkney Waters

Abbreviation	Meaning
RMS	Root-mean-square
SEPA	Scottish Environment Protection Agency
SMHI	Swedish Meteorological and Hydrological Institute
SMS	Surface Water Modeling System
SSW	Scottish Shelf Waters
UKHO	United Kingdom Hydrographic Office
UKMO	United Kingdom Meteorological Office
UM	Met Office Unified Model
WVS	World Vector Shoreline

1 Introduction

1.1 Background

Halcrow Group Ltd. 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 European Union 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 have been produced during the lifetime of the project whilst developing hydrodynamic models of the Scottish shelf waters.

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. A Scottish shelf waters model covering this study area has been developed to simulate the hydrodynamic conditions in three-dimensions, including meteorological and tidal forcings. The model resolution is variable and matched to the processes and bathymetry that are required for the simulations.

Within this region-wide shelf waters model, four local three-dimensional models have been 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:-

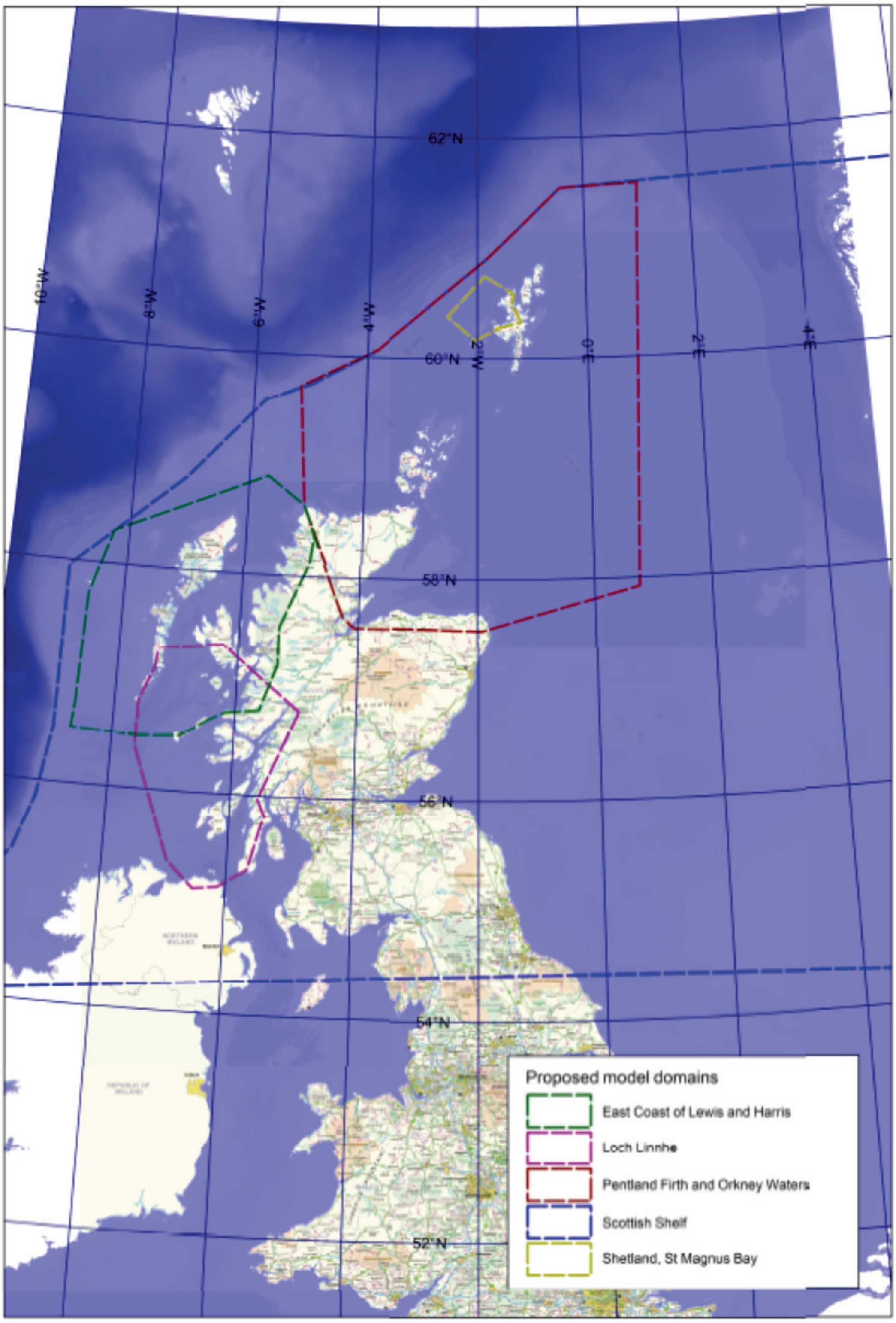
Case Study 1: Pentland Firth and Orkney Waters (PFOW)

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

The modelling provides 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 are a validated hydrodynamic model capable of predicting tidal and non-tidal currents for the whole of the Scottish shelf and inshore waters and include a more accurate assessment of the connectivity of different regions and the available energy resources in those regions. It also includes a description of methods for assessing the impact of extracting some of that energy upon the physical environment.

The modelling was undertaken using an open-source three-dimensional (3D) hydrodynamic model called FVCOM (Chen et al., 2003). One of the reasons behind the choice of this modelling software was 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 become 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 the 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 development of connectivity indices.

1.5 This Report

This report documents the work carried out in developing the whole Scottish Shelf Waters (SSW) model. This work includes: data collated and/or identified for the numerical modelling, setup and calibration of the flow model, 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 SSW area.

This report is Volume 1 of the SSW model report. A companion volume (Volume 2 – Model Documentation Report for SSW) contains additional details on model development (data preparation, mesh generation, preparation of model setup files, how to run the model, etc.) and lessons learnt.

1.6 Datums

Unless explicitly stated otherwise the following reference datums were 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 and George Slesser) for providing, requesting and collecting available data.

- UKHO for the bathymetry datasets we have received and those that we are still to receive.

- 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 will be very useful for this study.
- CEH (Robert Moore and team) for their work towards 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 for making the FVCOM software available for this project.

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 Scottish Shelf Waters (SSW), the following data were 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 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 Scottish Shelf Waters (SSW) model area. Where appropriate reference is made to the overall project data review report (Halcrow, 2012). Note that the proposed model domains shown in this section are not the final model domains but an approximation.

2.2 Bathymetric Data

2.2.1 Coastline Data

Two coastline data sets were 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. Some reference has also been made to coastline data from the US National Geophysical Data Centre, Marine Geology & Geophysics Division (MGGD), https://www.ngdc.noaa.gov/mgg/ for the whole NW European Shelf model.

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. The GSHHS data are considered appropriate for use in areas where the model resolution is coarse, the OS vector map district MHWS line should be 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 were 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).

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, note that a new version has come out in 2014, but too late for use in setting up the models).

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 2-1 shows the NOOS bathymetry (see section 2.2.4 below). Figure 2-2 shows the GEBCO_08 bathymetry for the NW European 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 was not considered further.

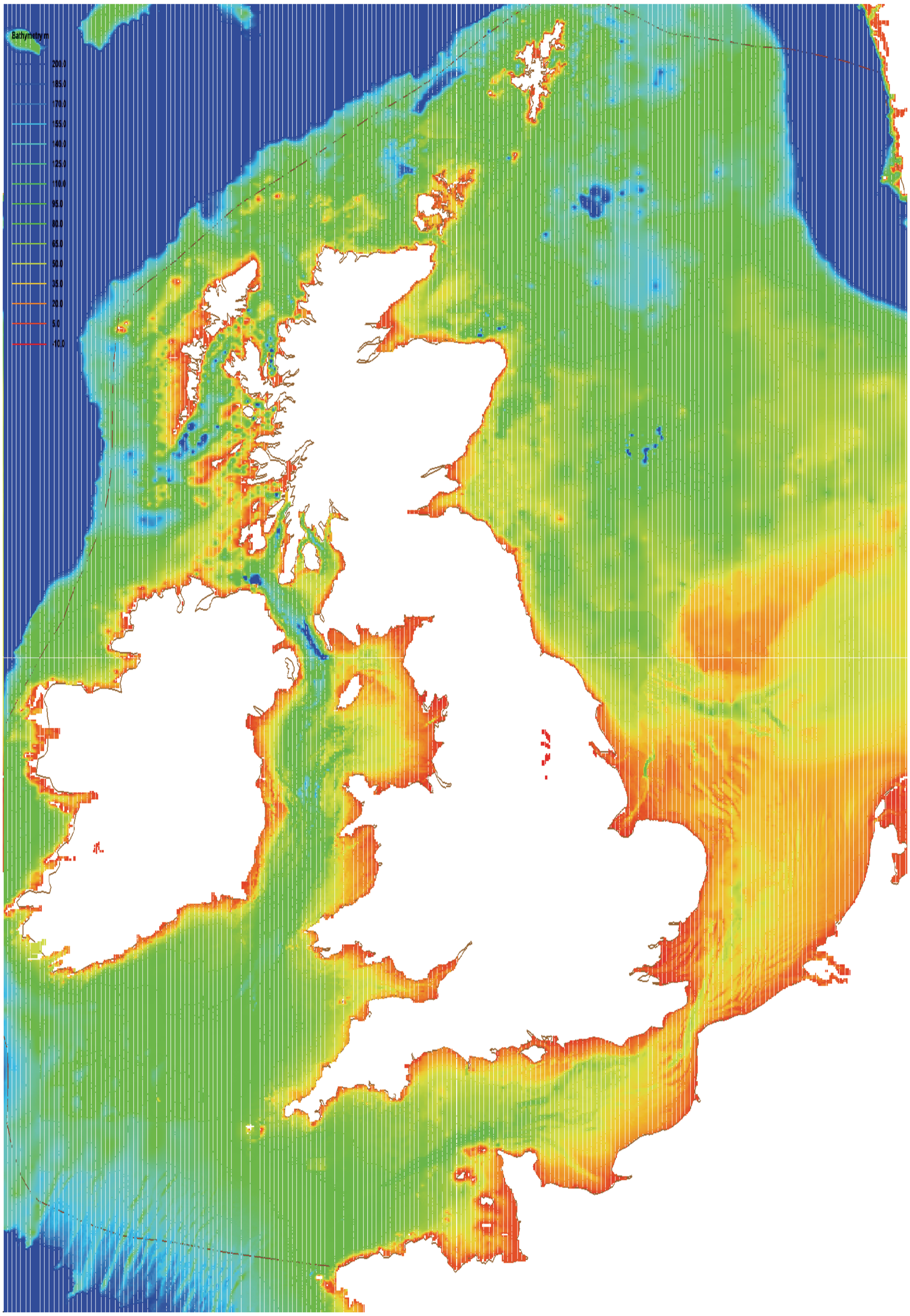
2.2.2.3 European Marine Observation and Data Network (EMODnet)

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/

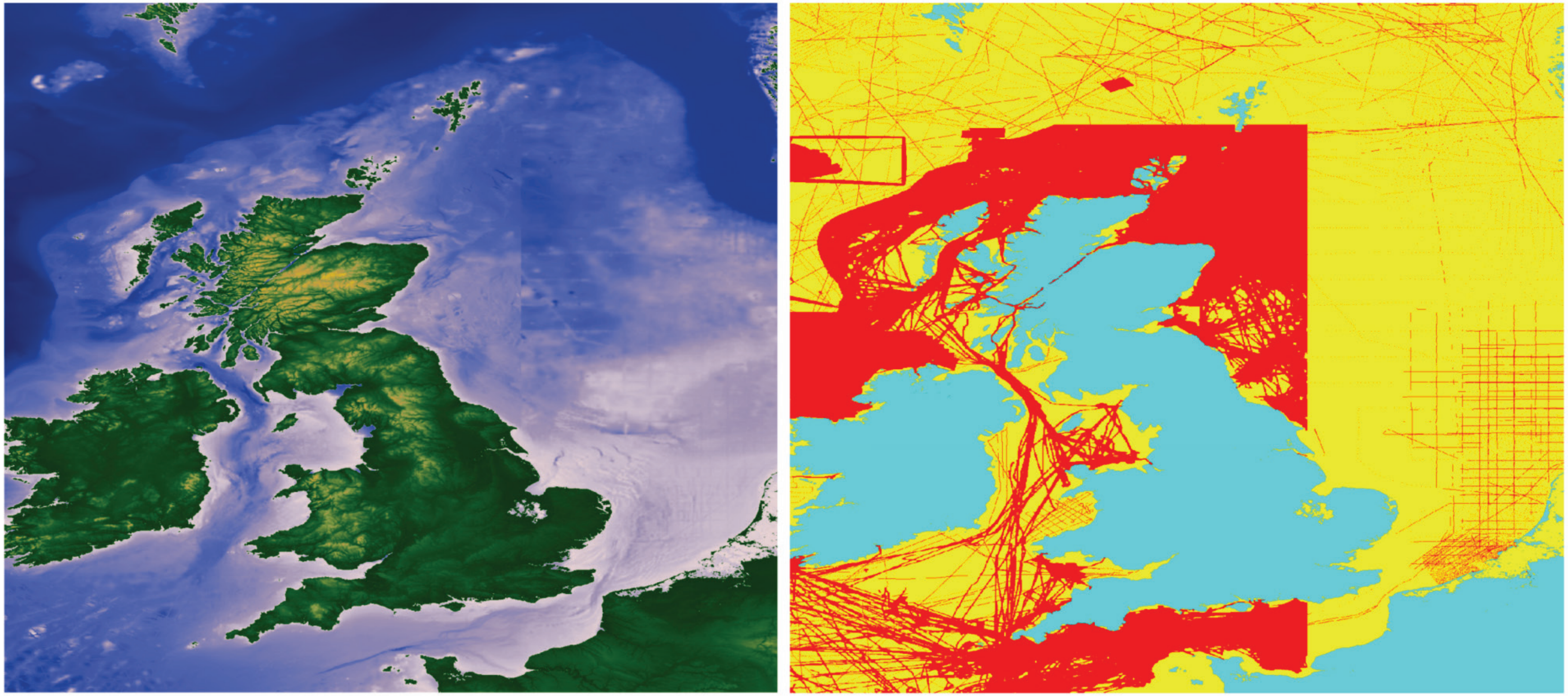
Further details of EMODNet are provided in Halcrow (2012).

Figure 2-3 a and b show 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 have 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 were not investigated as they were not considered important for the study area.

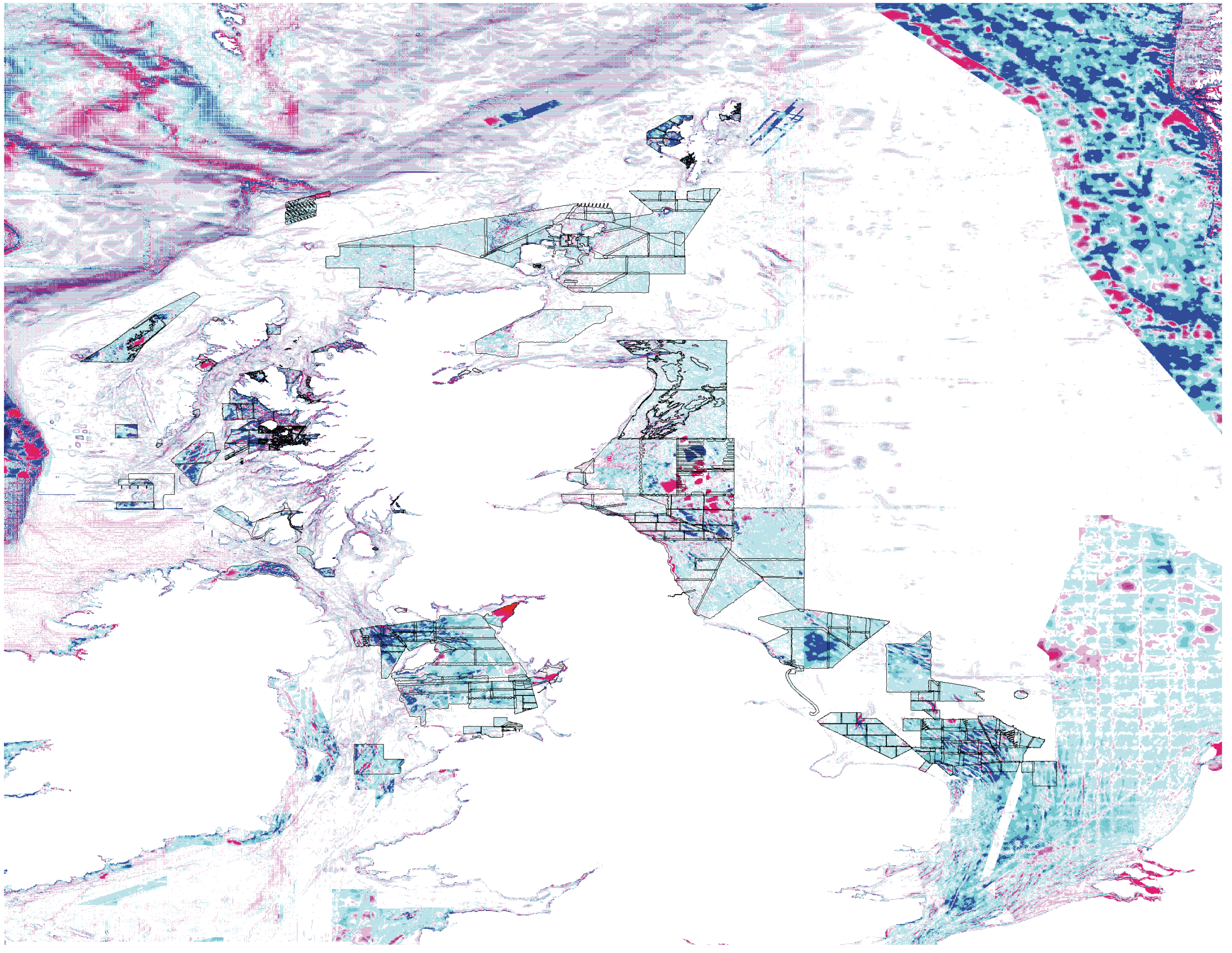
Due to the inclusion of the majority of the UKHO data, the EMODnet bathymetry is considered appropriate for use as the base bathymetry for model construction in areas where the resolution will be of the order of one kilometre. Higher resolution bathymetry data are however required in areas where the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



Client	Consulting Engineer	Project:	**Figure 2-1**
Marine Scotland	ch2m:	Scottish Shelf Waters Model	NOOS bathymetry



Client	Consulting Engineer	Project:	Figure Title:	Figure2-2		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Data sources used in the GEBCO data set	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012



Legend

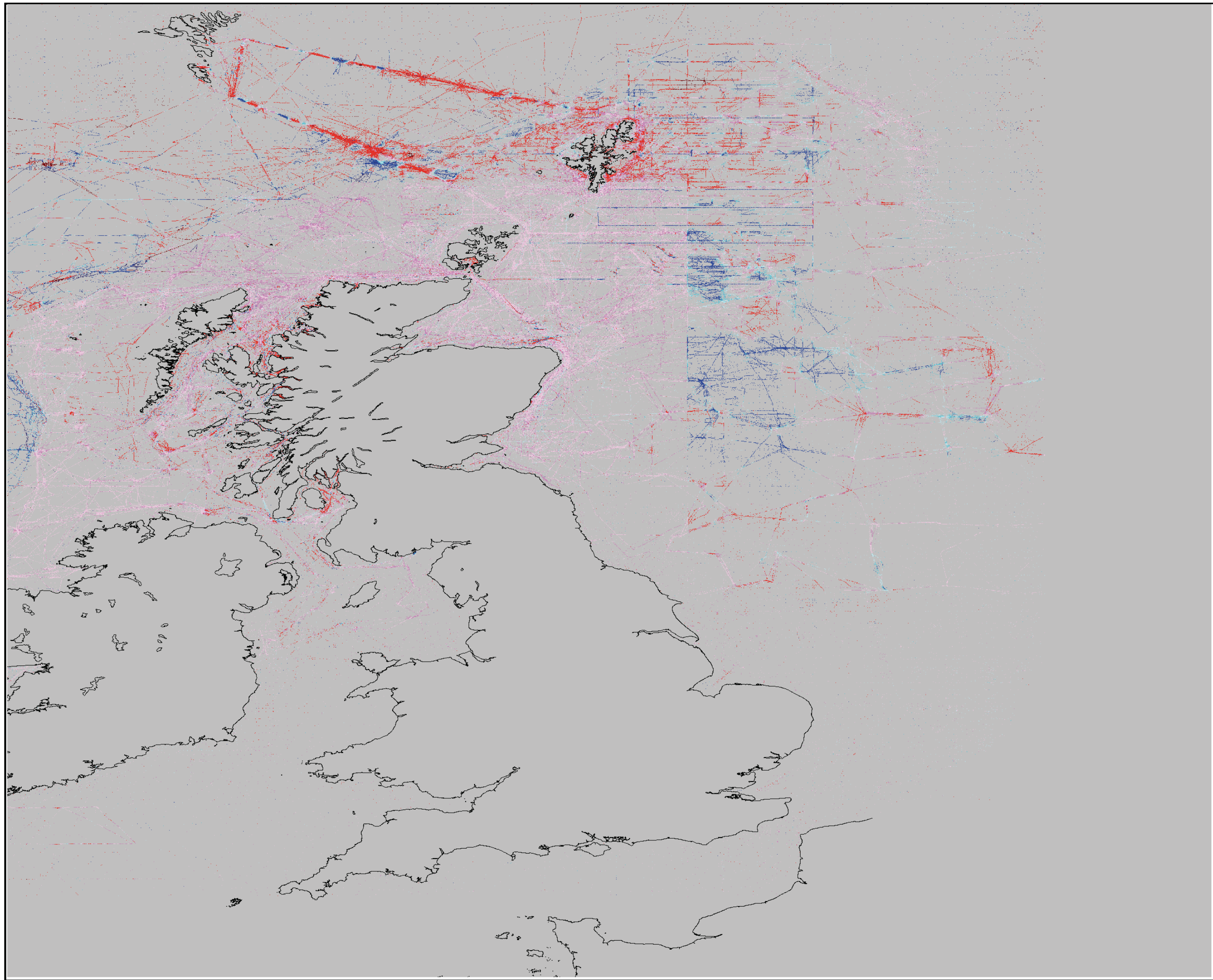
UKHO data included in EMODnet

EMODnet - GEBCO_08

- -100 m to -1000 m
- -10 m to -100 m
- -5 m to -10 m
- -1 m to -5 m
- -1 m to 1 m
- 1 m to 5 m
- 5 m to 10 m
- 10 m to 100 m
- 100 m to 1000 m

Client	Consulting Engineer	Project:	Figure Title:	Figure2-3a		
Marine Scotland	ch2m	Scottish Shelf 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

ch2m



EMODnet bathymetry - ICES depth soundings

- -100 m to -1000 m
- -10 m to -100 m
- -5 m to -10 m
- -1 m to -5 m
- -1 m to 1 m
- 1 m to 5 m
- 5 m to 10 m
- 10 m to 100 m
- 100 m to 1000 m

Client	Consulting Engineer	Project:	Figure Title:	Figure 2-3b		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Difference between mean ICES depth soundings over EMODnet grid cells and EMODnet 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 were identified: the United Kingdom Hydrographic Office (UKHO), the International Council for Exploration of the Sea (ICES) and Marine Scotland's data sets.

The UKHO has a memorandum of understanding with Marine Scotland making their high resolution bathymetric survey data available. Most of these data have already been incorporated into the EMODnet bathymetry, however further data have since become available. The location of the UKHO data is shown in Figure 2-3a. 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 the contributing organisations 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.

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 survey collected by the UKHO post-2004 is therefore not incorporated into 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, Figure 2-1), 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 shiptrack 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 was 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 were used to fill the gaps in the digital bathymetry data available for the PFOW model.

2.2.6 Summary of bathymetry data availability for Scottish Shelf Waters

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

High resolution bathymetric data is available, for most of the core study area of the Pentland Firth and Orkney Islands. EMODnet will form the base bathymetry for SSW with the NOOS data providing depths to the east of longitude 0°E.

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 were filled with data obtained by digitising the appropriate Admiralty Charts (after first obtaining a licence to do so from the Hydrographic Office). The final bathymetry for the SSW area was derived as a sub-sampled composite from various data sources, to harmonise with the high resolution case study areas.

2.3 Forcing Data

2.3.1 Introduction

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

2.3.2 Meteorological forcing

2.3.2.1 UK Met Office Unified Model (UM) Data

Two data streams from the Met Office forecast models have been archived at NOC (Liverpool) 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 the 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 (NAE) model output at 3-hour intervals – same variables

- Access to the UM model outputs was obtained via the BADC website

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 was provided by the European Centre for Medium range Weather Forecasting (ECMWF) for this study.

A one-year climatological forcing dataset for the temperature and salinity (i.e. heat flux and precipitation) has been derived. Further work would be necessary to define a typical year in terms of the high-frequency wind forcing i.e. storm climatology, see e.g. Wolf and Woolf (2006). A detailed description of the methodology used to derive the climatology forcing is provided in Section 5 of this report.

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 was used to supply freshwater inflows to the various coastal models for this study. The G2G model was extended to provide conditions for the Shetland Isles which were not available previously.

The outputs provided by CEH from the G2G model were:

1. Provision of river discharge data (time series data) at all coastal locations in Scottish waters from the G2G model. The data were supplied for a period covering 1 March 2007 to 30 September 2010 at 15 minute intervals.
2. Provision of river discharge data (time series data) at all coastal locations around Shetland and Northern Ireland from the G2G model. The data were supplied for a period covering 1 March 2007 to 30 September 2010.
3. Provision of river discharge climatological data (long term daily/seasonal discharge data) at all coastal locations for Scotland (including Shetland) and Northern Ireland from the G2G model. Daily averaged data were supplied for a period covering 1962-2011.

2.3.5 Tide

For the Shelf Model, the boundary data were derived from the NOC-L Atlantic Margin Model (AMM) with a 12km resolution, which was also used to force the NOC-L HRCS 1.8km model. Water levels along with temperature and salinity time-series were applied at the model boundaries for specific periods coincident with times for which calibration data were available.

Climatological runs were forced using results from the POLCOMS model hindcast from 1960-2004, which was run on the AMM 12km grid. These are available for monthly means but also held in-house at NOC-L as daily mean 3D temperature and salinity and current residual fields, together with hourly barotropic currents and elevations.

2.4 Validation and Calibration Data

2.4.1 Introduction

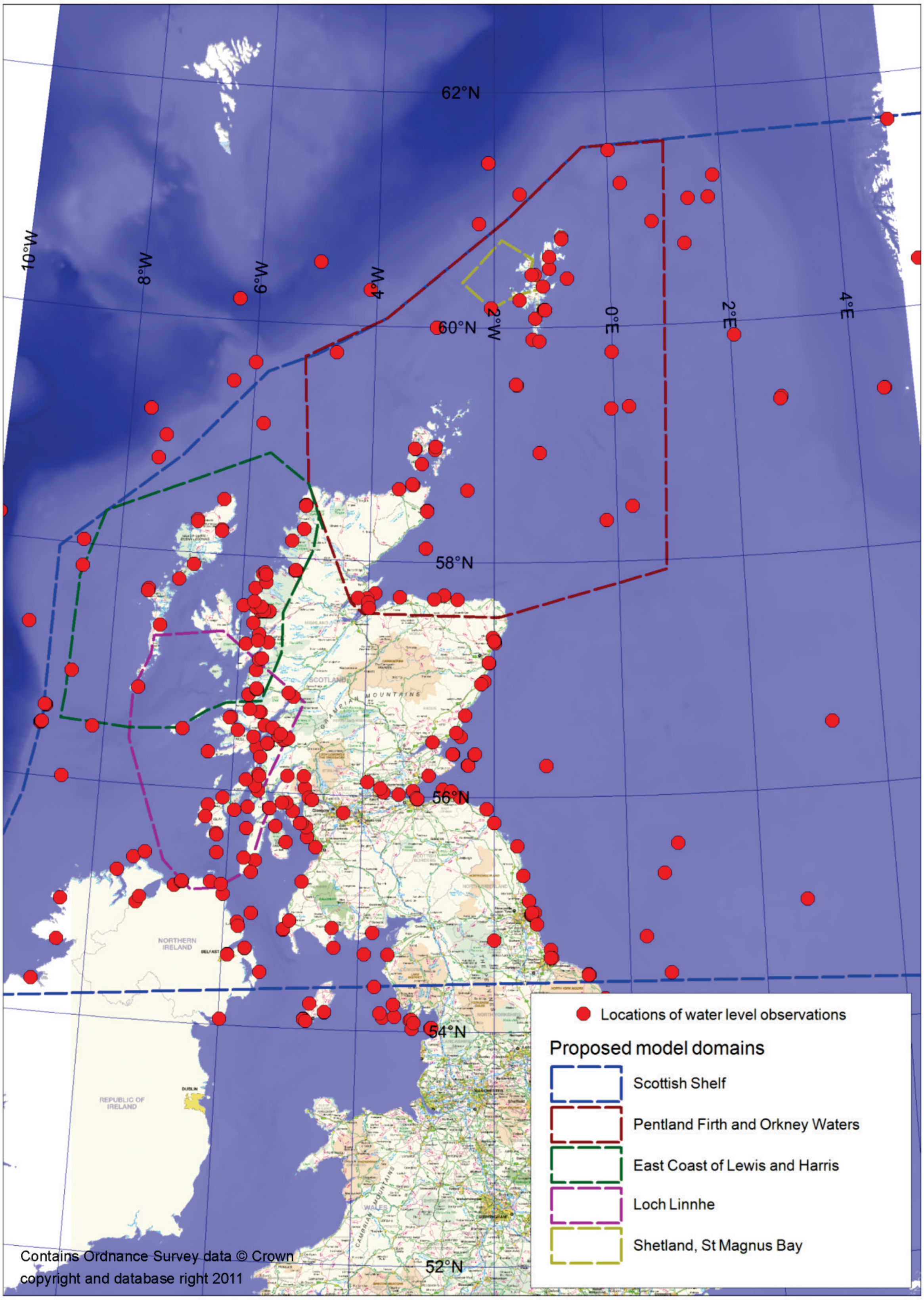
Model validation and calibration were undertaken against observation datasets for periods of up to 1 month. Calibration is required for water level, currents, temperature and salinity.

In addition calibration was required for the 1 year climatological runs against accepted general flow characteristics including current speed and direction (seasonal variability) and seasonal temperature and salinity cycles.

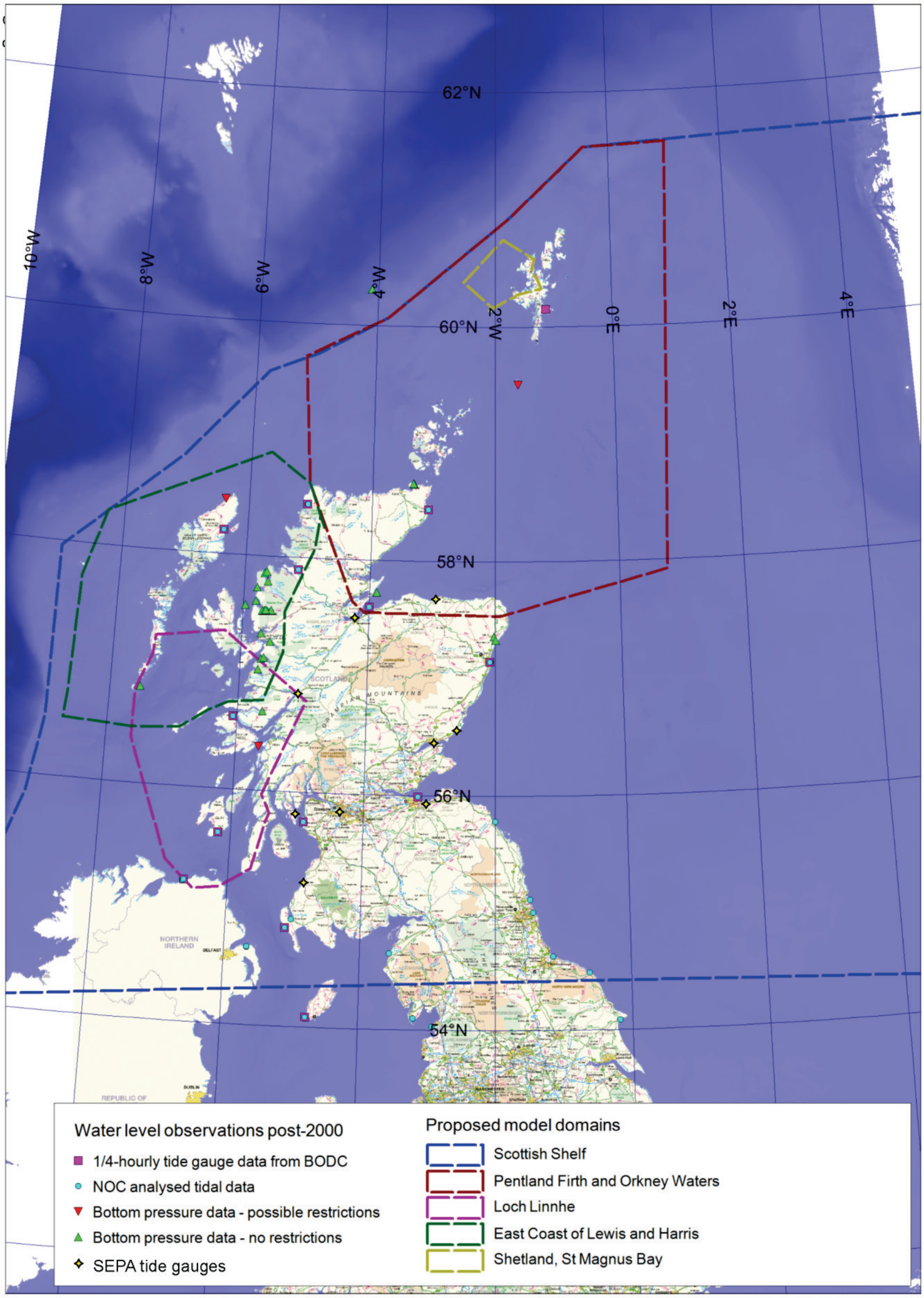
2.4.2 Water Level

Figure 2-4 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 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 2002. Their locations are shown in Figure 2-5.

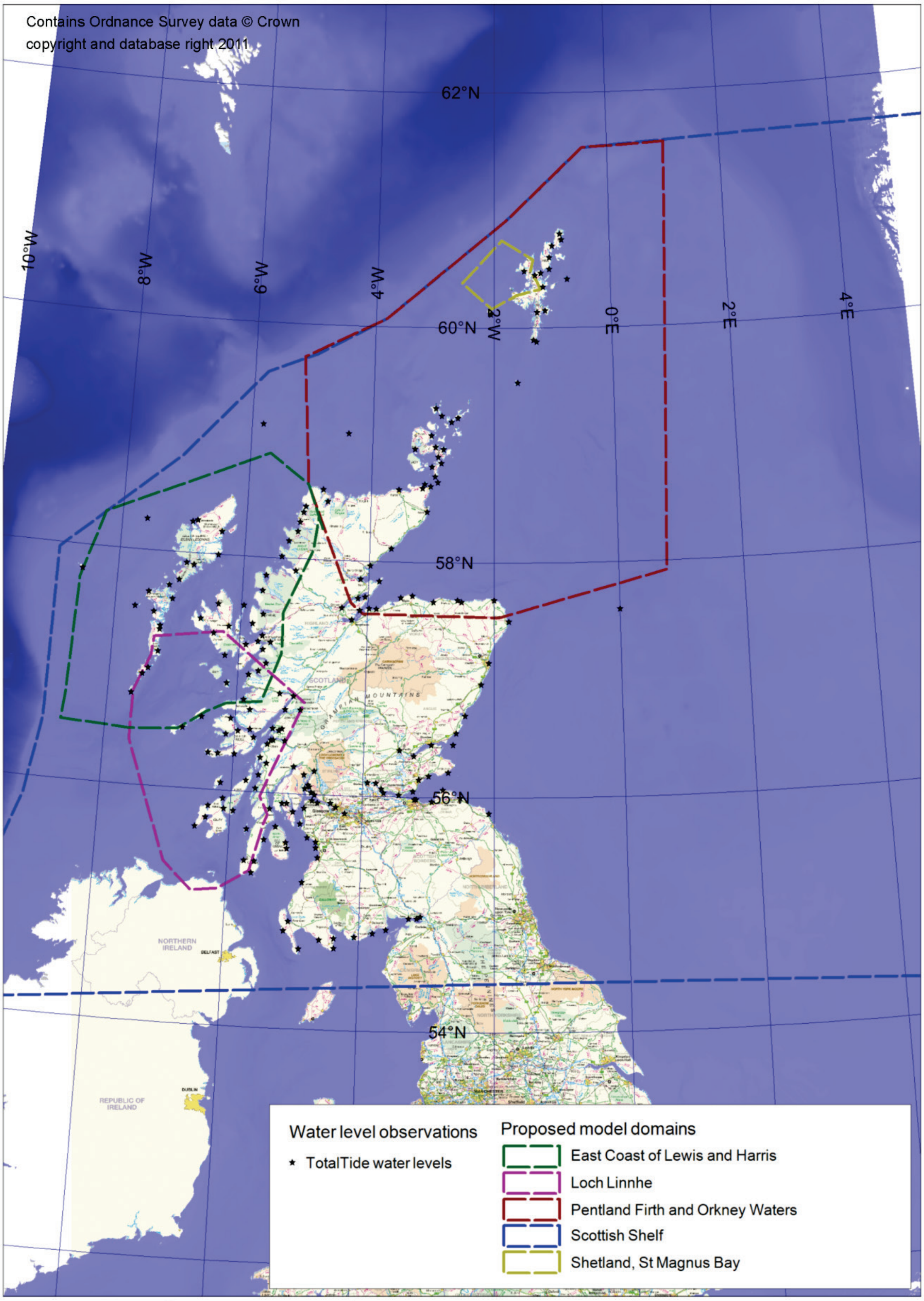
In addition, we have access to tidal data from TotalTide - a digital version of the UK Admiralty tide tables, from the UK Hydrographic Office. The locations of these datasets are shown in Figure 2-6. These data are based on harmonic analyses, and thus water level estimates for any past or future date are obtainable from these, or via the use of constituents from the Admiralty tide tables.



Client	Consulting Engineer	Project:	**Figure 2-4**
Marine Scotland	ch2m	Scottish Shelf Waters Model	All water level observations



Client	Consulting Engineer	Project:	**Figure 2-5**
Marine Scotland	ch2m	Scottish Shelf Waters Model	Post-2000 water level observations



Client	Consulting Engineer	Project:	**Figure 2-6**
Marine Scotland	ch2m	Scottish Shelf Waters Model	Total-tide water level locations

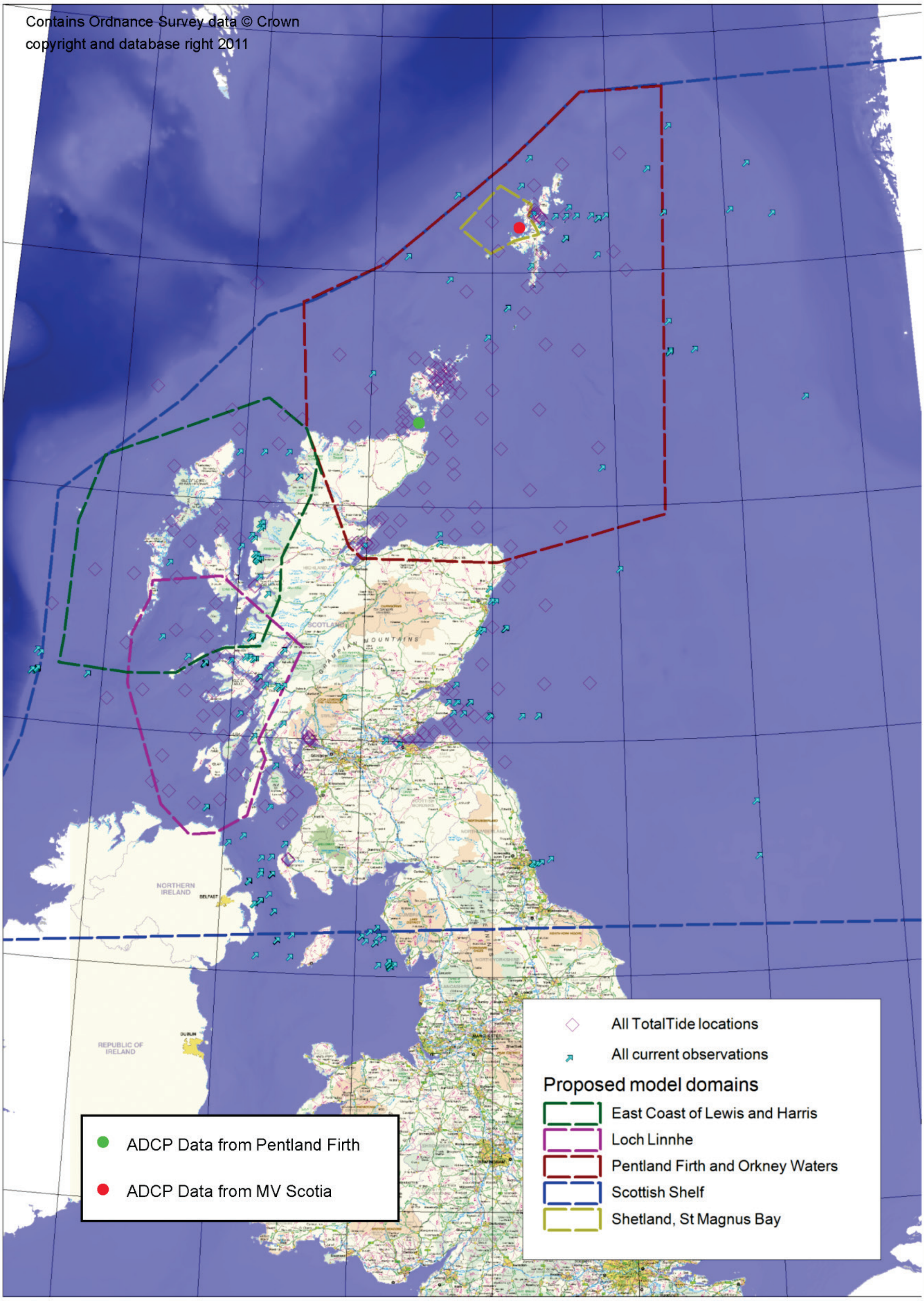
2.4.3 Currents

Datasets of currents have been found from a number of sources; all locations are shown in Figure 2-7. These come from the BODC National Oceanographic Database (NODB) and the TotalTide software, from the UK Hydrographic Office. As Figure 2-8 shows, there are only a few datasets from the BODC National Oceanographic Database since the 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 2-9.

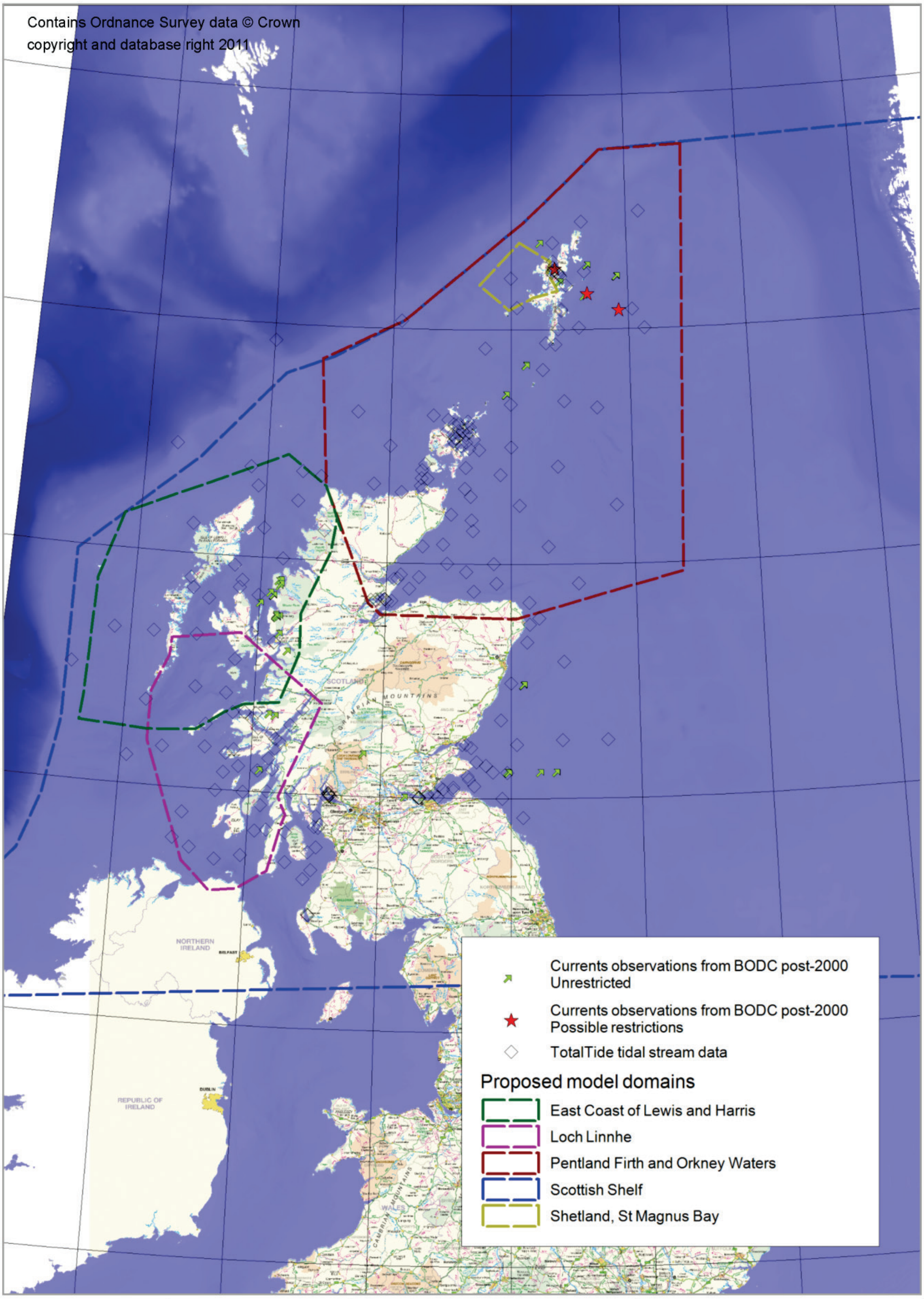
In the Pentland Firth, interest in tidal energy has led to the existence of other datasets. Baston and Harris (2011) presented results from Acoustic Doppler Current Profiler (ADCP) data collected in 2001. Also the Environmental Research Institute collected current data via ADCP in the Pentland Firth in 2009. These datasets have been obtained for calibration purposes.

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.

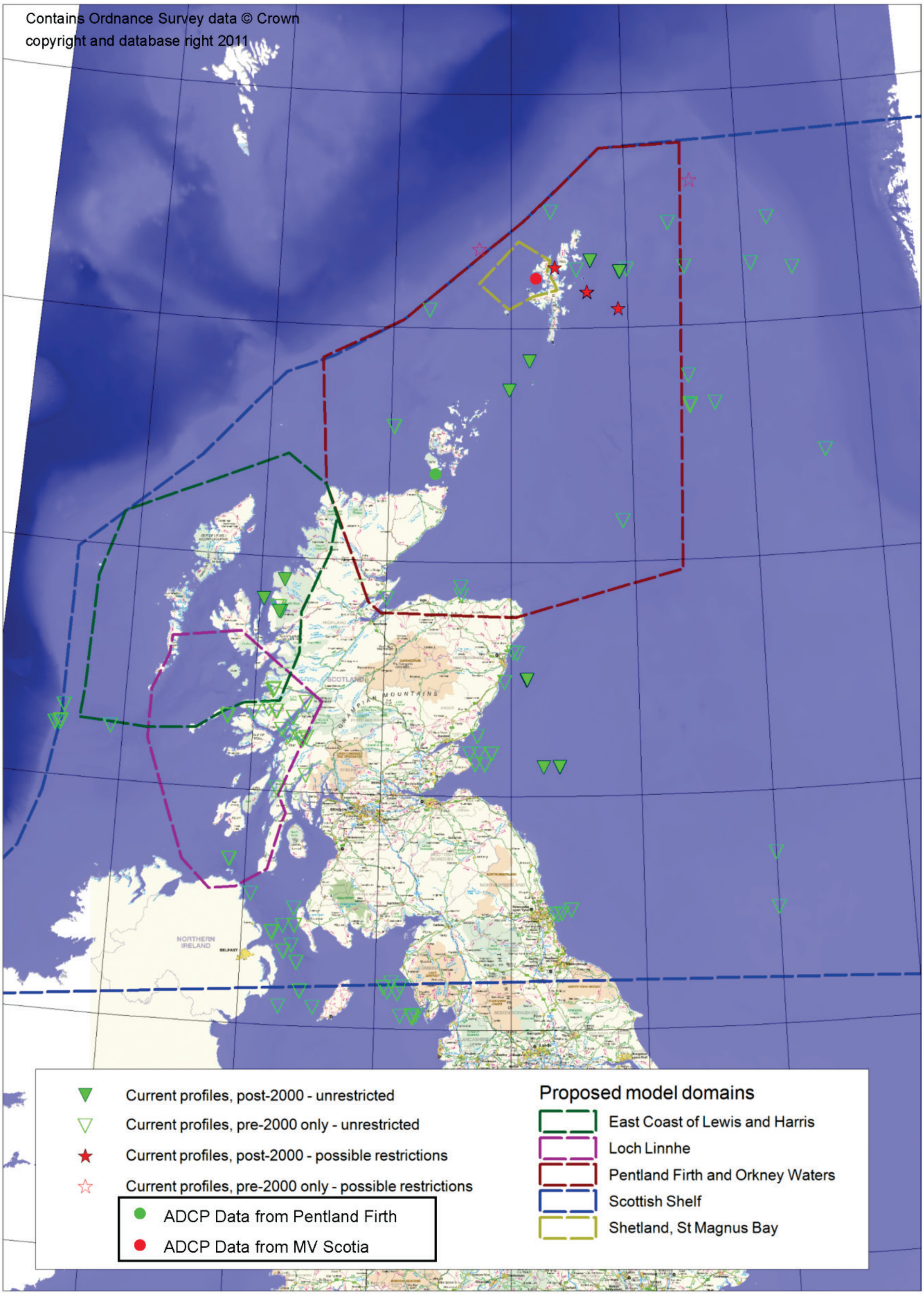
The Atlas of UK Marine Renewable Energy Resources (www.renewables-atlas.info) contains information on peak tidal current speeds over a mean spring and a mean neap tide. The dataset was derived from the POL HRCS Model, with peak spring and neap current speeds calculated from the major 2 or 4 tidal harmonics. 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 2-10.



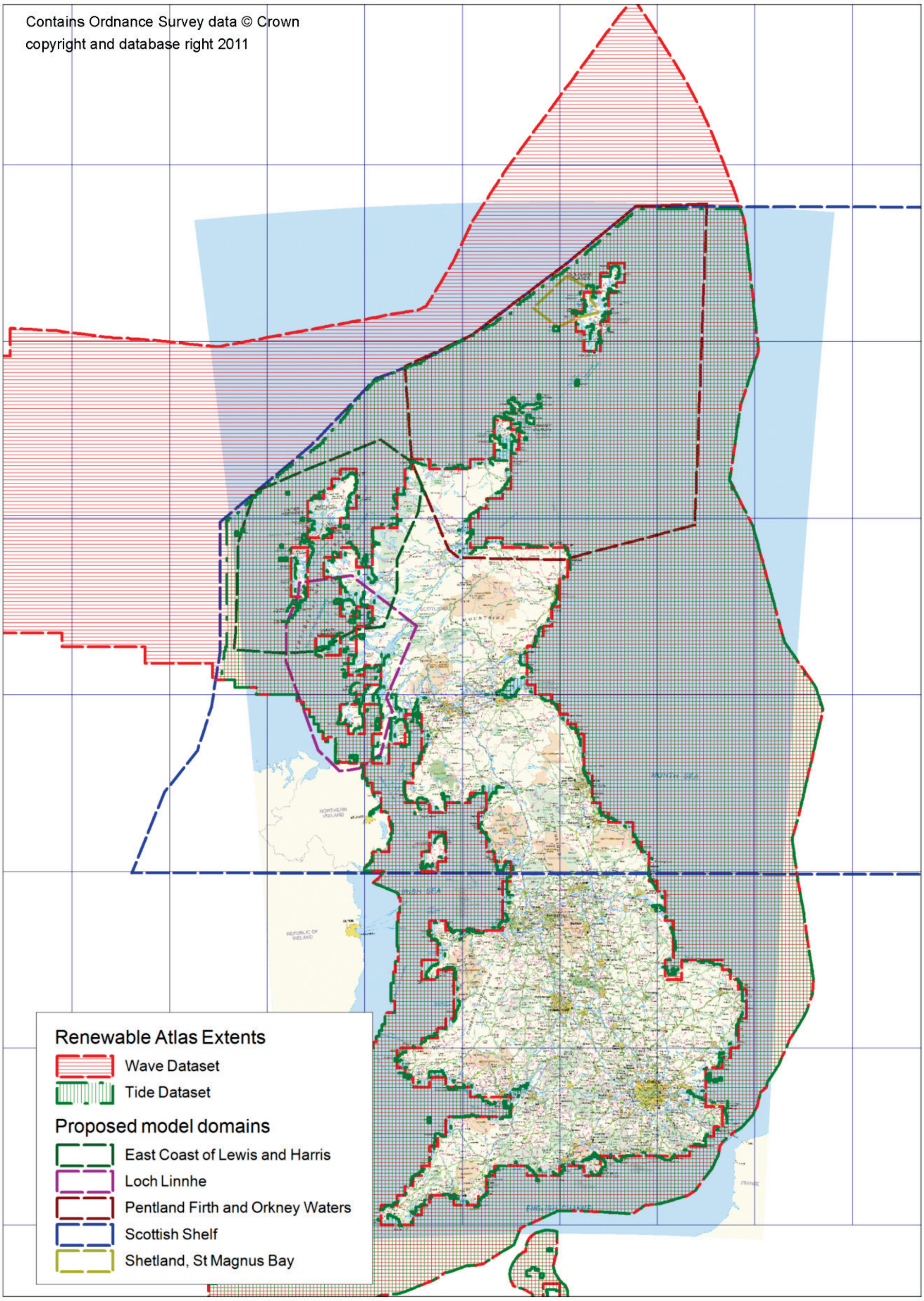
Client	Consulting Engineer	Project:	**Figure 2-7**
Marine Scotland	ch2m	Scottish Shelf Waters Model	All current observations and TotalTide tidal stream locations



Client	Consulting Engineer	Project:	**Figure 2-8**
Marine Scotland		Scottish Shelf Waters Model	Post-2000 current observations from BODC and TotalTide



Client	Consulting Engineer	Project:	**Figure 2-9**
Marine Scotland	ch2m	Scottish Shelf Waters Model	Pre and Post-2000 current profiles



Client	Consulting Engineer	Project:	**Figure 2-10**
Marine Scotland		Scottish Shelf Waters Model	Wave and tidal domains from the Renewables Atlas

2.4.4 Temperature and Salinity

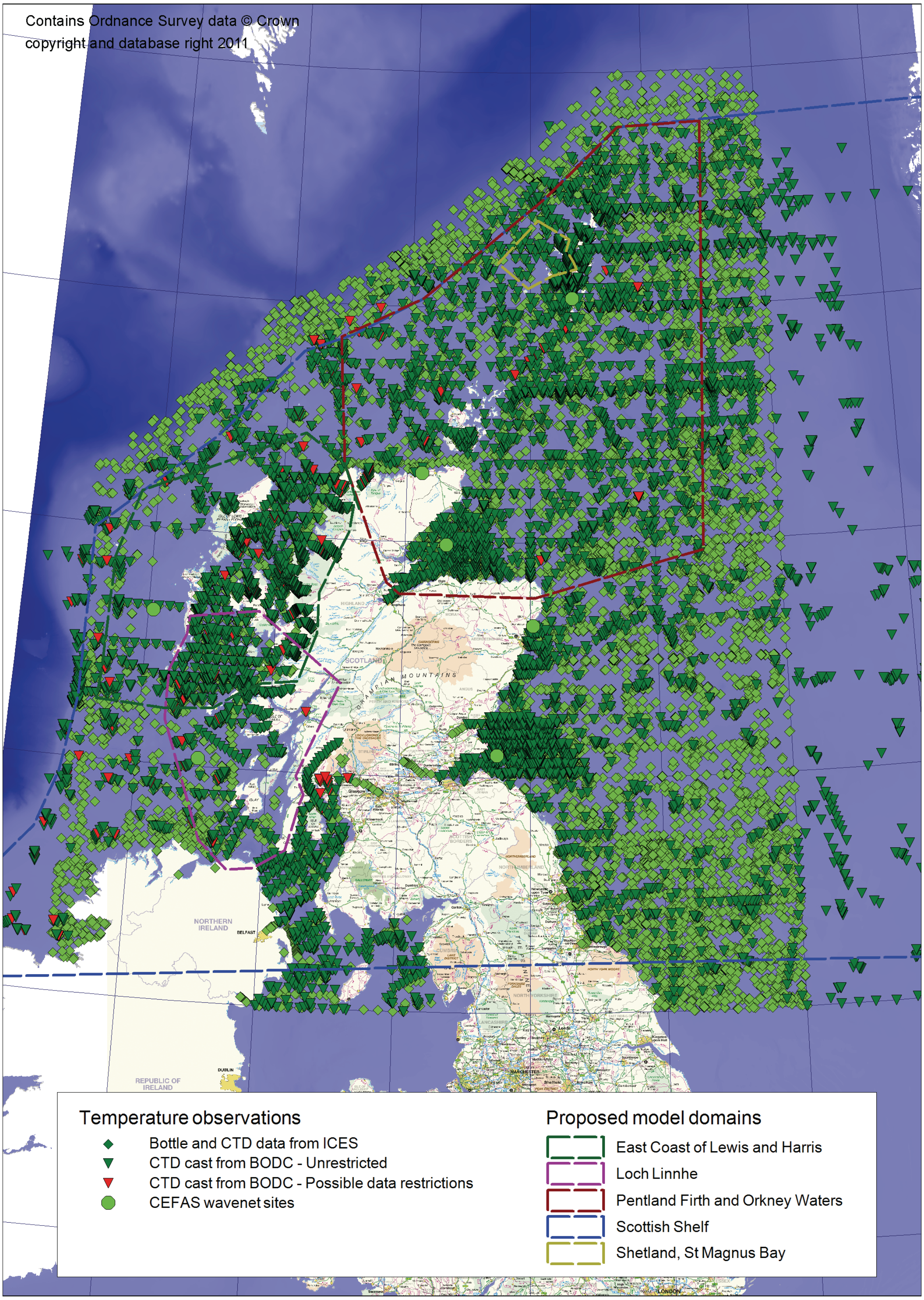
Temperature and salinity validation and calibration has been carried out using selected hydrographic stations which were identified from the British Oceanographic Data Centre data holdings for the UK. There are a very large number of datasets from CTD and bottle casts, both from the BODC National Oceanographic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

Figure 2-11 shows the locations of the temperature observations and Figure 2-12 shows the locations of the salinity observations. As Figure 2-13 shows, the temperature and salinity observations have occurred throughout the last two decades, with many observations throughout all model domains having occurred over the last two years. Figure 2-14 shows which of these observations include profiles over the entire water depth. Most temperature and salinity observations occurred at the same location and time.

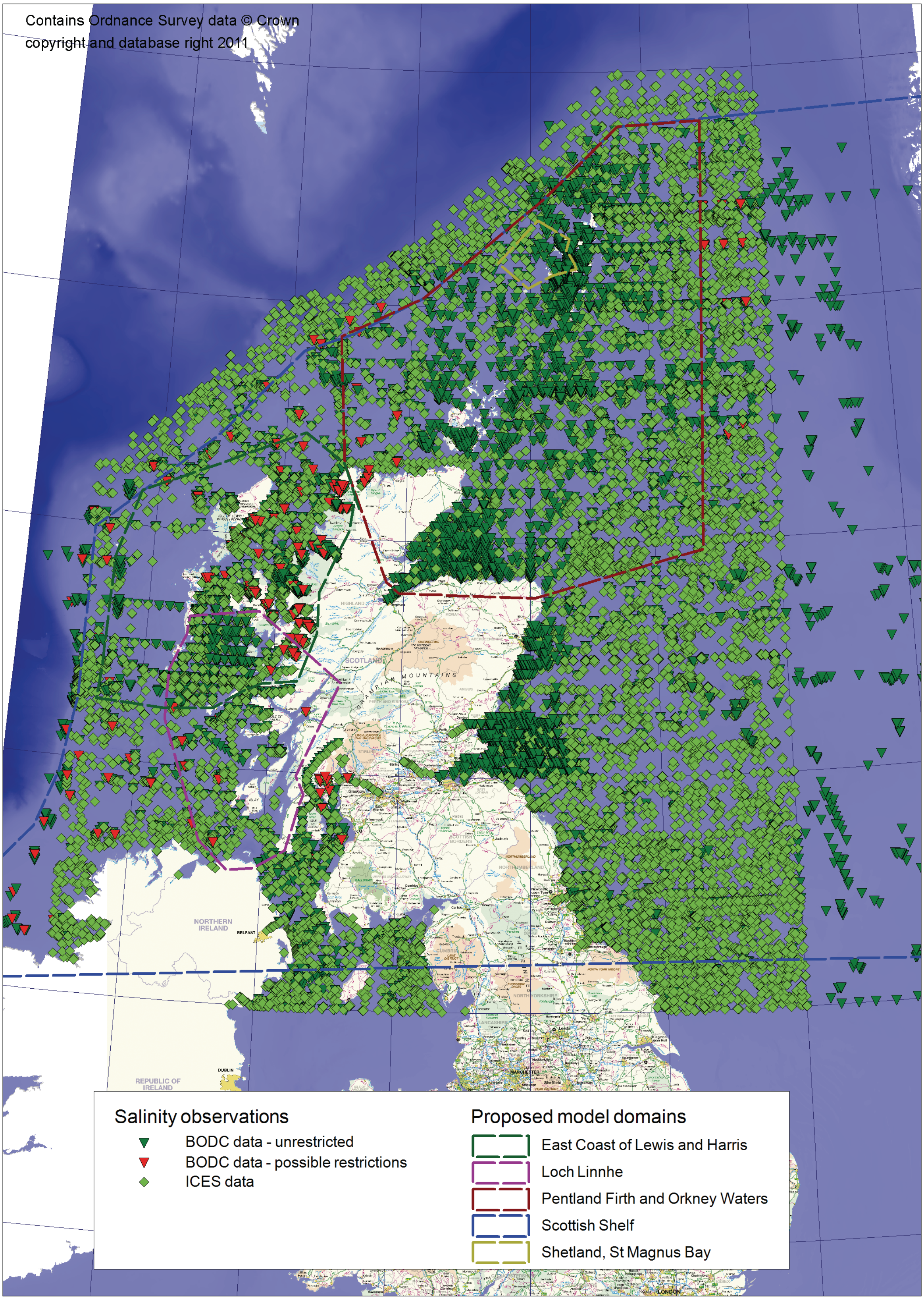
In addition, the Ocean Data analYsis System for SEA (ODYSSEA) dataset is a re-analysis of satellite observations of sea surface temperature. Daily mean average sea surface temperatures since 01/10/2007 have been obtained, on a 0.1° x 0.1° grid.

A 3-month calibration period for the baroclinic model was selected based on data availability and quality.

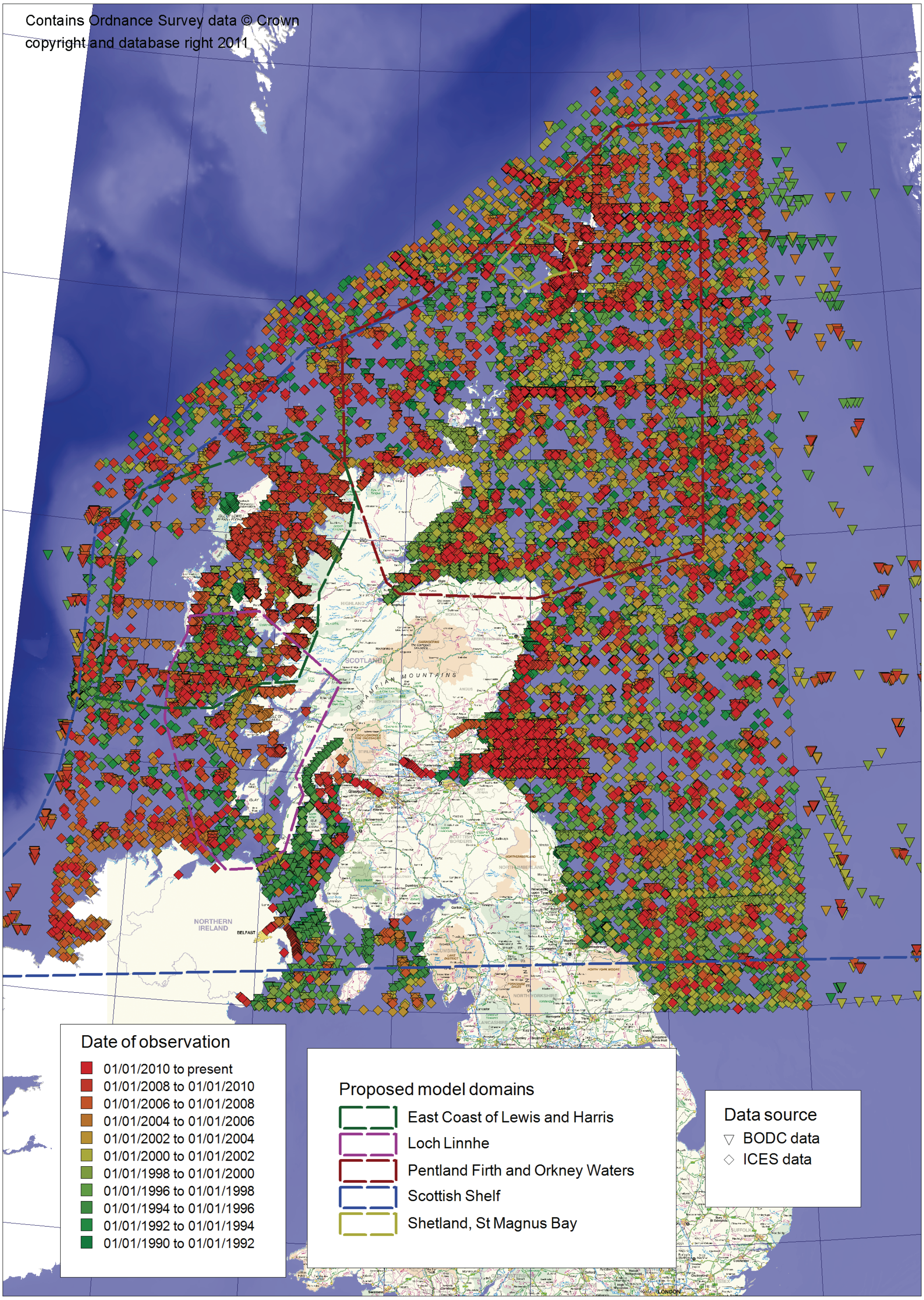
The results from the climatology run have been compared with climatological atlas information for temperature and salinity from the World Ocean Atlas (WOA) and International Council for Exploration of the Seas (ICES) climatological datasets.



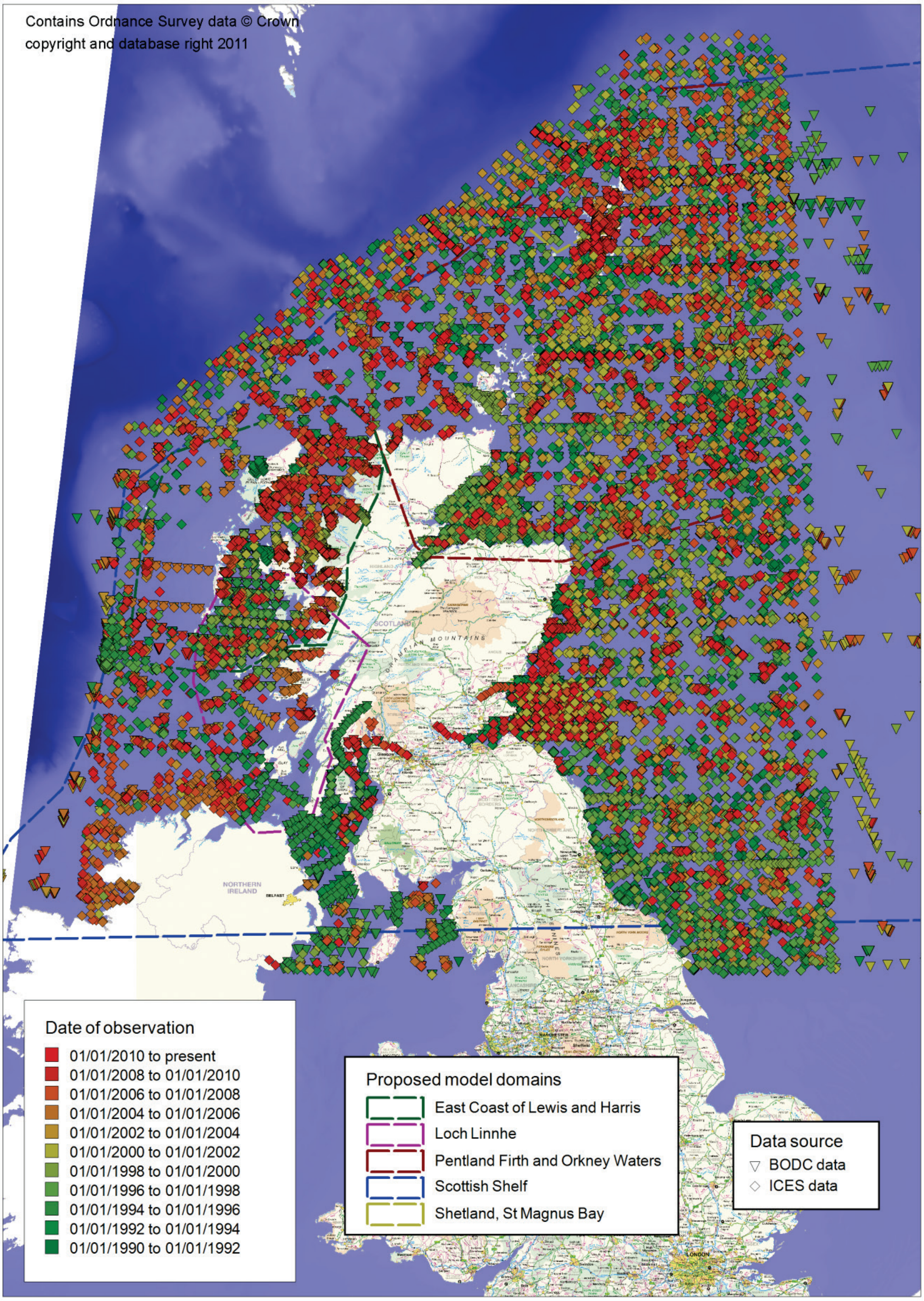
Client	Consulting Engineer	Project:	**Figure 2-11**
Marine Scotland	ch2m:	Scottish Shelf Waters Model	All temperature observations



Client	Consulting Engineer	Project:	**Figure** 2-12
Marine Scotland		Scottish Shelf Waters Model	All salinity observations



Client	Consulting Engineer	Project:	**Figure 2-13**
Marine Scotland	ch2m	Scottish Shelf Waters Model	Temperature and salinity observations by date, including surface observations and profiles



Client	Consulting Engineer	Project:	**Figure 2-14**
Marine Scotland	ch2m	Scottish Shelf Waters Model	Temperature and salinity profile observations by date

2.4.5. Summary of data availability for the SSW model

This section summarises the availability of calibration and validation data for the SSW model area and identifies any gaps in the available data. Furthermore, recommendations are made on how to fill the gaps.

Table 2-1 summarises the available water level, current, temperature/salinity and meteorological/river flow data available for calibration of the SSW model.

Table 2-1 SSW model and available data

Model	Year	Water level	Currents	Temperature /salinity	Meteorological	Wind	River
Scottish Shelf Waters	2001	✓	✓	✓	X	✓	X
	2009	✓	✓	✓	✓	✓	✓
	2012	✓	✓	✓	X	✓	X

It can be seen that the year 2009 appears to be the period where a complete set of the required data is available for calibration. The 3-month period of April-June 2009 has been used for calibration with other periods 2008-2009 being used for validation.

2.5 Conclusions and Recommendations

A review has been undertaken to identify and in many cases request / obtain data that are relevant to the setting up, forcing and calibration of the SSW model. It was found that there are many datasets available providing coverage over a wide spatial and temporal extent.

2.5.1 Bathymetry

The EMODnet data are considered appropriate for use as the base bathymetry for model construction. These data formed the basic coarser resolution data for the SSW model.

Further UKHO data and other higher resolution datasets from ICES and Marine Scotland were 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 were 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, for the high resolution models.

2.5.2 Forcing data

T**emperature and salinity data** have been obtained from the NOC-L AMM mode to provide boundary conditions to the SSW model. The AMM model was initially used for the tidal forcing at the open boundary, however it became necessary to move the boundary into the Atlantic and the alternative method of using the TPXO7.2 global tidal inversion from TOPEX/Poseidon altimeter data was then used (Oregon State University, Egbert and Erofeeva, 2002).

Meteorological forcing for the SSW model has been 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 limited the periods where calibration data are available coincident with full meteorological forcing. Due to the lack of full meteorological forcing during many of the potential calibration periods all calibration runs will be during 2009 , although no current measurements are available for this period harmonic analysis of the results can be carried out for comparison with observed data.

Extra UM fields were downloaded from the BADC website.

Fluvial inputs have been derived from G2G river flow data obtained from CEH for the SSW area.

2.5.3 Validation and Calibration Data

Section 2.4.5 presents information about which data are available for the SSW model. In general there are sufficient data with which to undertake calibration for water levels, currents, temperature and salinity. A summary of the dates where suitable calibration data is available is provided in Table 2-1.

3 Hydrodynamic Model Development

3.1 Introduction

This section of the report describes the setting up of the SSW model mesh, bathymetry and the calibration of the flow model.

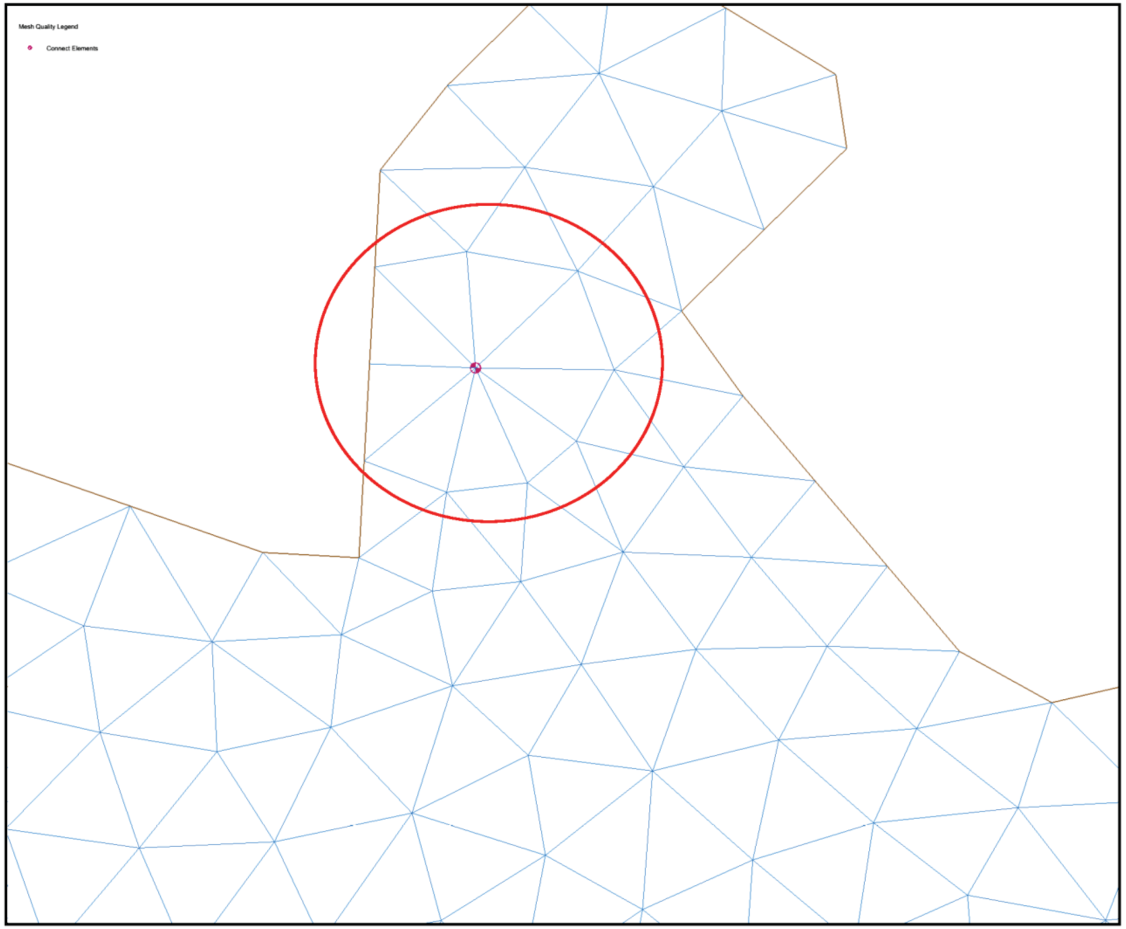
3.2 SSW flow model setup

3.2.1 Model mesh

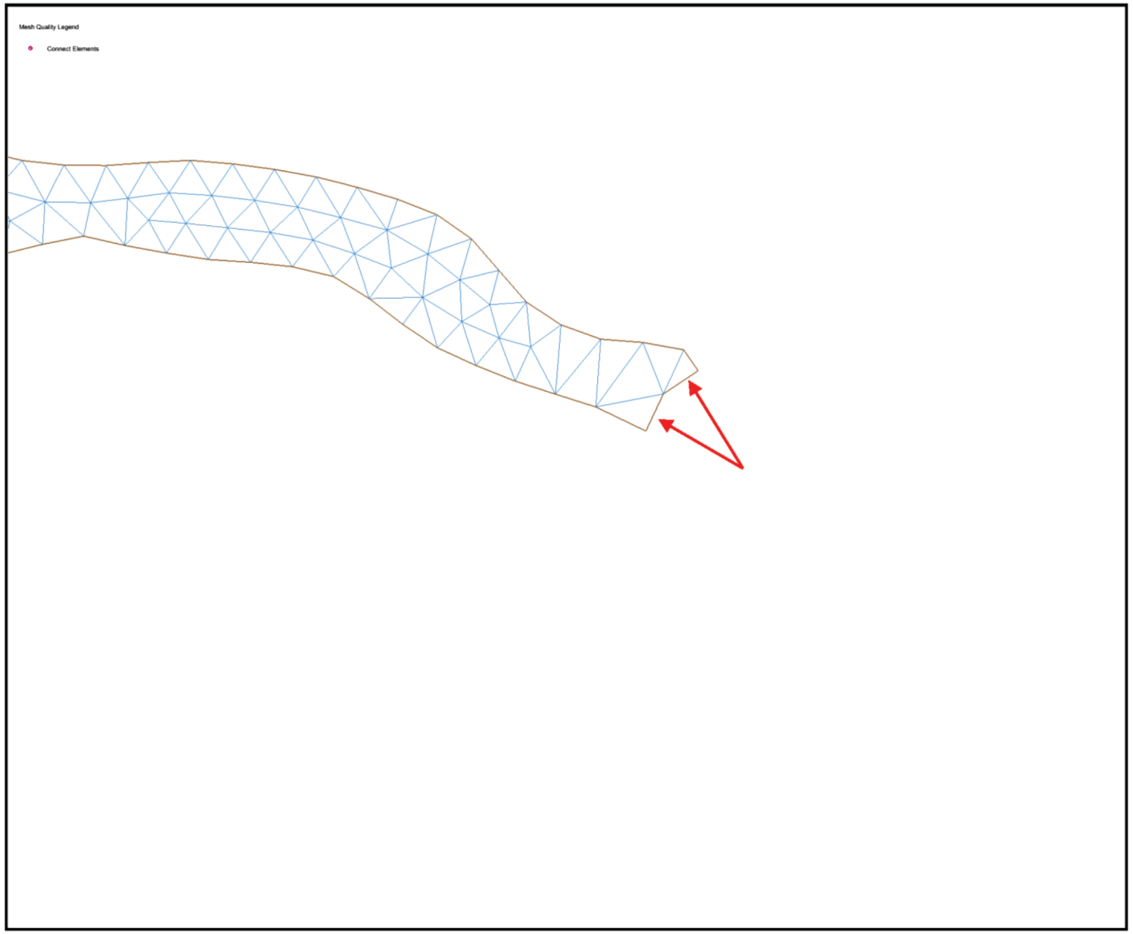
The model mesh developed for the SSW model was created using the SMS mesh generator. The horizontal coordinate system used is latitude and longitude with a vertical datum of mean sea level.

The SMS 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.

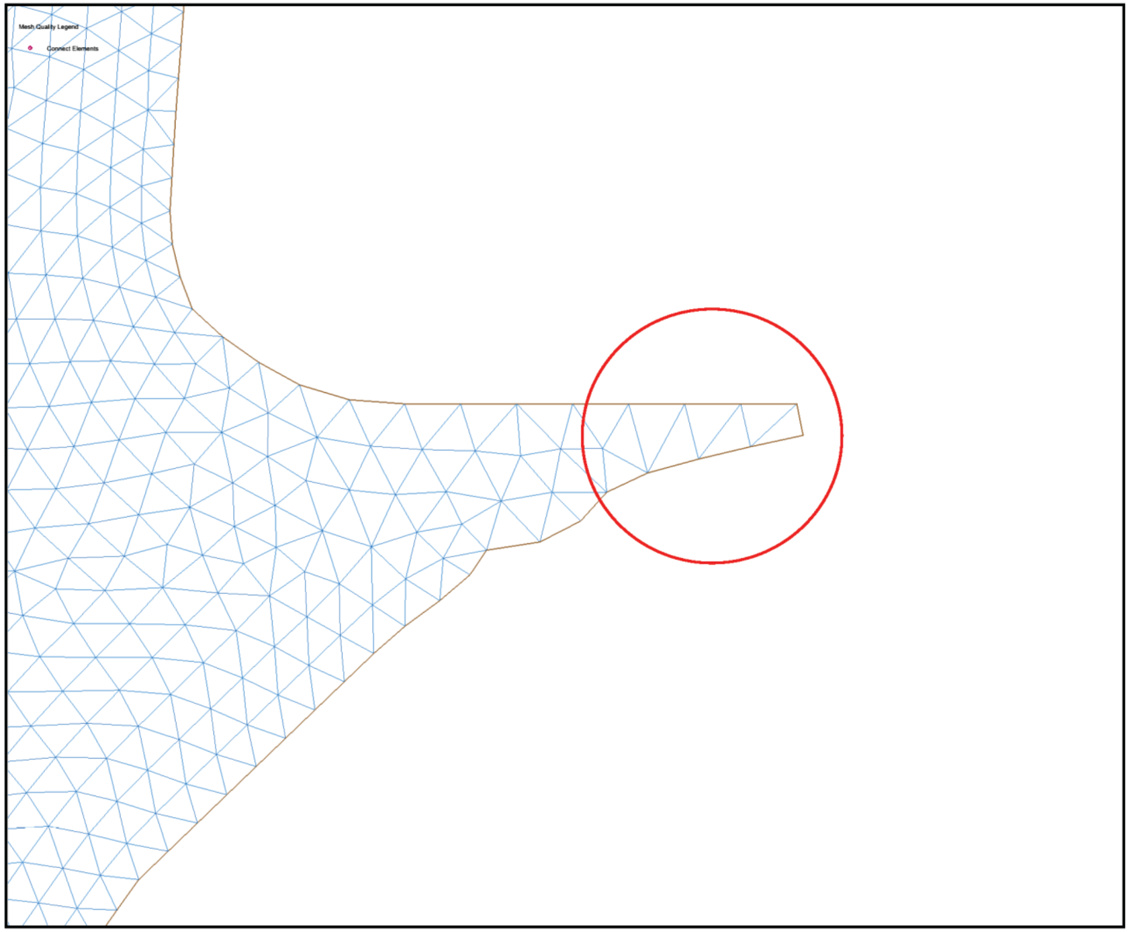
Mesh generation is an iterative process in order to get a mesh that varies smoothly (for both area change between connected triangles, and for the bathymetry), with triangles that do not have angles that are too acute (less than 30°, which is the FVCOM recommended setting), and finest resolution that does not require an overly small model timestep. Generally, resolution is much larger away from areas of interest (Scottish Waters) in order to limit the grid size and hence overall model run times. Other mesh quality control checks can be done e.g. each model node must not be connected to more than 8 adjacent elements and at coastal nodes where river discharge is specified, the node must not be part of an element where all three nodes are on land. Additionally, for estuaries and inlets, there must be more than one triangle between the land sides of the estuary. These last two corrections are needed because FVCOM forms “ponds” where the grid has these features. Mesh refinement is at best a semi-automatic process, requiring the application of modelling knowledge and judgement. Examples of these three issues are shown in Figure 3-1, 3-2 and 3-3.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-1		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Example of grid refinement issues – more than 8 triangles connected to a node, identified by SMS**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-2		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Example of grid refinement issues – "ponds" with two land boundaries**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



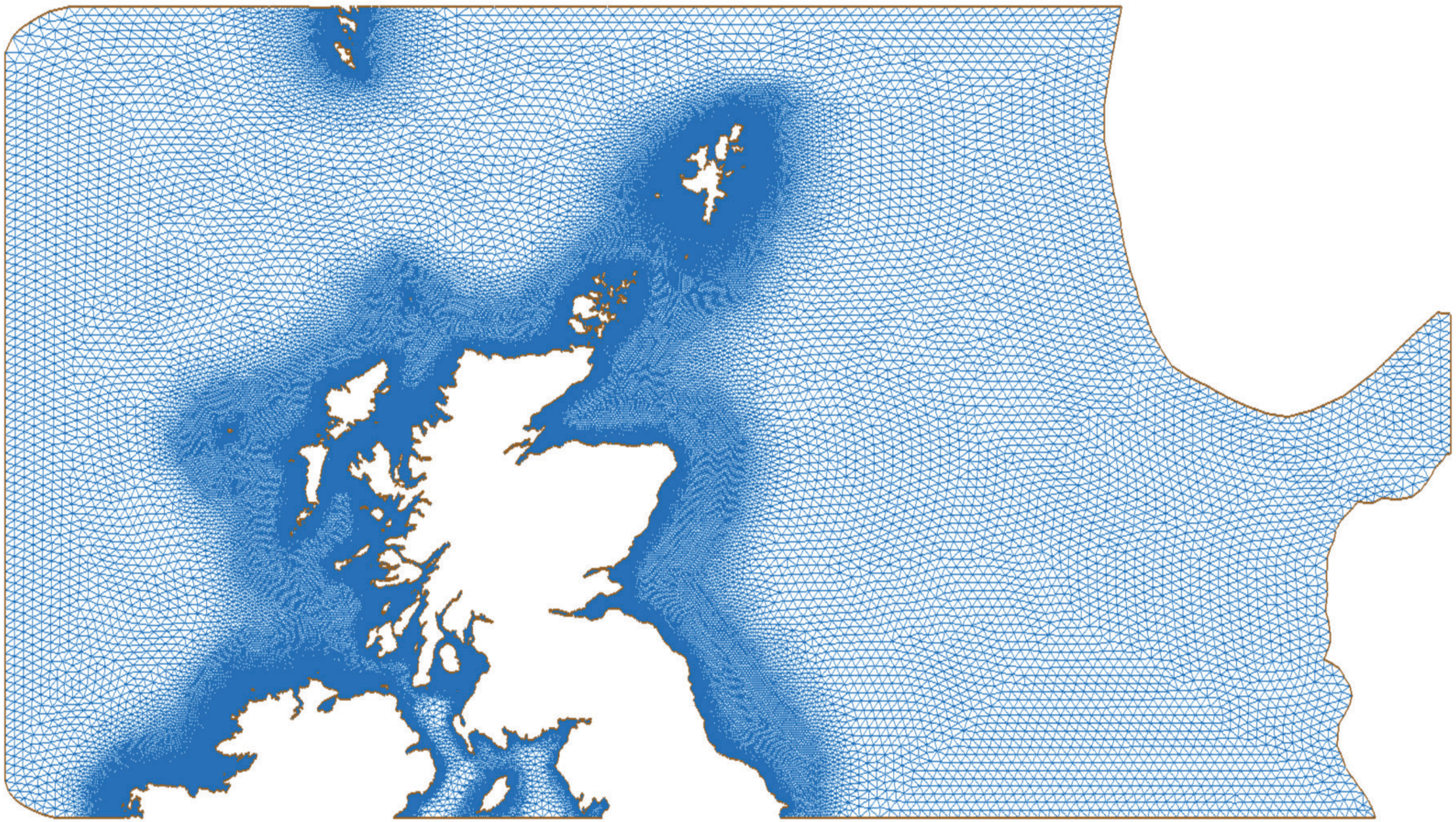
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3		
Marine Scotland	ch2m:	Scottish Shelf Waters Model	**Example of grid refinement issues – estuary / inlet with only one triangle between land boundaries**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m:

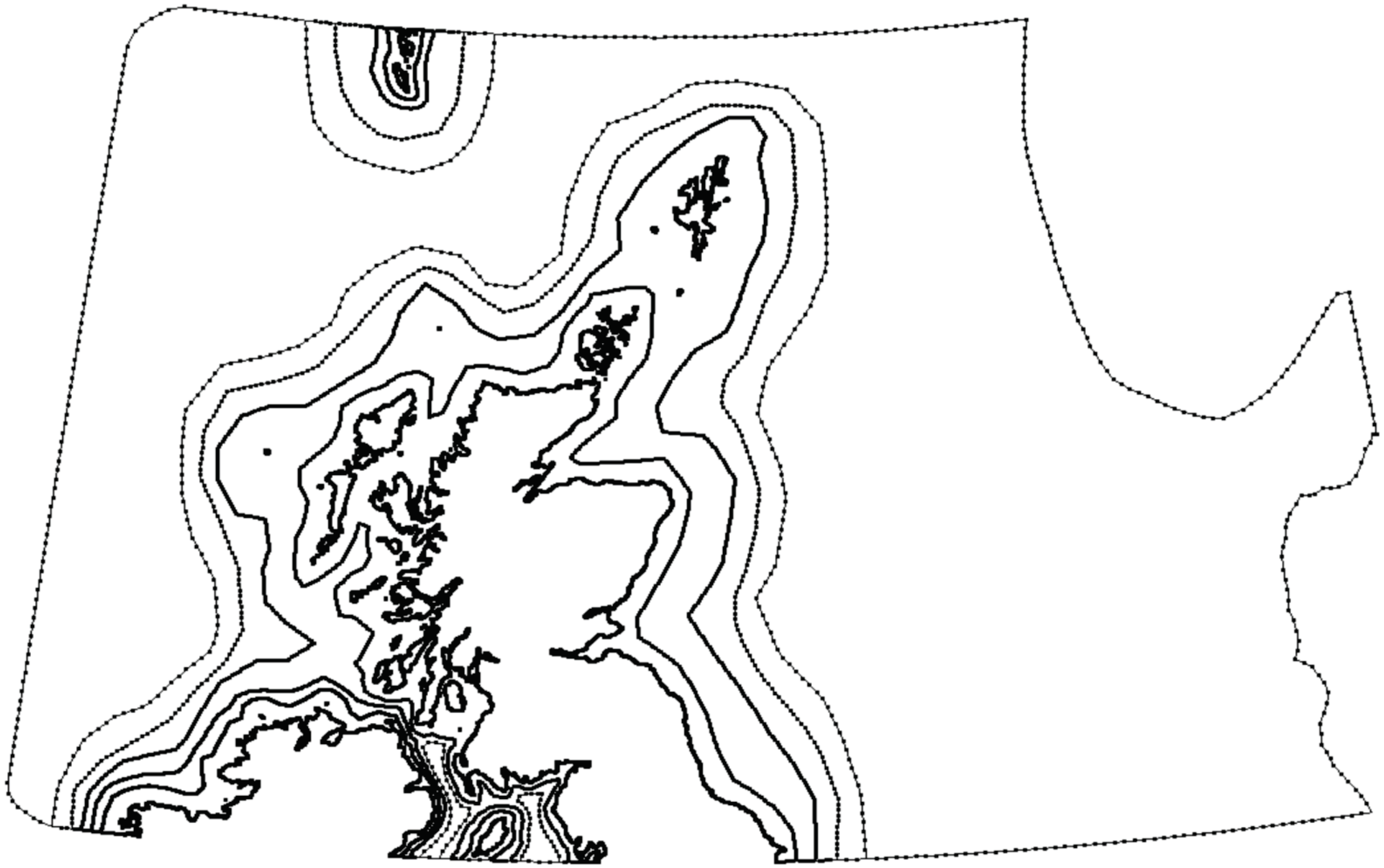
The first mesh generated for the whole of Scottish Shelf Waters is shown in Figure 3-4. This shows the variable resolution employed in the mesh. The resolution varies from 10km offshore to 1km at the coast. This mesh was set up on a quasi-rectangular area, defined by latitude and longitude limits, for simplicity. The coastline and the polylines used to define areas with different resolutions can be seen in Figure 3-5. Further iterations were carried out to accommodate appropriate resolution in the areas of higher resolution.

The mesh file produced by the SMS mesh generator is in an ASCII format that is easily converted into a format that can be used by FVCOM. This was done by using a piece of Matlab code to read and write the data into the necessary format.

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 2.2.1.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4		
Marine Scotland	ch2m	Scottish Shelf Waters Model	SSW model first mesh	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



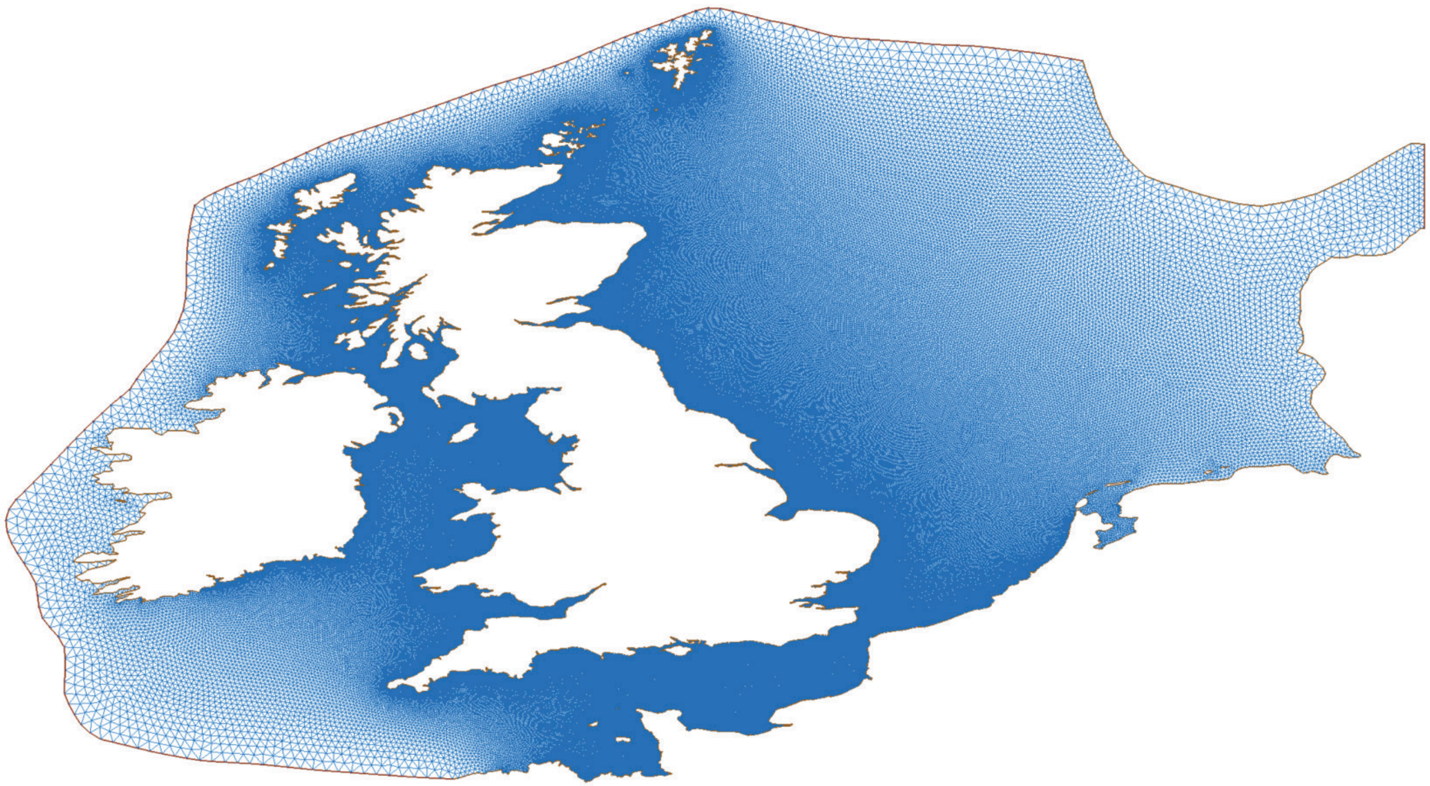
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5		
Marine Scotland	ch2m	Scottish Shelf Waters Model	First stage Scottish Waters Model boundary with polylines for mesh refinement	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

A second model mesh (Figure 3-6) was generated by moving the open boundary to the shelf edge (~200m depth) to avoid issues with resolution of the steep shelf edge topography (which causes topographic Rossby waves, particularly at diurnal tidal frequencies). The coastline and the open boundary polyline used to define this area can be seen in Figure 3-7. The coastline of the rest of the UK and Ireland was included at ~1km resolution using an earlier dataset from MGGD (now superseded by GSHHS). The bathymetry data are then interpolated onto the element nodes.

As can be seen from Figure 3-6, the western model boundary was relatively close to the coast of Ireland. Model stability issues were experienced with this model, due to reflections off the Irish coast and the nearby clamped model open boundary. As FVCOM does not support a radiative boundary condition (which might have resolved this issue), the model mesh was changed slightly to increase the distance between the boundary and Irish coast (Figure 3-8). (On further discussion within the FVCOM user community, another potential solution is to generate a sub-nest forced by elevation and currents). A final model mesh (Figure 3-9) was required by the more limited geographical coverage of the available meteorological forcing data.

Some improved coastal resolution has also been introduced in some areas in order to ensure proper resolution of inlets and straits, and to improve model stability when running with river freshwater inputs. It is necessary to ensure sufficient water depth in the elements in which the freshwater is introduced and also that the element is not connected to 2 closed boundary sides.

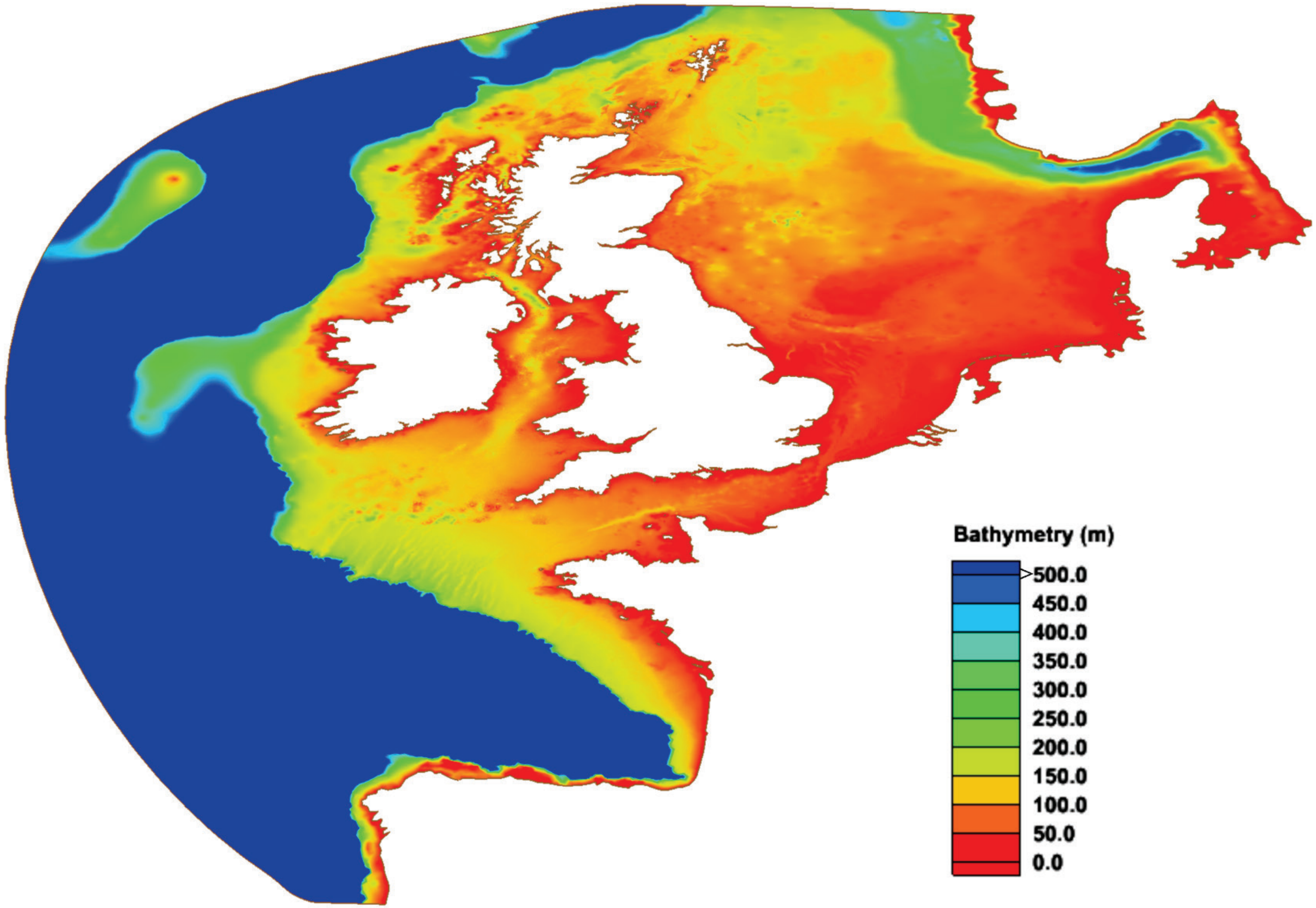
The vertical model resolution was initially selected to be 10 sigma-levels as this was found previously to be adequate resolution for shelf seas. Further examination of the vertical resolution was done during calibration of the baroclinic model.



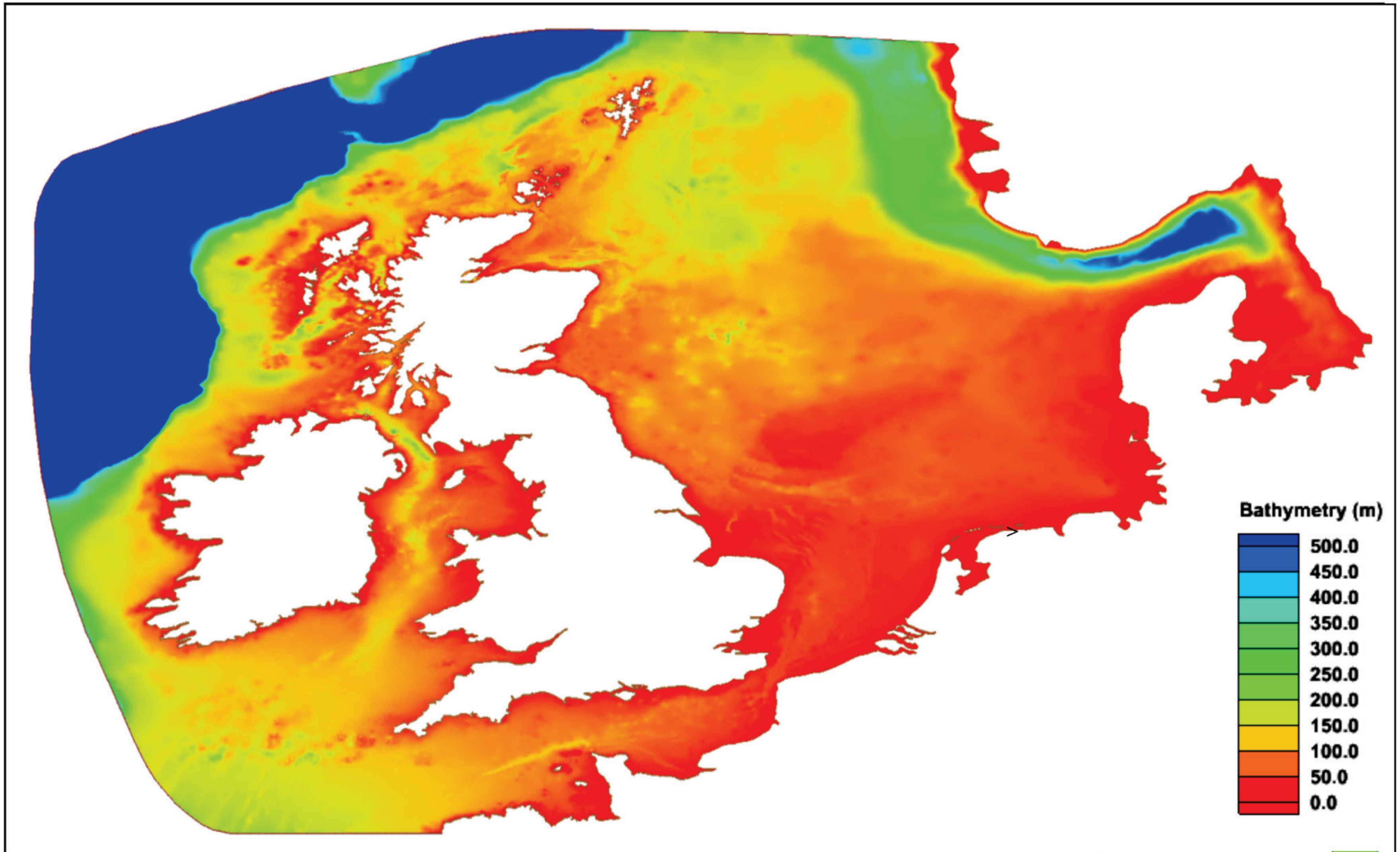
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Scottish Shelf Waters 2nd Model Mesh, March 2013	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m

Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7		
Marine Scotland		Scottish Shelf Waters Model	Full SSW model coastline and open boundary polyline	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-8		
Marine Scotland	ch2m:	Scottish Shelf Waters Model	Third SSW model grid	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Final SSW model grid	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.2.2 Model bathymetry

The NOOS bathymetry (as used in the NOC-L HRCS model) was used for the first stage of SSW model development. For the tidal calibration stage the EMODnet data were used.

3.2.3 Boundary data

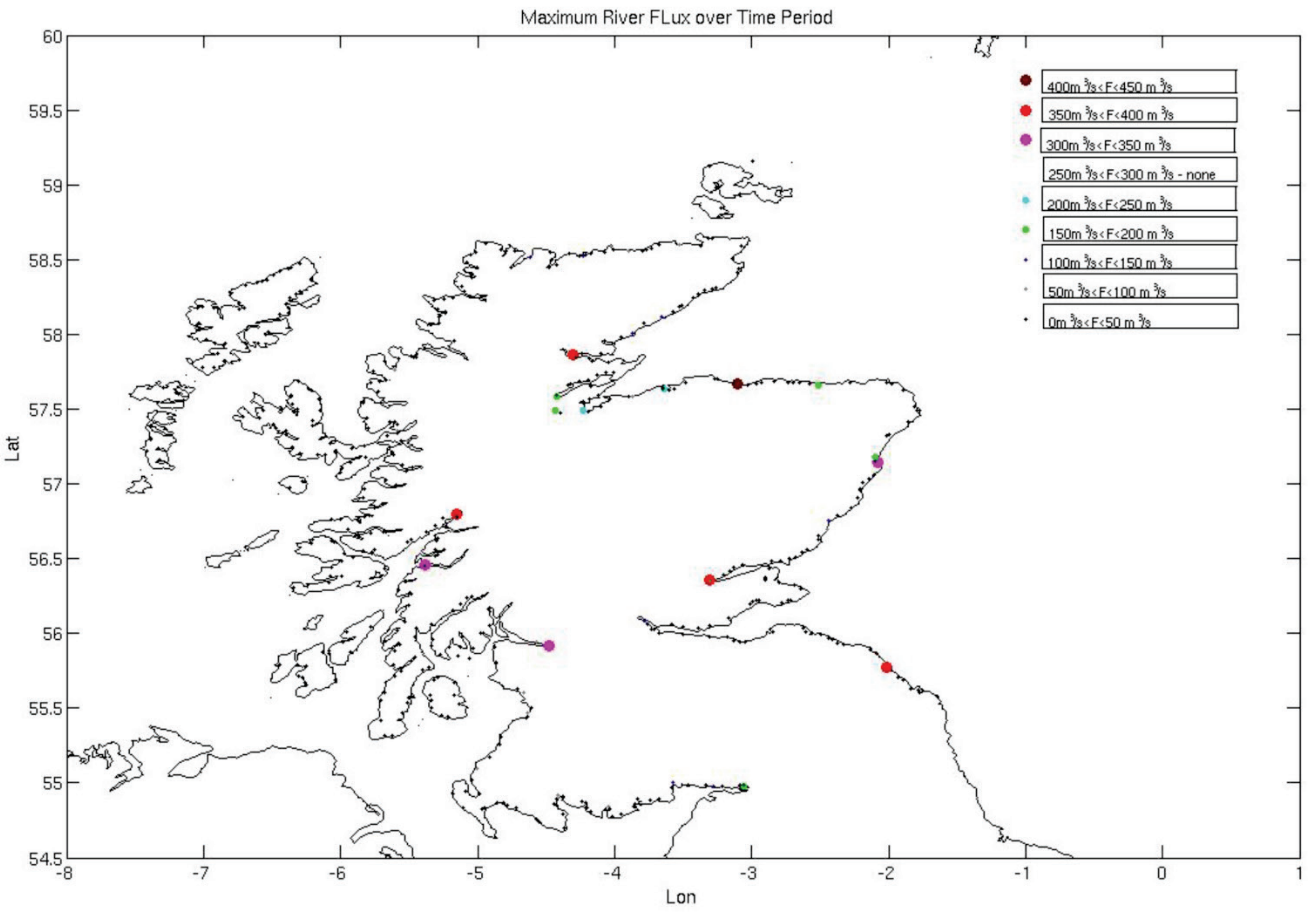
The tidal boundary was initially forced with 15 tidal constituents from the NOC-L HRCS tidal model, using tidal elevation only. However after the model was extended, the TPXO7.2 global tidal inversion data were used to force the open boundary.

For the baroclinic model run, the boundary was also forced with daily temperature and salinity profiles from the NOC-L AMM model. River data was included at the coastal boundary, using the CEH G2G model output. These data give instantaneous flow rates (m^3/sec) for each river at 15 minute intervals. The data do not provide temperature, which has been taken as a constant 10°C. Because of large file sizes (and related processing time issues), this 15 minute data were averaged to produce a daily flow rate which was used in the FVCOM model runs.

The river input locations are shown in Figure 3-10, which also shows the maximum discharge for each river. Figure 3-11 shows the location of the top ten rivers by discharge with their average daily mean discharge.

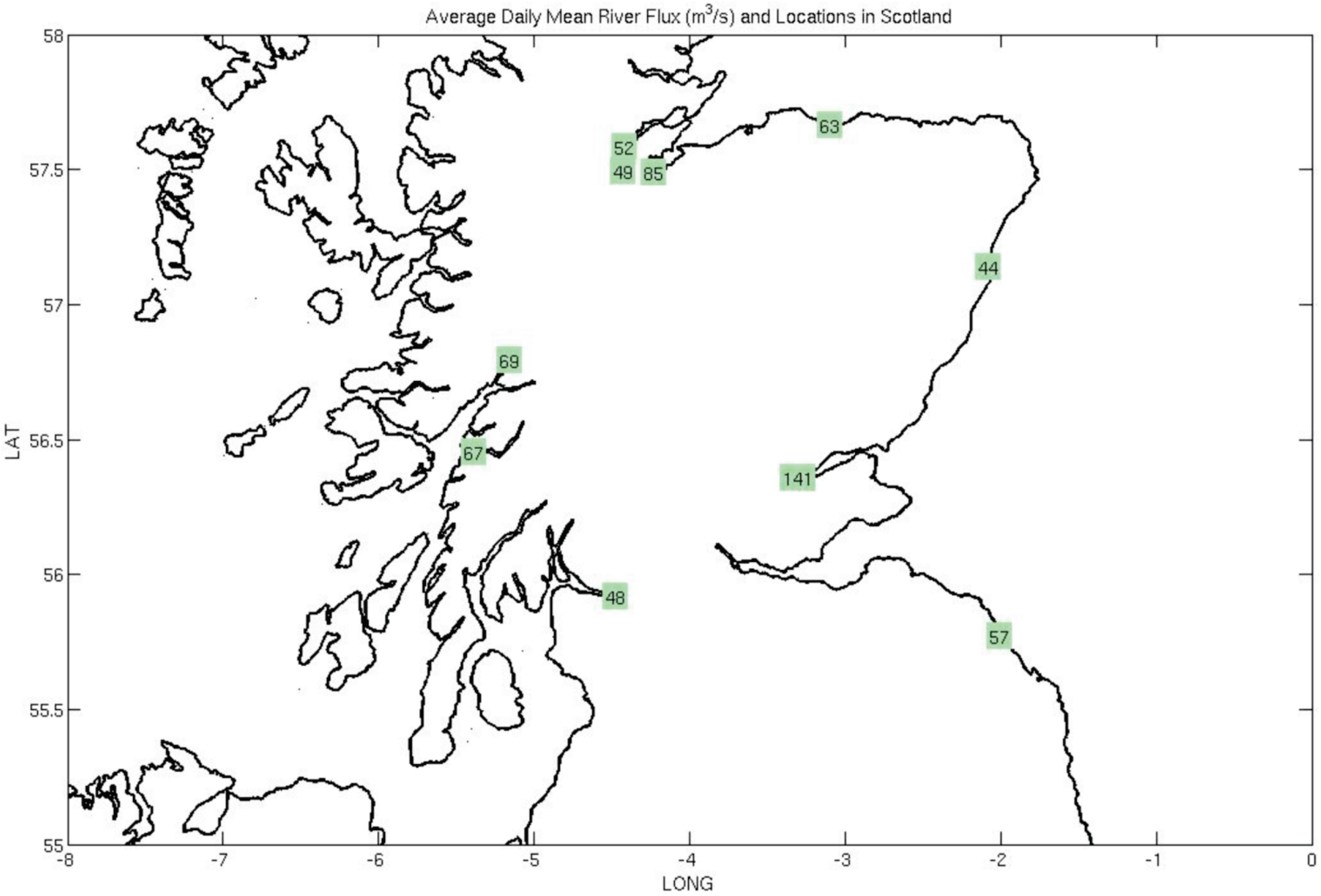
3.2.4 Meteorological forcing data

The met forcing data was retrieved for 2009. Further access to the Met Office Unified Model data was acquired via BADC. The meteorological forcings available for FVCOM include the surface wind stress, sea level pressure, heat flux and precipitation/evaporation (see chapter 5 of FVCOM User Manual). The net surface heat flux consists of four components: net downward shortwave radiation, net downward longwave radiation, sensible, and latent fluxes. Two options exist for applying the heat flux: (i) providing the heat flux directly from the atmospheric model (ii) calculating the heat flux within FVCOM, given various atmospheric model outputs. The following fields were extracted from the UKMO UM via BADC, in addition to the wind, pressure, air temperature and precipitation data already available for the AMM model:



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Location of River Input Scottish Shelf Model, also showing their maximum discharge**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-11		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Location of the top 10 river inputs by discharge for the Scottish Shelf Model, also showing their average daily mean discharge**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

01201 – net downward surface SW flux

02201 – net downward surface LW flux

03217 – surface (sensible) heat flux

03234 – surface latent heat flux

01235 – total downward surface SW flux

02207 – downward LW rad flux: surface

03245 – relative humidity at 1.5m

00024 – surface temperature

16222 – pressure at mean sea level (*Pa*)

Evaporation (E ms^{-1}) was calculated using the following procedure:

(a) Calculate saturated water vapour pressure, E_W (mb) at given air temperature, T (deg C), see Gill (1982, p 30, 606)

$$E_W = 10^{0.7859+0.03477T/_{1+0.00412T}}$$

(b) Calculate actual water vapour pressure E_A using relative humidity, h_R

$$E_A = 0.01 h_R E_W$$

(c) Calculate saturated and actual specific humidity (Q_W, Q_A), using M_r (ratio of molecular weight of water to air = 0.622) and sea level pressure, P_a

$$Q_W = \frac{M_r E_W}{(P_a - (1 - M_r E_W}\ , \qquad Q_A = \frac{M_r E_A}{(P_a - (1 - M_r E_A}$$

(d) Calculate evaporation, using wind-speed (W_S ms^{-1}) and Dalton number (C_E=0.0015)

$$E = C_E W_S (Q_W - Q_A)$$

3.3 Flow model calibration

Model validation and calibration refers to the process of comparing the model output with observations in a systematic way. Validation is just this comparison, which should be based on quantitative metrics, and then making a judgement about whether the model results are sufficiently good, with respect to some objective criteria. Calibration is the process of tuning the model, based on model options, optimising the selection of certain more-or-less unknown parameters and improving the mesh and bathymetry. There may also be some selection to be made between different forcing datasets. It is to be expected that tidal currents and elevation, and sea surface temperature can be well modelled, whereas residual current speed and salinity may have RMS errors similar to the standard deviation of the data (Holt et al., 2005). Issues of modelling and validation of the residual currents and salinity comparison are related both to the model forcing (e.g. river input) and the mixing/turbulence formulation and also the accuracy of the observations.

For the tidal model the model was run by generating time series of open boundary forcing using the T_TIDE (tidal analysis and prediction) Matlab software (Pawlowicz et al., 2002), as there was found to be a problem in using the harmonic forcing with tidal constituent amplitude and phase specified at the boundary. Further investigation is required to clarify the time origin for the model tides (when spectral forcing is used) as there appear to be phase errors with standard assumptions. The model was run for selected periods from a few days to a month then the elevation and current time series output at selected points were analysed using the T_TIDE software.

Comparisons with observed data were carried out by both statistical means and the use of expert judgement. We followed the guidelines for model calibration laid out in the document "Quality Control Manual for Computational Estuarine modelling, Technical Report W168, section A.4.2.1" produced by the Environment Agency of England and Wales. This document suggests the calibration limits in the Table 3-1 below for coastal waters:

Table 3-1 Calibration limits for coastal waters

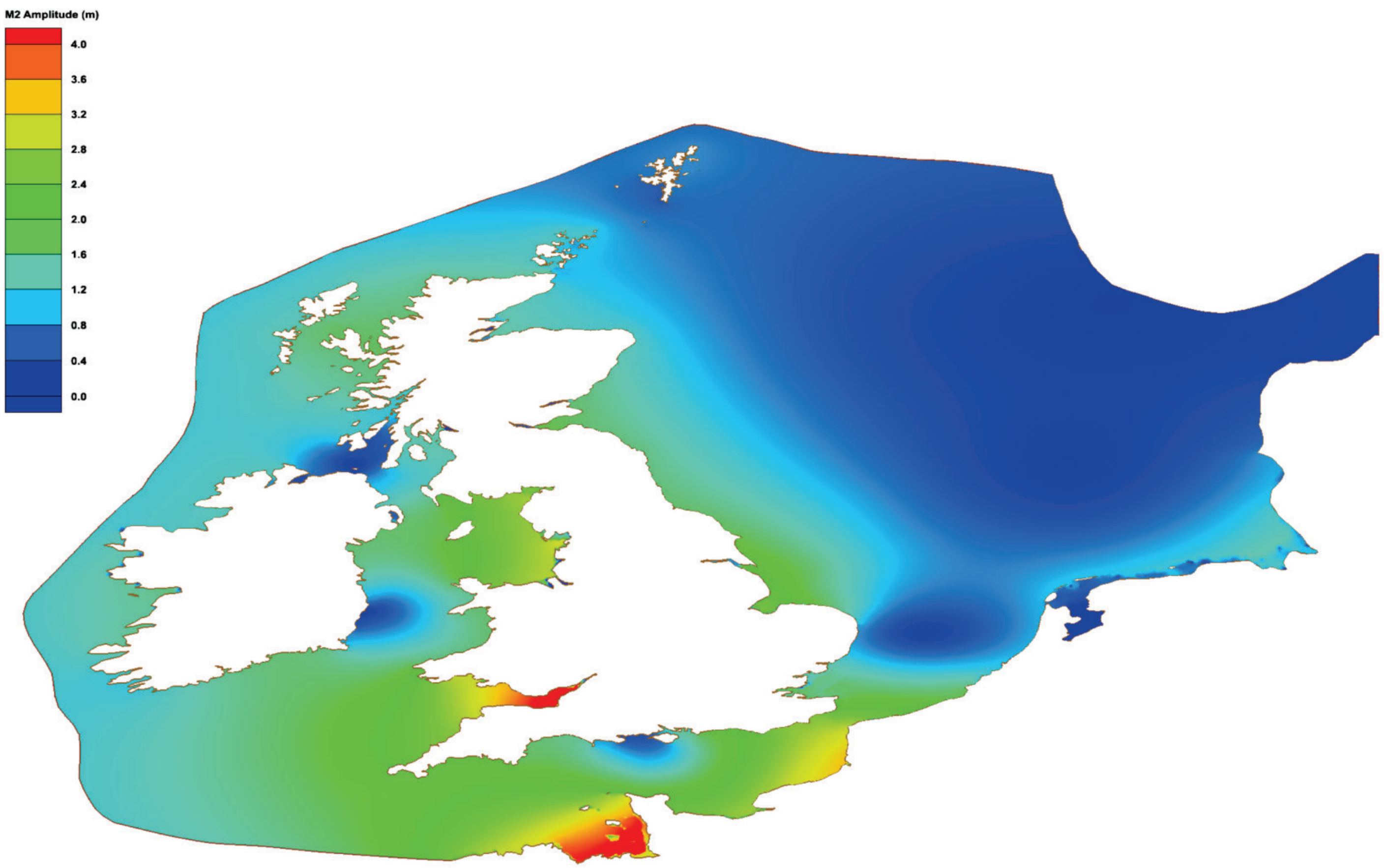
Parameter	Suggested limits (in absolute values)	Alternative limits (in terms of percentages)
Water Levels	Within ± 0.1m	Within ± 10% of spring tide ranges and ± 15% of neap tide ranges Condition to be satisfied 90% of time.
Current speeds	Within ± 0.1m/s	Within ± 10 to 20%
Current directions	Within ± 10 deg	
Timing of high water	Within ± 15 mins	
Temperature	Within ± 0.5 deg C	
Salinity	Within ± 1 psu	

A set of statistics (e.g. mean error/bias, RMS error) are commonly used to compare model results with observations for tidal elevation, currents, temperature and salinity.

3.3.1 Tidal calibration

A set of points has been extracted by Eric Jones at NOC-L for previous projects, for the whole UK shelf, at which tidal constituents (typically M_2, S_2, O_1 and K_1) have been derived from tide gauges and bottom pressure recorders (236 locations in Scottish Waters), a subset of which has been used for the tidal range calibration. Another data set has similarly been put together for the tidal ellipse parameters from current meter deployments where a tidal analysis has been performed (390 locations in Scottish Waters, see Davies and Kwong, 2000). A subset of these has been used for the tidal current calibration. A subset of 27 stations was selected for the elevation points, to include coastal tide gauges (especially A-class gauges) and offshore pressure gauges. Similarly a subset of 24 current meter locations was selected, to represent each different sea area around Scotland.

First results for the M_2 tidal elevation amplitude can be seen in Figure 3-12, which shows that the main tidal amphidromes are in approximately the correct locations (see Howarth, 1990). A selected subset of coastal tide gauges was used for a first look at the M_2 quantitative tidal validation, see Table 3-2. In general this showed some model skill but an underestimate of the tidal amplitude.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-12		
Marine Scotland	ch2m:	Scottish Shelf Waters Model	M_2 tidal amplitude – first full shelf model result, March 2013	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

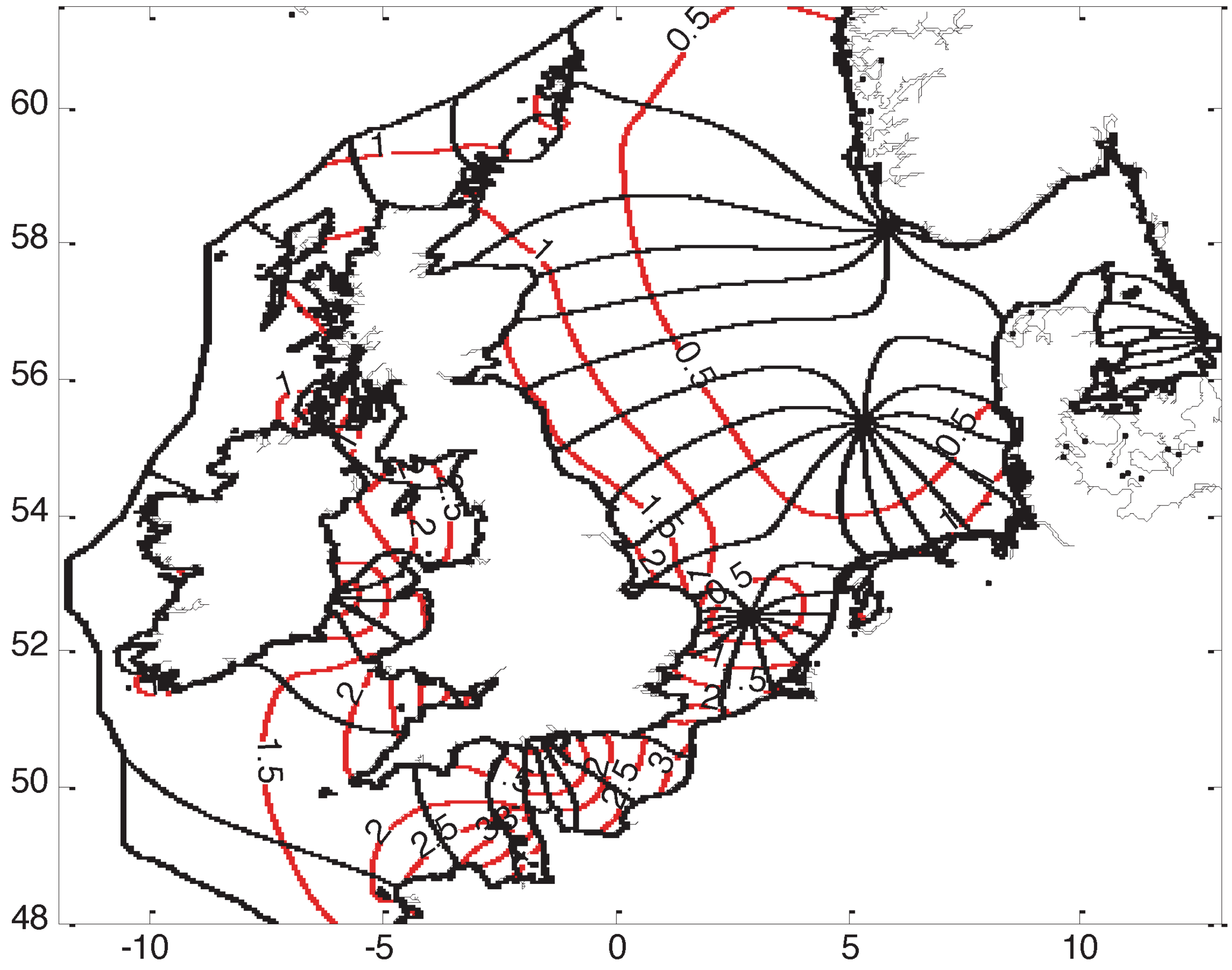
ch2m:

Table 3-2 M_2 tidal amplitude, first validation at Class A tide gauges

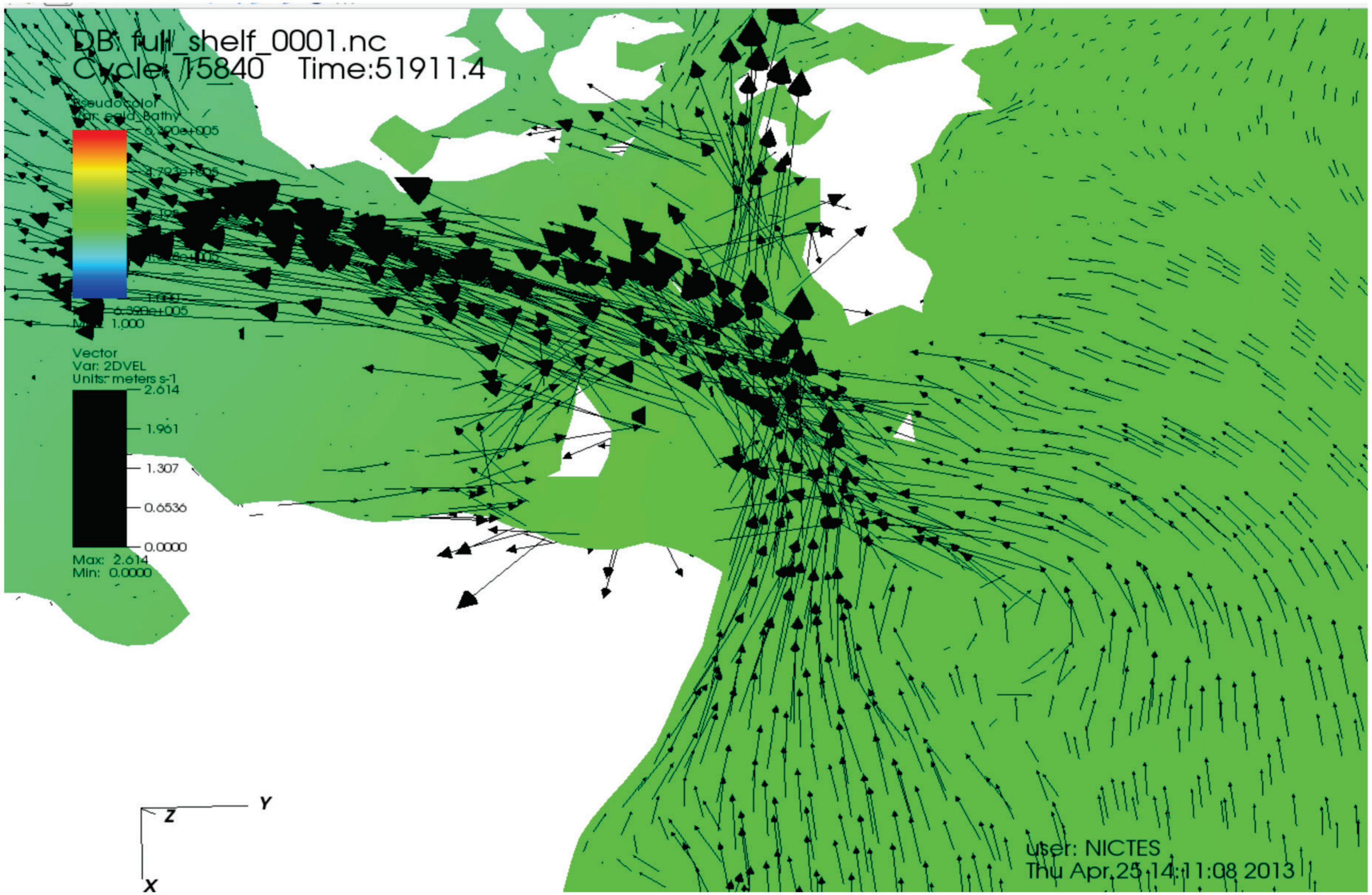
Class A Tide Gauges - data from Full Shelf Model Run							
Loca-tion	**Observed**			**Model**			**Differ-ence**
	Lat. (deg N)	Lon. (deg E)	M_2 Amp. (m)	Lat. (deg N)	Lon. (deg E)	M_2 Amp. (m)	
Aber-deen	57.15	-2.08	1.30	57.17	-2.02	1.16	-10.9%
Lerwick	60.15	-1.14	0.58	60.12	-1.14	0.53	-8.3%
Tober-mory	56.62	-6.06	1.30	56.67	-6.26	1.31	1.0%
Storno-way	58.21	-6.39	1.39	58.15	-6.33	1.34	-3.3%
Kinloch-bervie	58.46	-5.05	1.43	58.46	-5.16	1.33	-7.5%
Wick	58.44	-3.09	1.02	58.43	-3.03	0.96	-5.3%
Ullapool	57.90	-5.16	1.50	57.97	-5.36	1.44	-3.9%

The following procedure was followed to validate the model:

- Check locations of M_2 amphidromes against (i) HRCS cotidal chart (Figure 3-13) and (ii) John Howarth's cotidal chart from observations (Howarth, 1990).
- Check hourly plots of surface elevations and currents through the tidal cycle using the Visit software. Are there any areas of spurious currents and elevations? Especially focus on the 4 sub-areas. An example of a snapshot of the Pentland Firth at maximum ebb tide is shown in Figure 3-14, showing currents of up to 2.6ms-1.
- Compare elevation and current time series (E and N components) from selected locations. Check for systematic amplitude and phase errors.
- Check tidal analysis for water surface elevations for selected locations, starting with M2, then S2, O1 and K1 tidal harmonics
- Compare tidal analysis for selected current meter locations, using mid-depth current meters compared to depth-averaged model currents.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-13		
Marine Scotland		Scottish Shelf Waters Model	NOC-L HRCS model M_2 cotidal chart	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Snapshot of depth-averaged current vectors, shading corresponds to water depth, length of vectors (shown by black bar) corresponds to current speed (0-2.614 ms^{-1})**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

The acceptance criteria in Table 3-1 may be approximated, since the main part of the variance is due to the dominant lunar semi-diurnal tide, M_2, thus we required the elevation error for M_2 to be <10% amplitude, <10° phase (a timing error of 15mins corresponds to about 7.5° phase error). Other constituents were required to be <20%, <20°. For currents the semi-major axis <10%, orientation within +/- 10°, phase error <10°, eccentricity within 10% for M_2 was used as a guide.

For the calibration/tuning of the model various statistics of the model goodness of fit were examined, such as bias, RMS error and the scatter index (RMS error divided by mean observed value). It is important to ensure that the errors are not dominated by large errors in quantities of smaller magnitude. The correlation between 2 time series was also used as a model metric.

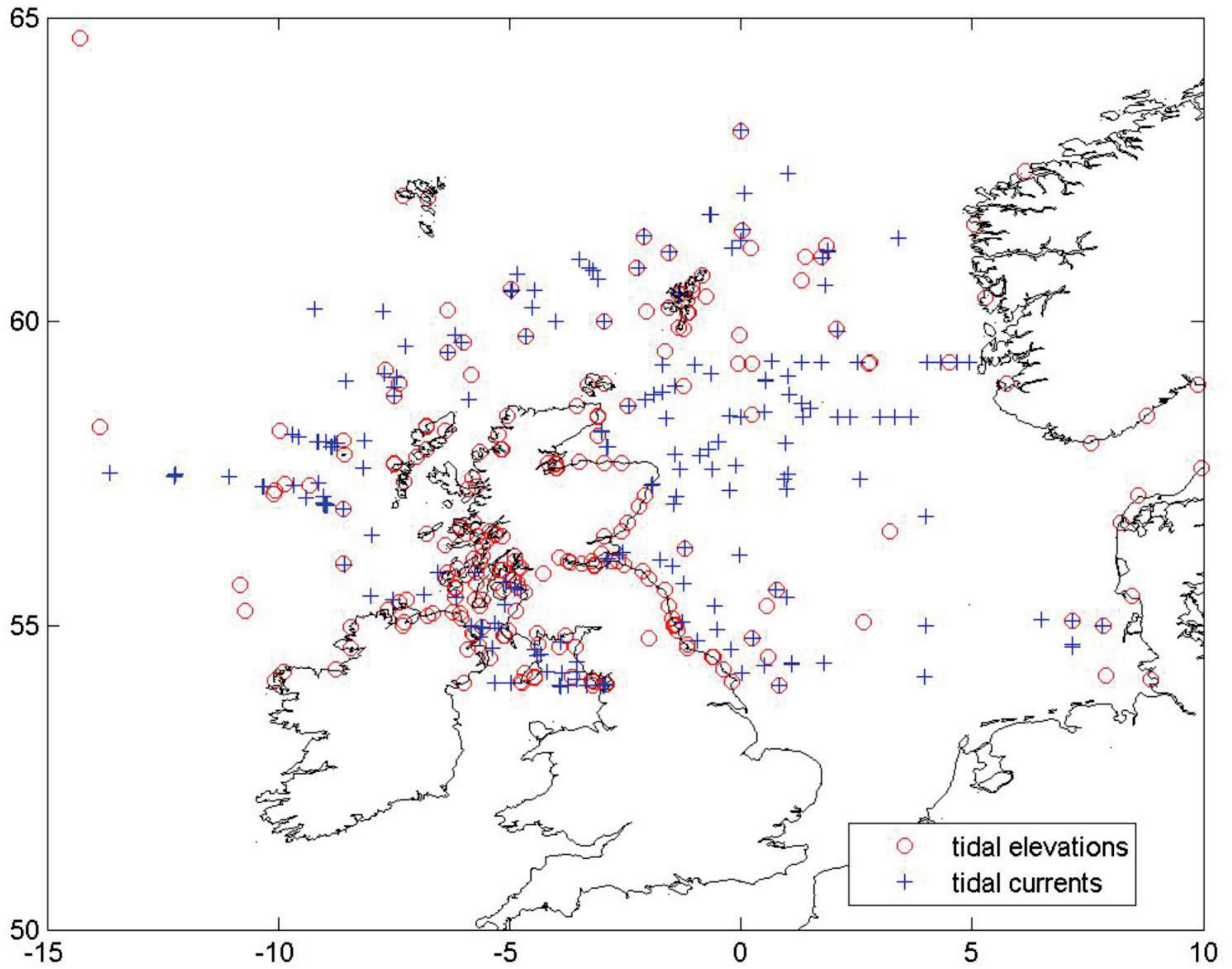
A variable, *K,* was designed for the quick intercomparison of different model versions based on Davies and Kwong (2000), where:

$$K = \frac{1}{k}\sum_{i=1}^{k}\sqrt{(h_m \cos g_m - h_o \cos g_o)_i{}^2 + (h_m \sin g_m - h_o \sin g_o)_i{}^2}$$

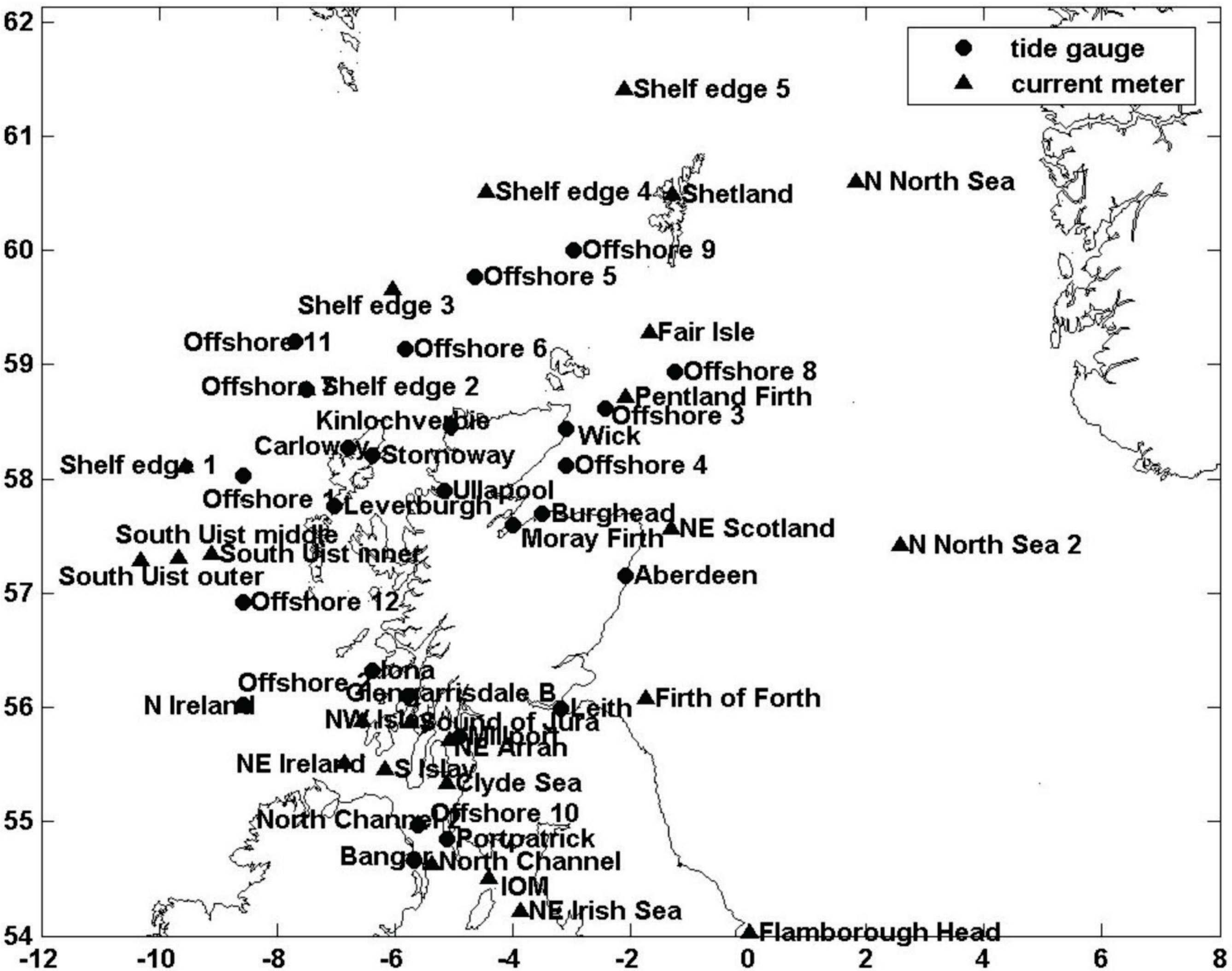
It is a measure of the “goodness of fit” for an individual point where model and observed values are being compared.

K represents a measure of the average model error for a given tidal constituent, averaging over all the *k* points at which model and observations have been compared; the subscript *m* indicates the model value and *o* indicates the observed value, *h* is amplitude and *g* is phase of the tidal elevation. The values *h*cos*g* and *h*sin*g* are used to provide smooth functions combining amplitude and phase information. A similar metric was used to calculate the average error for the semi-major axis of the tidal current i.e. using the amplitude and phase of the tidal constituent of the current resolved along the semi-major axis of the current ellipse. Ideally the procedure is to minimise all the error metrics. Various attributes of the model were adjusted as described in the following sections. Initially a 15-day run (a single spring-neap cycle) using the default model settings was run. Then some 5-day (and some shorter 1.5-day) M_2-only runs were used to quickly test various model configurations. Finally a 29-day run (the shortest period allowing for direct separation of the M_2 and S_2 constituents in the harmonic analysis) forced by 8 constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1 and Q_1) was completed, using the optimum settings.

Figure 3-15 shows the full set of elevation and current meter tidal analyses locations and Figure 3-16 shows the selected stations (27 elevation and 24 current points) used in the calibration.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15		
Marine Scotland	ch2m	Scottish Shelf Waters Model	All tidal analysis points (N of 54 deg N)	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-16		
Marine Scotland		Scottish Shelf Waters Model	Location of selected SSW tidal calibration points	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.3.2 Open boundary forcing and model extent

Model evolution is discussed in Section 3.2.1. The current model extent is shown in Figure 3-9. The TPXO7.2 tidal forcing was acquired to force the new boundary rather than interpolating the AMM data as it was expected that this would give a better boundary forcing, being derived from altimeter observations.

3.3.3 Mesh optimisation and evolution

As part of mesh optimisation, scripts were written to calculate the CFL timestep for all the triangles in the grid. The CFL condition is a criterion that must be met in order to solve partial differential equations using explicit time integration schemes for finite difference solution of the equations. For example, if a wave is moving across a discrete spatial grid and we want to compute its amplitude at discrete time steps of equal length, then this length must be less than the time for the wave to travel between adjacent grid points. The smallest CFL timestep determines the time step of the entire model.

The CFL timestep was calculated as:

$$\Delta t = \frac{\Delta L}{\sqrt{gD}}$$

where Δt is the time step, ΔL shortest edge of an individual triangular grid element, g is the acceleration dues to gravity and D is the local (bathymetry) depth.

From the equation, it can be seen that the overall model timestep is dictated by triangles having short edges in deep water. Since this calculation was performed for all triangle edges, it was possible to identify the triangles with the smallest CFL timestep. These were eliminated by either merging triangles, or by moving nodes, both within SMS.

This optimisation proved to be only partially successful with FVCOM. In fact the model timestep needed to be smaller than that suggested by this CFL calculation.

3.3.4 Coastline and bathymetry

The accuracy of the coastline was checked against chart data and the requirement to ensure that the flow could pass through the main straits and passages. The coastline and bathymetry were adjusted as necessary.

3.3.5 Bottom friction

The model was operated in 3D mode and different values of the bottom friction were selected by means of a constant roughness length applied to the whole model. The drag coefficient C_D in the quadratic drag law (which relates the bottom stress to the square of the velocity) is fitted to a logarithmic boundary layer applied in the lowest model level (near-bed layer):

$$C_D = \max\left(\frac{\kappa^2}{(\ln(z_1/z_0))^2}, C_{Dmin}\right),$$

where κ is von Karman's constant (=0.4) and z_1 is half the thickness of the lowest level above the bed. The values of z_0 and C_{Dmin} may be selected. Default values are 0.003m and 0.0025 respectively (see FVCOM Manual, Chen et al., 2011). Using this method the drag coefficient increases almost linearly with the roughness length. The drag coefficient is larger in shallower water since the bottom layer thickness reduces (using sigma-levels) and the bed stress is thus calculated nearer to the bed. Specifying the minimum drag coefficient prevents it becoming very small in deeper water. We increased the roughness length to 0.01m and the minimum drag coefficient to 0.005. Further increase of the bottom friction did not produce a stable solution.

3.3.6 Horizontal viscosity

Tests were carried out with double and half the default value of horizontal eddy viscosity, using the Smagorinsky formulation (which is grid-size-dependent) as well as a uniform constant value (see FVCOM Manual, Chen et al., 2011). These tests were only made with a short M_2 run and the results were rather puzzling. Longer runs of the M_2 tide or the full tidal model are needed to resolve this.

3.3.7 Summary of tidal calibration

Tables 3-3 and 3-4 show the values of *K* along with mean bias, RMS error and the percentage of data points reaching the acceptance criteria, for various model configurations. The different statistics produced sometimes conflicting results in terms of the model improvement. The baseline *K*-values were different for different lengths of run, thus it was not always possible to compare like with like.

For the elevation results, in Table 3-3, the 29-day run with 8 tidal constituents was slightly less accurate, according to the *K*-value, with the same model settings, than the M_2-only run. The 15-day run should be nearly equivalent to a baseline 29-day run. However, due to the different method of separation of M_2 and S_2 it is not clear that the runs are equivalent and a 29-day baseline run was carried out.

Increasing the bottom friction in the M_2-only run reduced the *K*-value and the mean amplitude bias and improved the number of points satisfying the acceptance criteria for the M_2 phase. However it reduced the number of acceptable points for the M_2 amplitude.

Changing the horizontal viscosity was difficult to interpret as these runs were only carried out for short periods and there was no comparable baseline run. The amplitude and phase biases were very small and negligible errors were seen with different settings.

The current results, Table 3-4, were more sensitive to the enhanced friction than the water elevations. All the metrics were improved, except the RMS phase error, by increasing friction.

From the tests run the optimised model settings were selected to be an enhanced bed roughness and the default horizontal viscosity (see Tables 3-3 and 3-4). A further adjustment of the bottom friction in different sea areas may be advisable (e.g. Baston and Harris, 2011). In fact the acceptance criteria were not met for all the selected comparison points. For the final 29-day analysis only 70% of the points were acceptable for M_2 amplitude and 85% for M_2 phase. This shows that the parameter set that gives the minimum *K* value and reduced amplitude bias also gives the lowest % acceptable points (where amplitude error is < 10%). The better performance in phase may offset the worse amplitude performance to produce a lower *K* value. If correct prediction of tidal range is more important than phase, this set of parameters may not be optimal. Also the results may be dominated by an outlier (see below). The *K* metric may be more effective for assessing a much larger number of points, as outliers will be less likely to dominate the results.

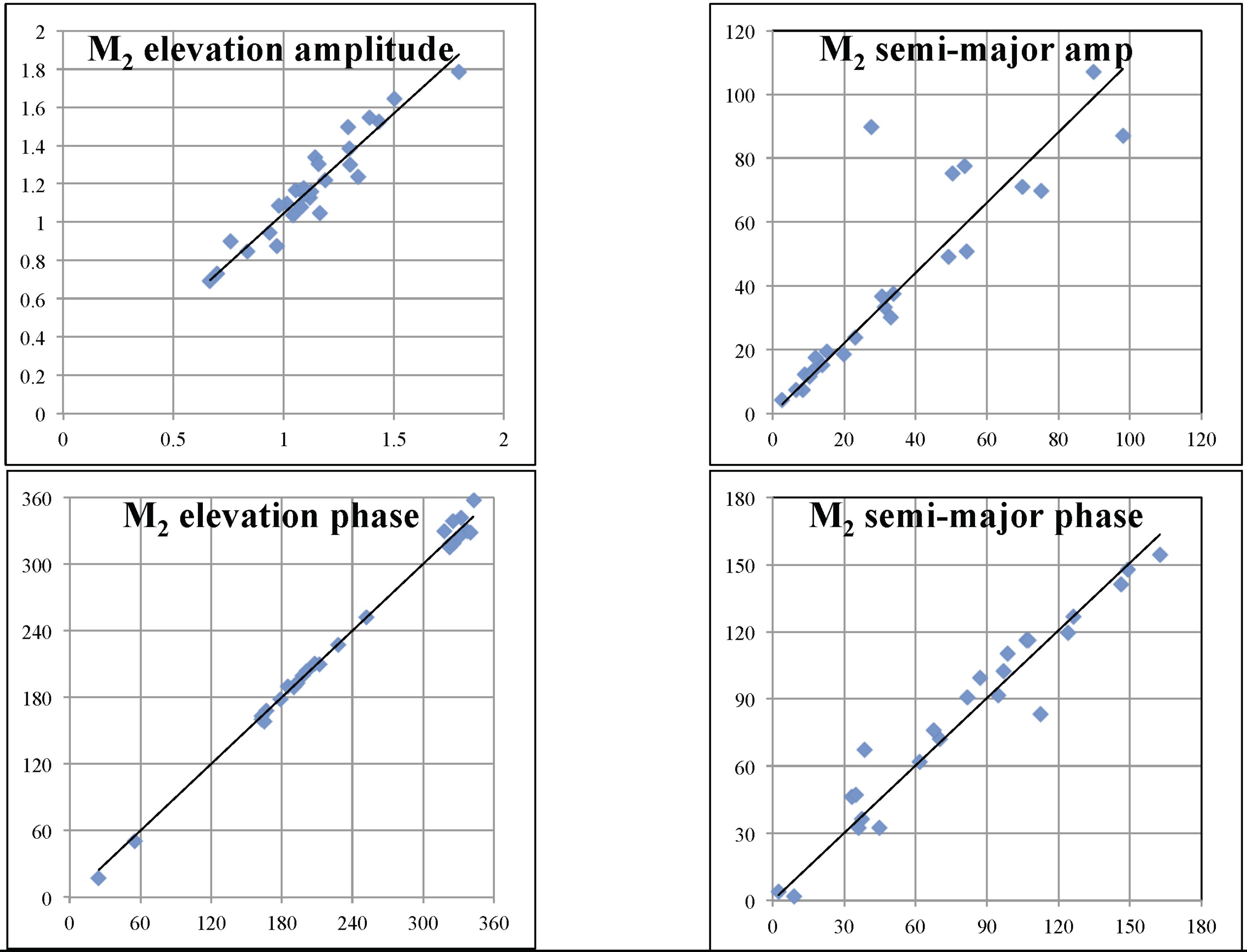
Table 3-3 Statistics for M2 component of surface elevation

Run	Bottom Friction			Horizontal mixing									
	Type	Min C_D	z_0 (m)	Type	Kind	Coeff-icient	*K* (cm)	% Points with amplitude < 10%	Mean amplitude bias (cm)	RMS amp error (cm)	% Points with Phase Diff < 10°	Mean phase bias (deg)	RMS phase error (deg)
15-day, 8 tidal constits, default settings	3D	0.0025	0.003	'closure'	'constant'	0.2	12.2	81	5.3	7.5	85	-1	6
5-day M_2 only, default settings	3D	0.0025	0.003	'closure'	'constant'	0.2	13.8	81	5.2	8.3	78	-1	7
5-day M_2 only, increased friction	3D	0.005	0.01	'closure'	'constant'	0.2	13.5	74	2.6	9.0	81	-1	7
1.5 day M_2 only reduced horiz viscos	3D	0.0025	0.003	'closure'	'constant'	0.1	16.2	78	-1.0	8.2	70	-1	9
1.5 day M_2 only increased horiz viscos	3D	0.0025	0.003	'closure'	'constant'	0.4	16.1	78	-0.8	8.3	74	-1	9
1.5 day M_2 only constant horiz viscos	3D	0.0025	0.003	'constant'	'constant'	0.001 m^2s^{-1}	16.2	78	1.0	8.2	70	-1	9
29-day 8 tidal constits, optimised settings	3D	0.005	0.01	'closure'	'constant'	0.2	13.8	70	5.2	9.8	85	-0.3	7

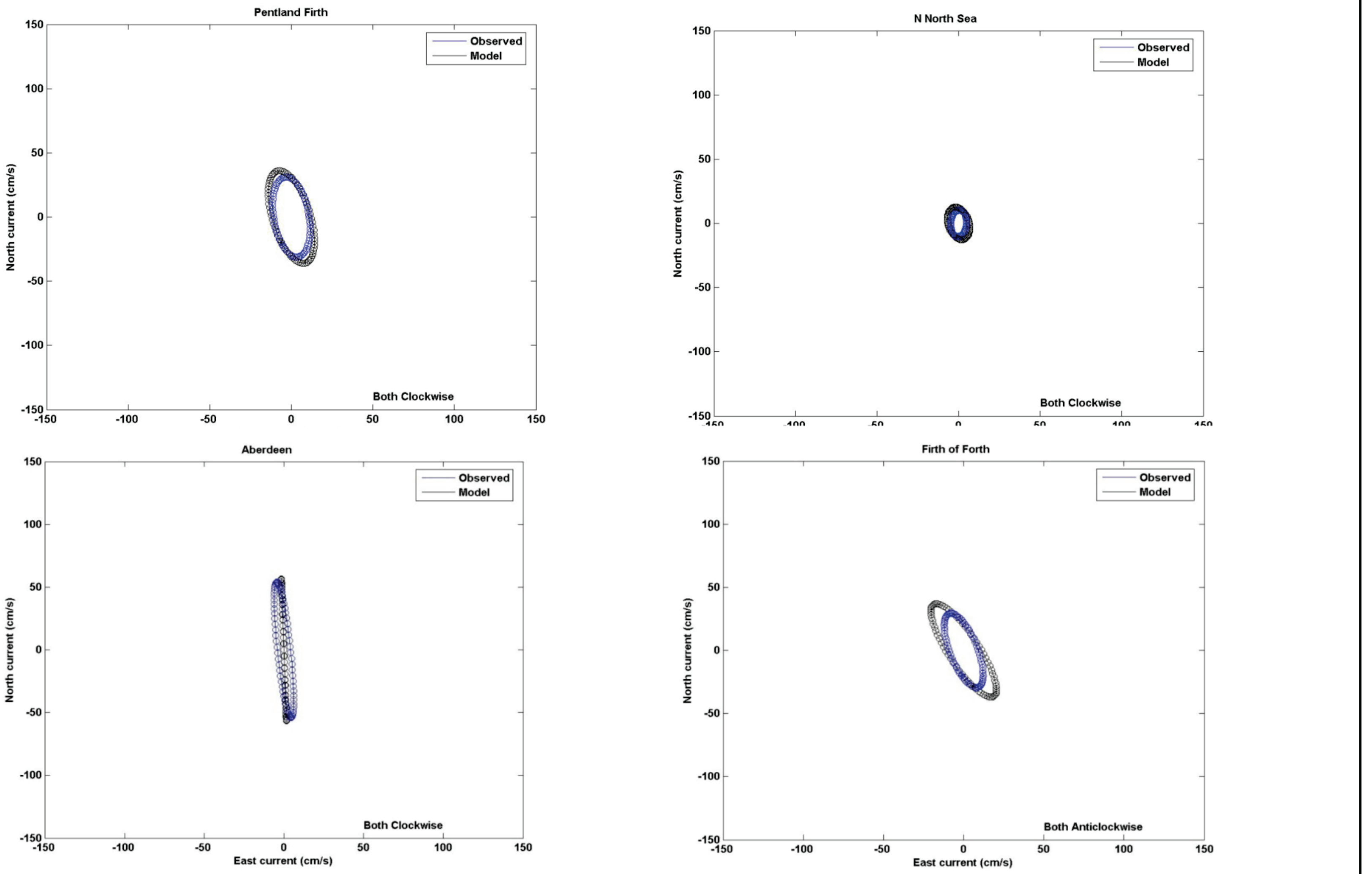
Table 3-4 Statistics for M_2 component of semi-major axis of depth-averaged current

Run	Bottom Friction			Horizontal mixing							
	Type	Min C_D	z_0 (m)	Type	Kind	Coeff-icient	*K* (cm/s)	Mean bias (cm/s)	RMS error (cm/s)	Mean bias (deg)	RMS error (deg)
15-day, 8 tidal constits, default settings	3D	0.0025	0.003	'closure'	'constant''	0.2	12.7	10.9	20.0	2	11
5-day M_2 only, default settings	3D	0.0025	0.003	'closure'	'constant''	0.2	10.5	6.6	16.4	2	11
5-day M_2 only, increased friction	3D	0.005	0.01	'closure'	'constant'	0.2	9.7	4.9	14.9	2	11
29-day 8 tidal constits, optimised settings	3D	0.005	0.01	'closure'	'constant'	0.2	9.9	5.7	15.4	2	11

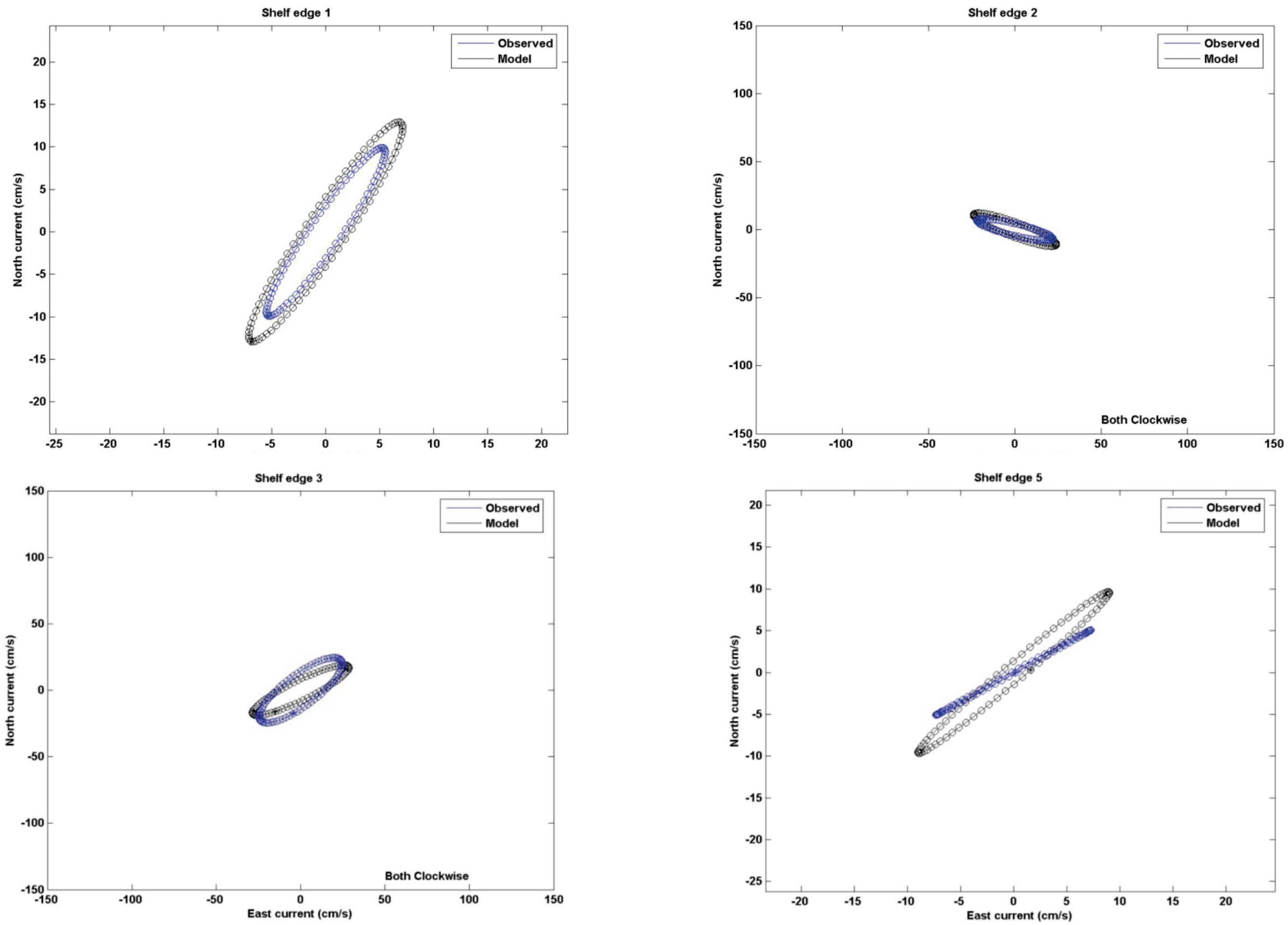
Further investigation regarding the distribution of errors is shown in Figures 3-17 to 3-22. Figure 3-17 shows scatter plots of M_2 amplitude and phase for model versus observations both for elevations and currents, for the 29-day run with increased bottom friction. It can be seen that the elevation phase is very good, but there is more scatter in the tidal amplitude. The outlier in the semi-major axis amplitude is in the North Channel of the Irish Sea. Figures 3-18, 3-19 and 3-20 show M_2 tidal ellipses (hodographs) comparing the model and observations for 3 different areas: NE Scotland, the shelf edge and W Scotland respectively. Qualitatively there is good agreement of the ellipses overall, with the model getting the sense of rotation right in every case. The amplitude, orientation and eccentricity are generally similar, with some exceptions. Figure 3-21 and 3-22 shows the relative error in M_2 elevations as a % error in amplitude and absolute phase error, respectively, plotted as a spatial map. This shows an unacceptable overestimate of the amplitude (>10%) at 2 coastal locations in the western isles and one offshore location east of the Pentland Firth (station Offshore 8). The tide is underestimated by up to 10% in the North Channel but this is close to a tidal amphidrome. The phase is generally very good except in this same area where the phase changes very rapidly. It may be advisable to select some alternative points rather than including this area, which may be too heavily represented in the limited set of data points.



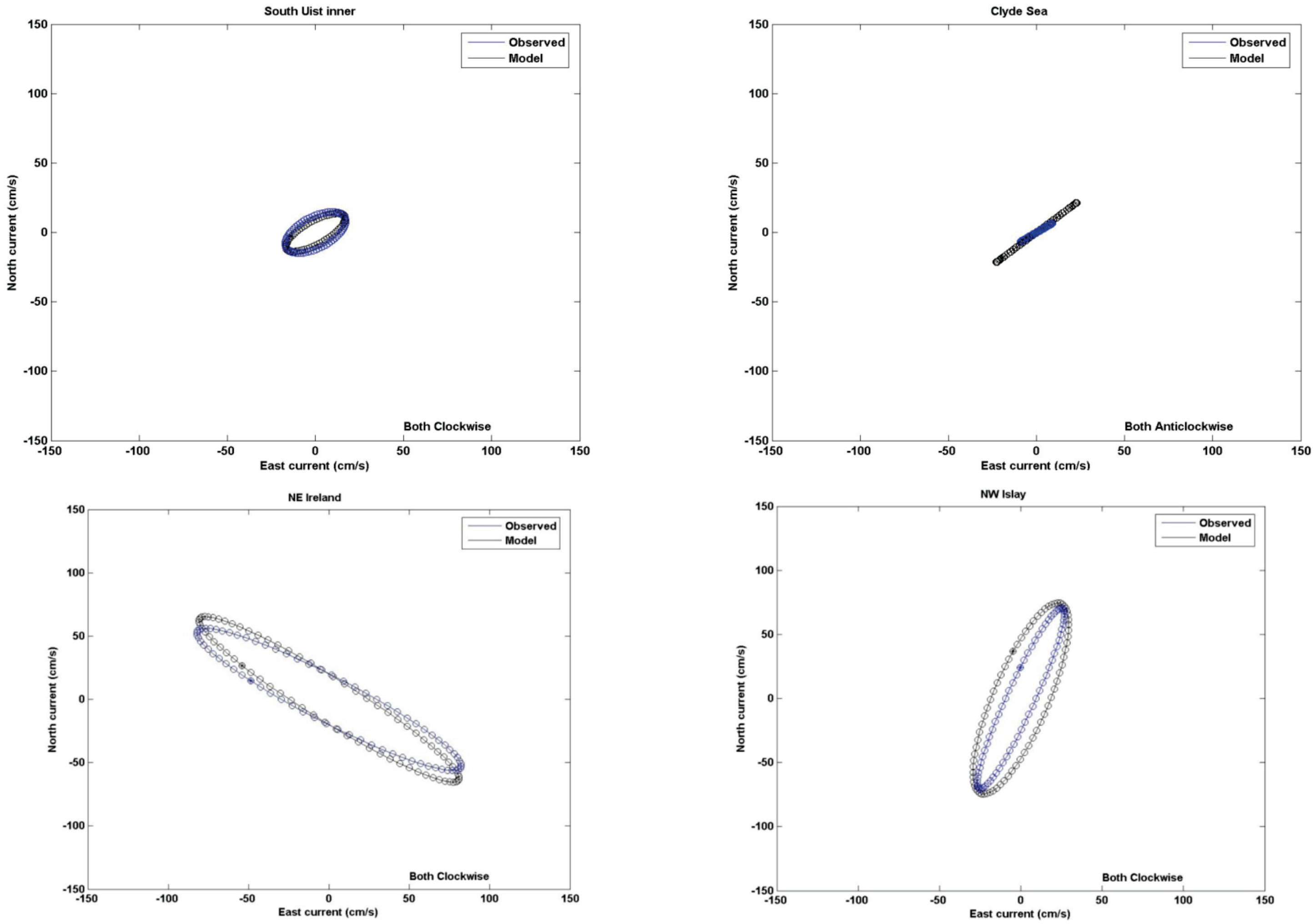
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17		
Marine Scotland		Scottish Shelf Waters Model	Scatter plots of selected M_2 amplitude and phase: left – elevations, right - currents	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



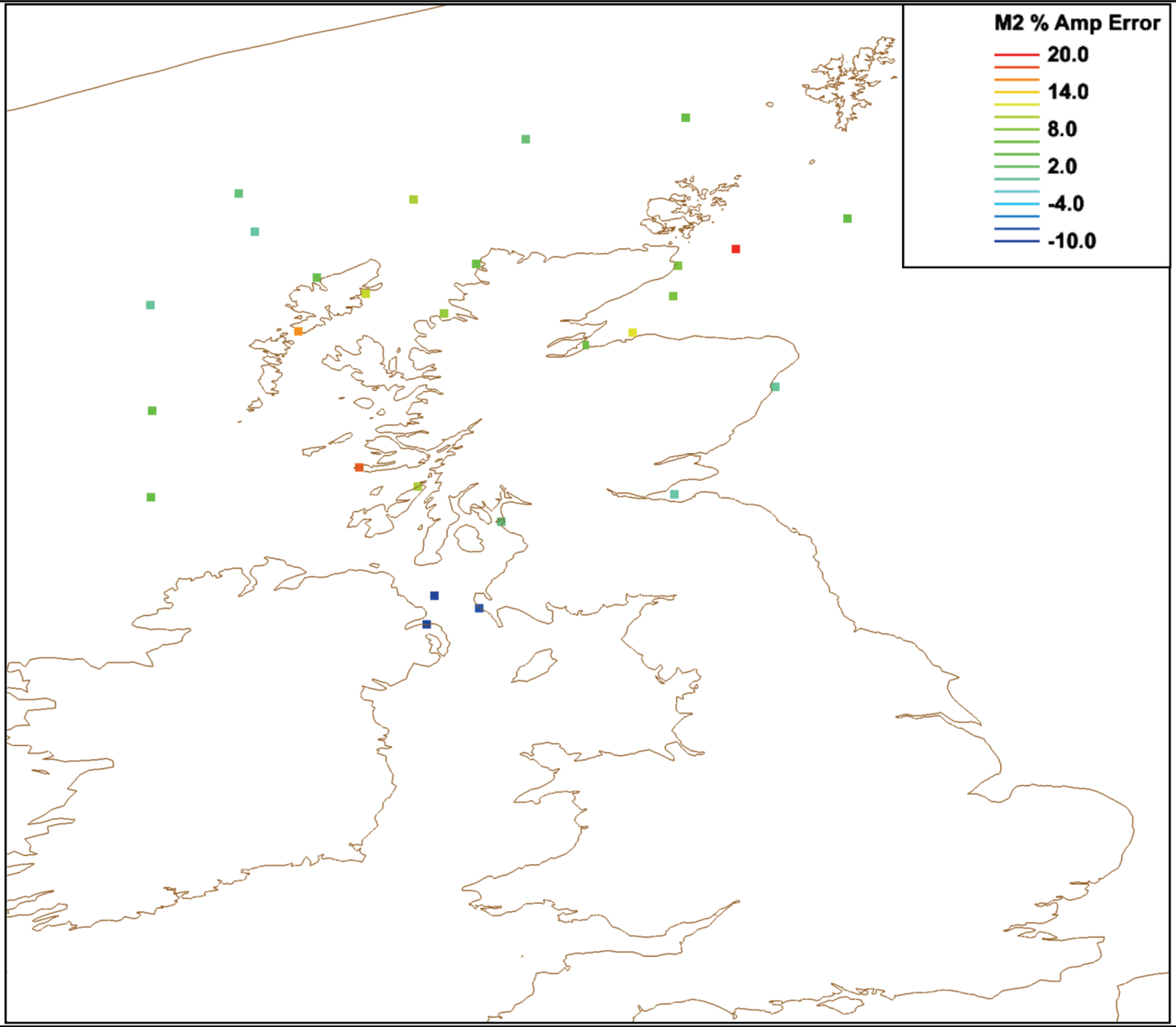
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18		
Marine Scotland	ch2m:	Scottish Shelf Waters Model	M2 tidal ellipses, NE Scotland	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



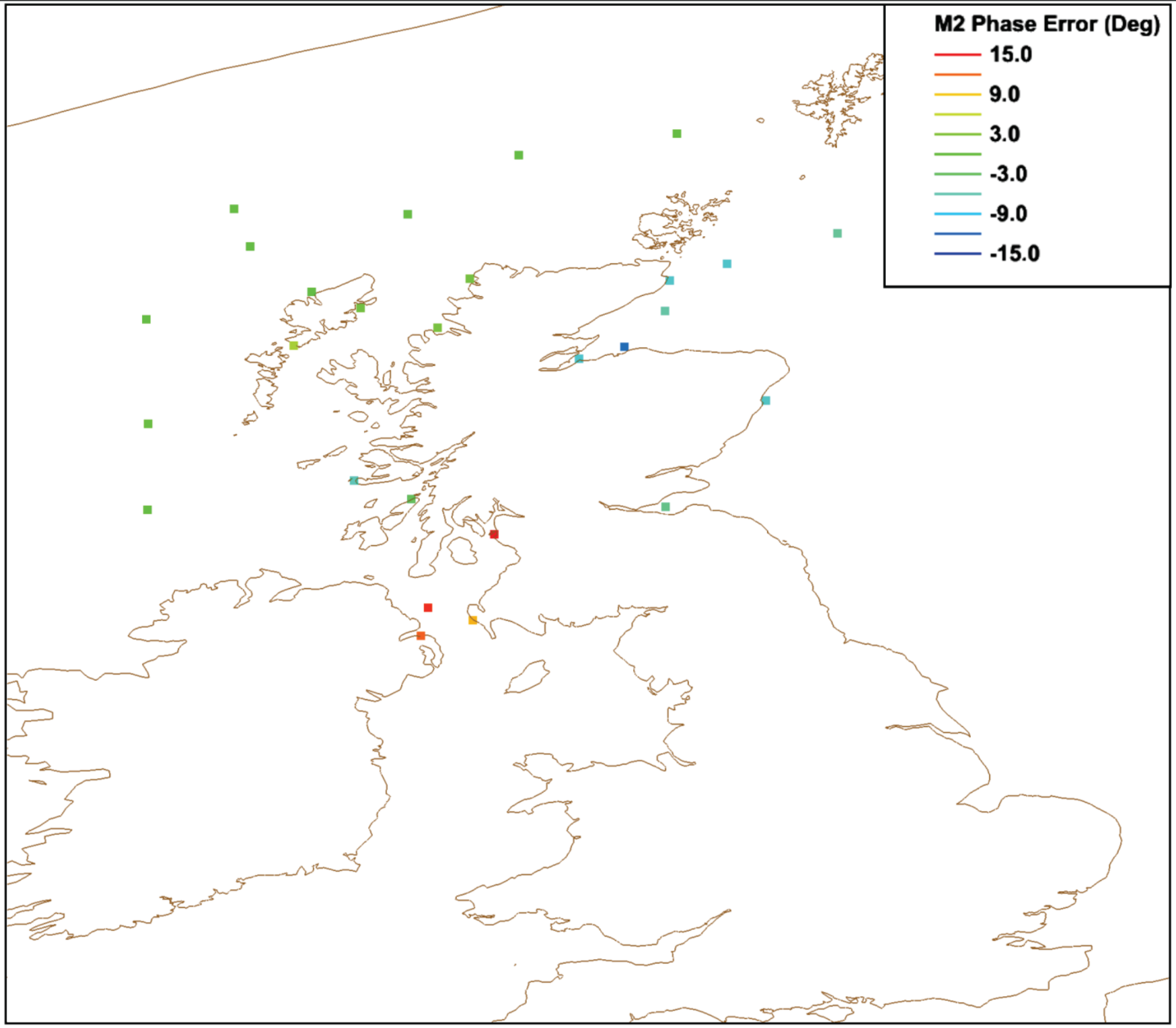
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-19		
Marine Scotland	ch2m	Scottish Shelf Waters Model	M2 tidal ellipses, Shelf Edge	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-20		
Marine Scotland	ch2m	Scottish Shelf Waters Model	M2 tidal ellipses, W Scotland	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-21		
Marine Scotland	ch2m	Scottish Shelf Waters Model	M2 tidal elevation, % error in amplitude	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client Marine Scotland	Consulting Engineer ch2m	Project: Scottish Shelf Waters Model	Figure Title: M2 tidal elevation, absolute phase error	Figure 3-22		
				Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

The results for the average amplitude and phase error for the S_2, O_1 and K_1 tidal elevations are given in Table 3-5, for the final 29-day run. S_2 and O_1 are both underestimated, with a delay in the phase. This may indicate a need to reduce the friction slightly as the extra constituents will tend to enhance the currents and hence the (quadratic) friction acting on the M_2 tide and other constituents. However K_1 is very much overestimated.

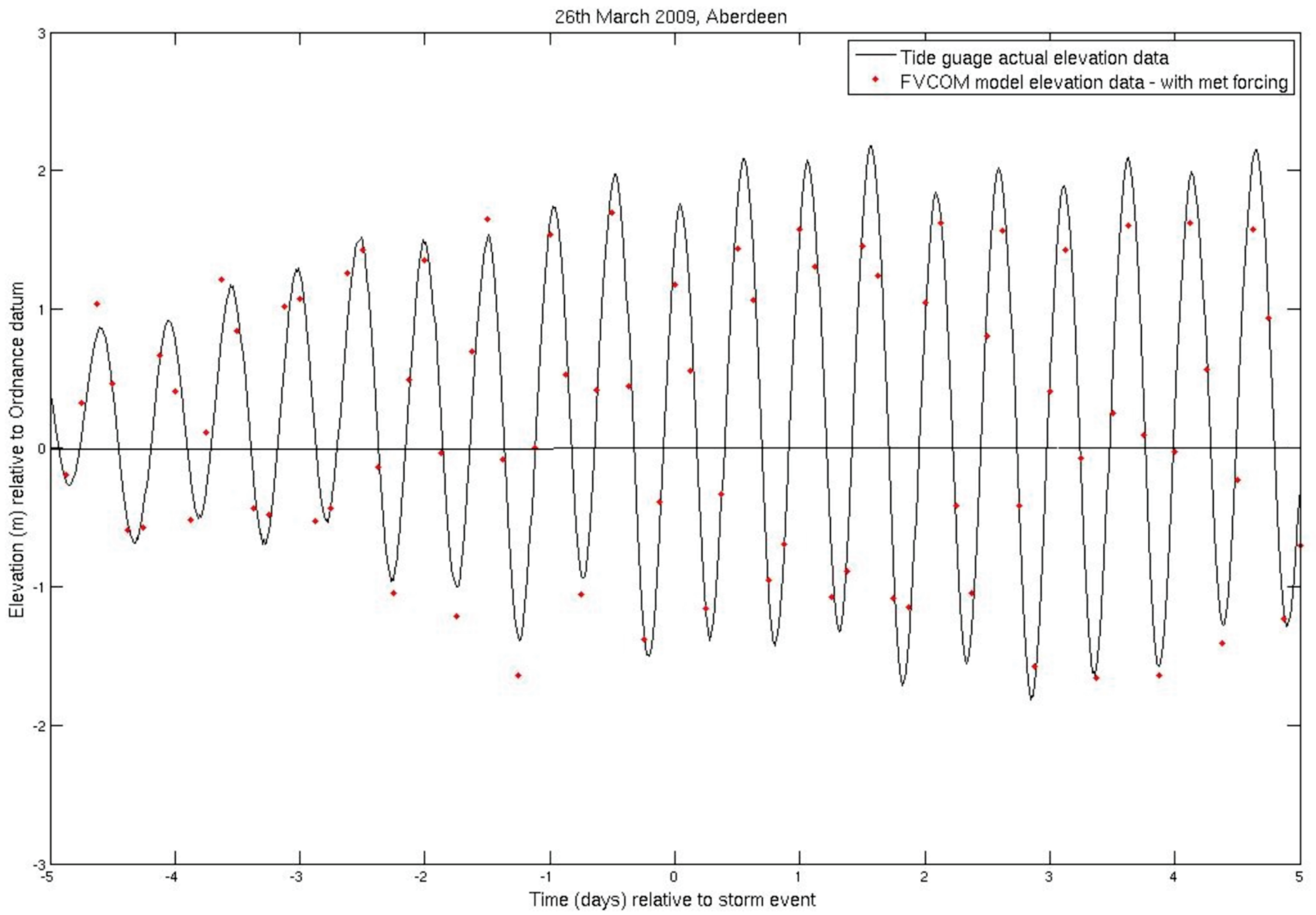
Table 3-5 Amplitude and phase errors for S2, O1 and K1 tides from 29-day optimised run

Tidal constituent	Mean Amplitude error	Mean absolute phase error
S2	-18%	10°
O1	-19%	19°
K1	+55%	8°

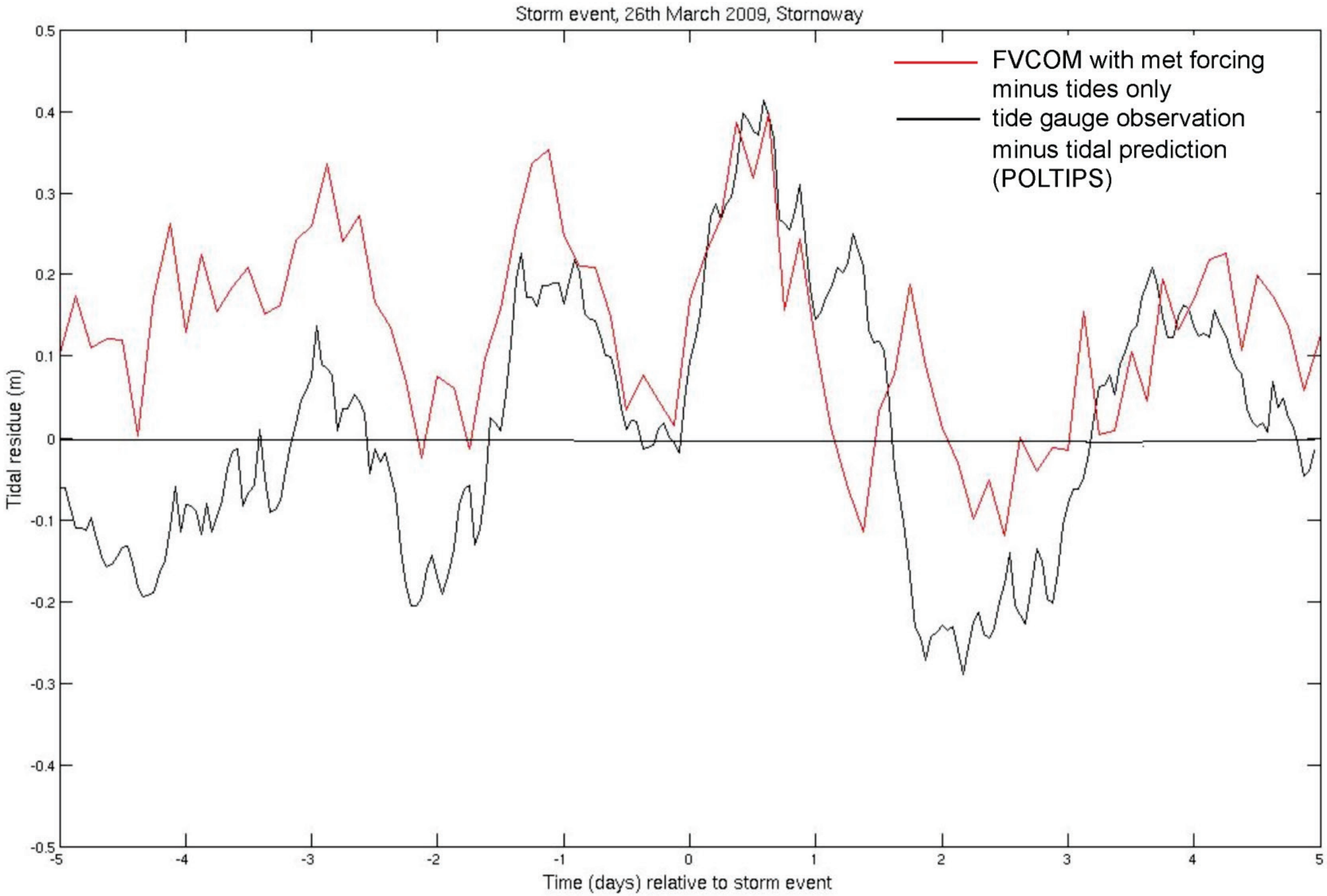
Water levels and current time series were examined at some of the selected observation locations, from the 29-day run and during a storm period in the met-forcing run (March-June 2009), when the peak wind-stress was observed on 28 March 2009. In Figures 3-23 and 3-24 the water levels at Aberdeen and Stornoway from FVCOM were compared with the tide gauge observations. Figure 3-23 shows total water level while 3-24 shows tidal residuals (i.e. meteorologically-driven storm surge. The maximum surge can be seen to be in good agreement with observations at Stornoway.

The key conclusions from the tidal calibration are as follows:

- The model results have been compared with the established HRCS model M_2 co-tidal chart, and also with M_2 tidal analyses from observational data at several locations.
- The tidal phase is generally very good, with poorer results for the amplitude of the tidal water level, however we have not met the calibration targets in Table 3-1. It may be that the subset of data points may be dominated by some locations where the data is less reliable, too close to shore or to a tidal amphidrome.
- It may be possible to adjust the bottom friction spatially to get a slightly better result.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-23		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Water levels at Aberdeen during storm event 23 March – 2 April 2009	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-24		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Tidal residual water levels at Stornoway during storm event 28 March 2009	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.3.8 Temperature and salinity calibration

The SSW model was run for 4 months for March-June 2009 as a calibration period using the meteorological and river forcing. March 2009 was the spin-up period, when the sea should still be well-mixed before the onset of seasonal stratification. In order to limit the length of the spin-up period (which can be several years from a constant temperature and salinity), the AMM fields of temperature and salinity for the 1st March 2009 were used as an initial condition. The temperature and salinity from AMM were also used through the model run, as a nudging correction to the open boundary values. Two options were used for the turbulent closure: (i) Mellor-Yamada 2.5 (the default, MY) and (ii) the Generalised Ocean Turbulence Model (GOTM, www.gotm.net; Umlauf and Burchard, 2003). Two options were tested for the number of vertical levels, viz. 10 and 20 levels. These combinations are denominated MY10, MY20, GOTM10 and GOTM20.

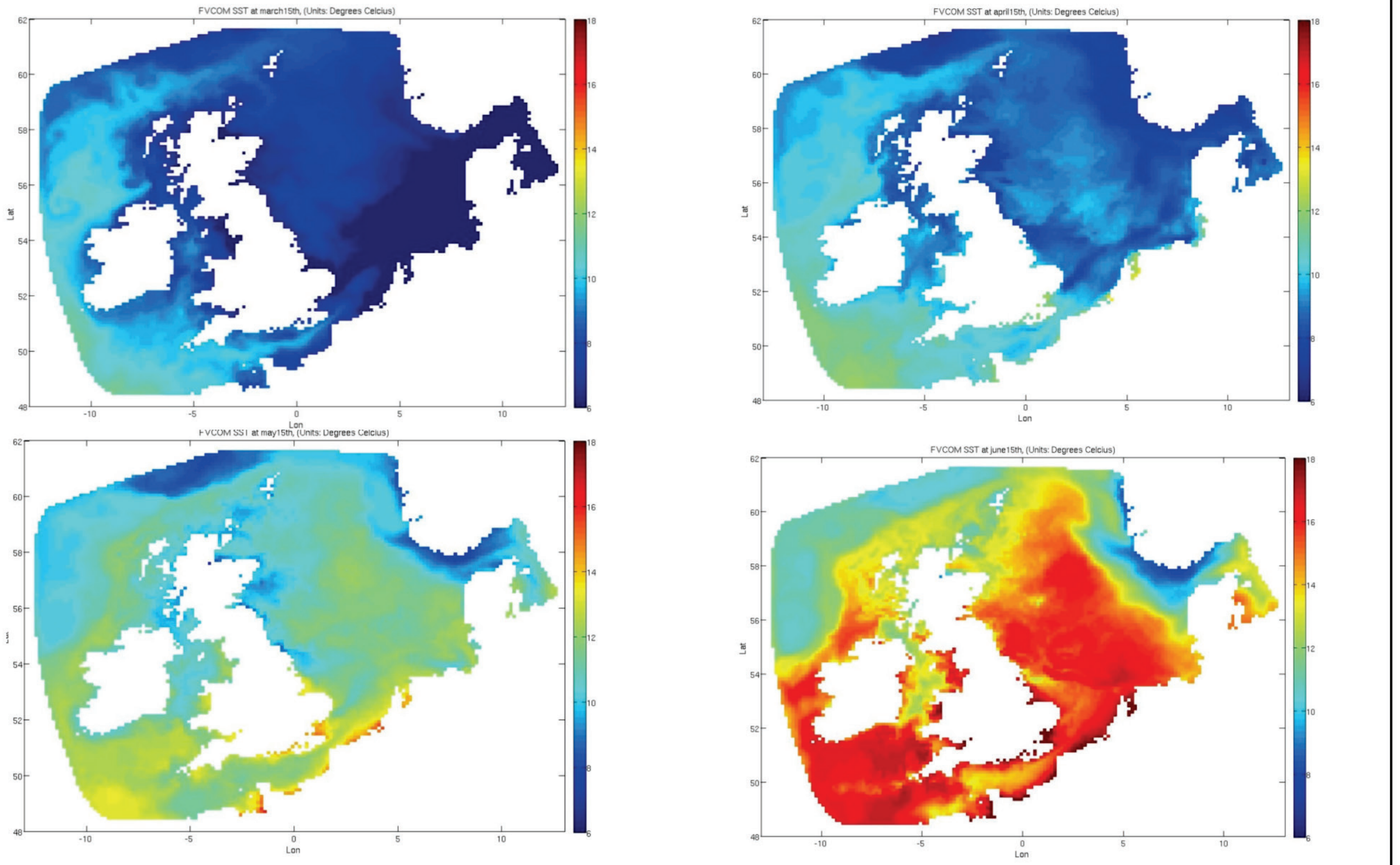
The first attempt was made using the HEATING_ON option in FVCOM (see section 3.2.5, option (i)) however in this case the SST was found to drift substantially away from the values seen in AMM, overheating the sea surface. It was thought to be necessary to modify the FVCOM code in this case, in order to introduce the Haney correction (Gill, 1982), adjusting the model to a prescribed SST to be consistent with the atmospheric model, however this option was not attempted. Instead the HEATING_CALCULATED option (section 3.2.5 (ii)) was selected. This uses a modified COARE2.6 algorithm (see FVCOM manual). This option appeared to give a better result for SST without a significant drift. The results for the SST at monthly intervals are shown in Figure 3-25, in which the temperature can be seen to increase from March to June, from about 8C to 16C in the central North Sea, for the default MY10 option.

Figure 3-26 shows the stratification which has developed by June in the FVCOM model compared to that in the AMM model, expressed as the surface minus bottom temperature. The models appear to have a similar degree of stratification, with the tidal mixing fronts, between the well-mixed and stratified water, in similar locations.

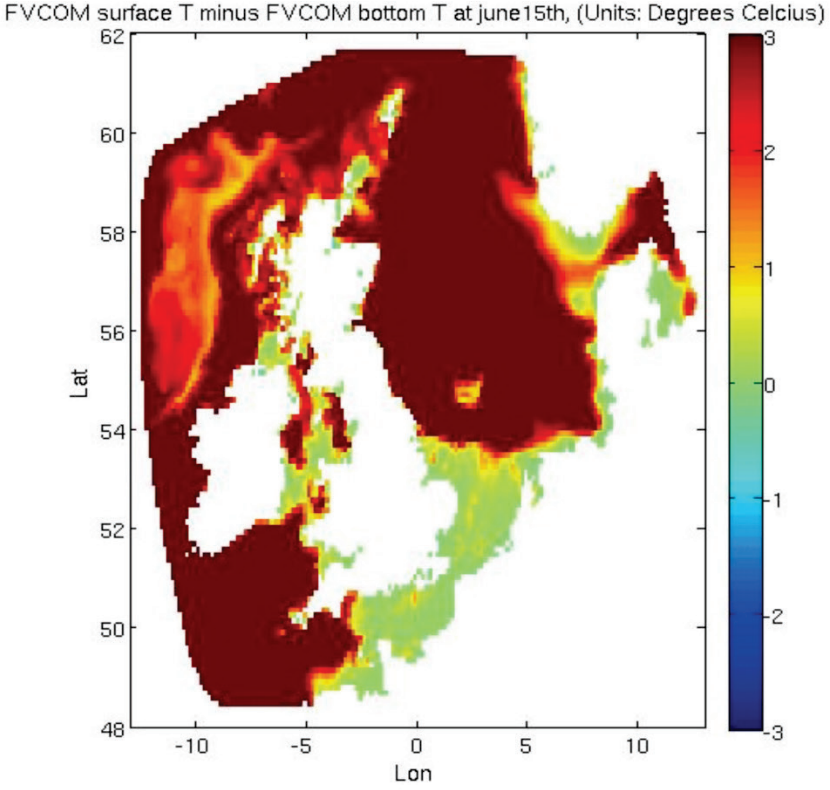
In Figure 3-27 the difference between the SST for the FVCOM model minus that for the AMM model is shown, together with a set of 6 selected stations, which were used for comparison of the depth-averaged temperature evolution (Figure 3-28) and temperature and salinity profiles for June 2009 (Figure 3-29 and Figure 3-30) in the 2 models.

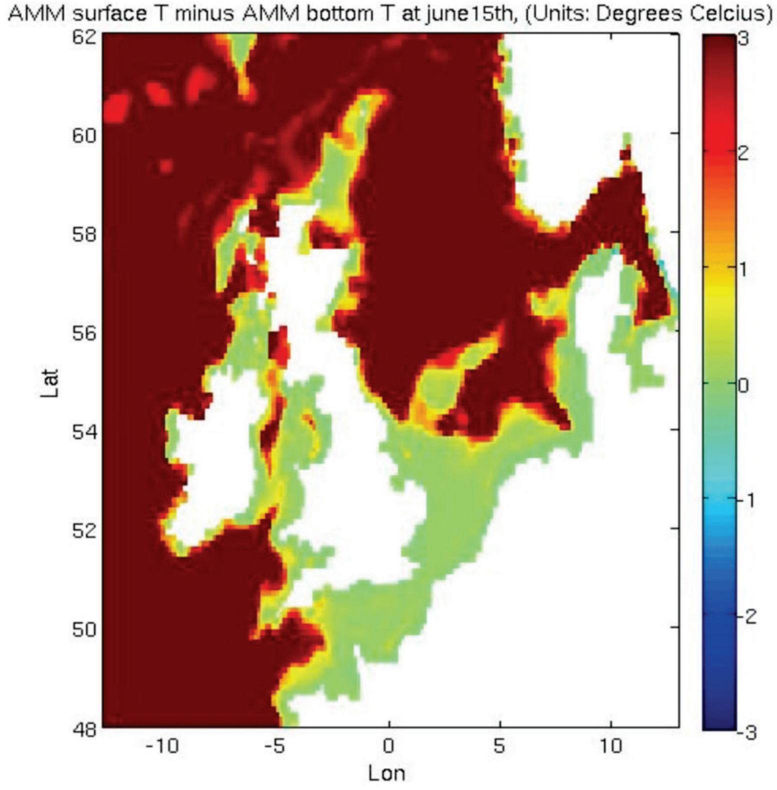
The temporal evolution of the temperature (Figure 3-28) is quite similar in FVCOM and AMM, except for points 1 and 4 where the temperature in FVCOM increases rather too much. Point 4 is in the Atlantic in deep water off the shelf, whereas point 1 is in the central North Sea. In Figure 3-29 temperature profiles at the 6 stations were examined to better understand the drift. It was found that both the turbulence closure options were rather similar for FVCOM, although MY gave slightly more mixing, both results showed an overestimate of the SST in most cases, with a lack of the surface mixed layer which characterised AMM.

In order to clarify whether AMM or FVCOM is more correct a set of CTD stations were identified during March-June 2009 (Figure 3-31). For 5 selected locations and times the temperature profiles are compared in Figure 3-32.



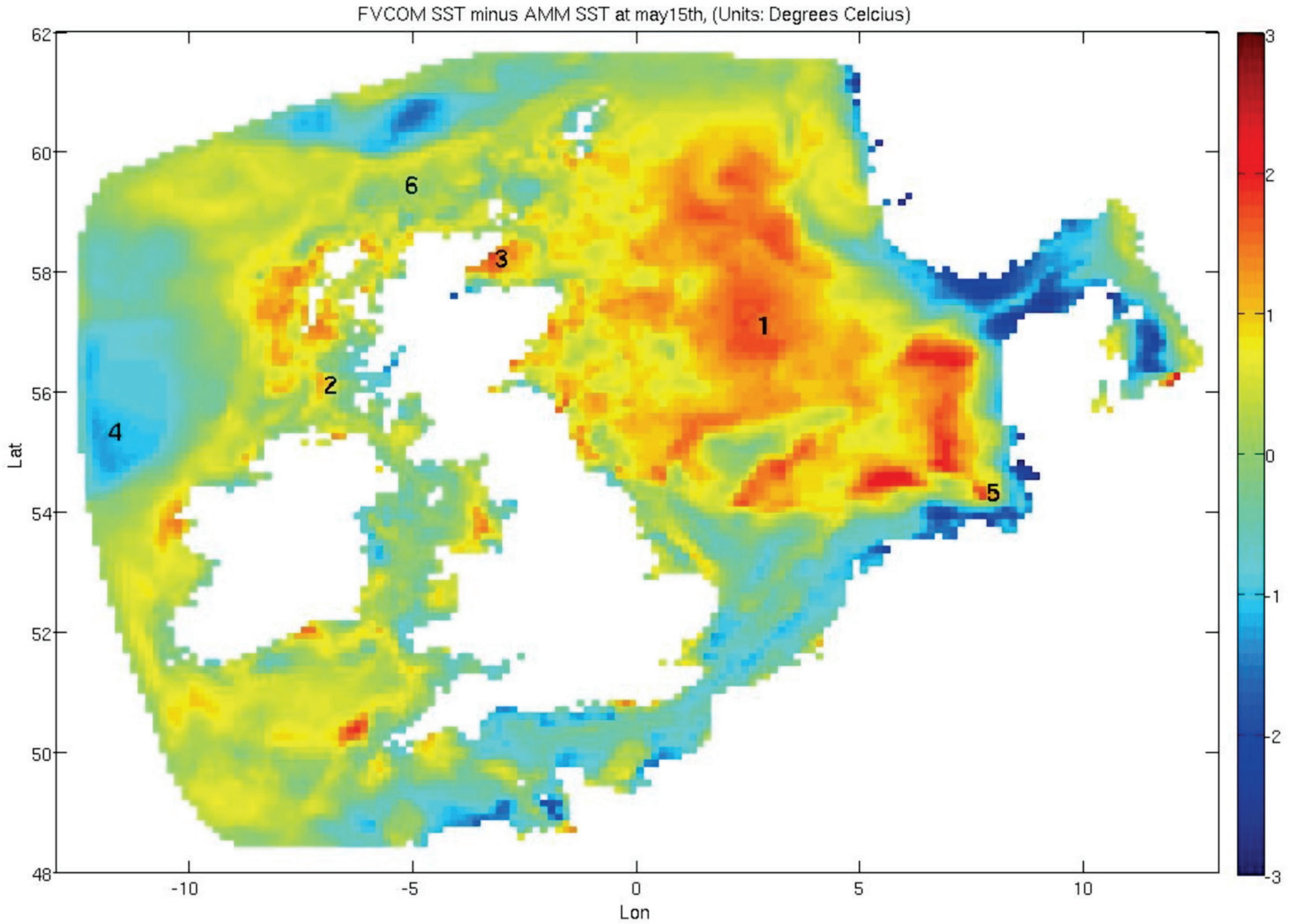
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-25		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Sea surface temperature March- June 2009, from FVCOM**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014



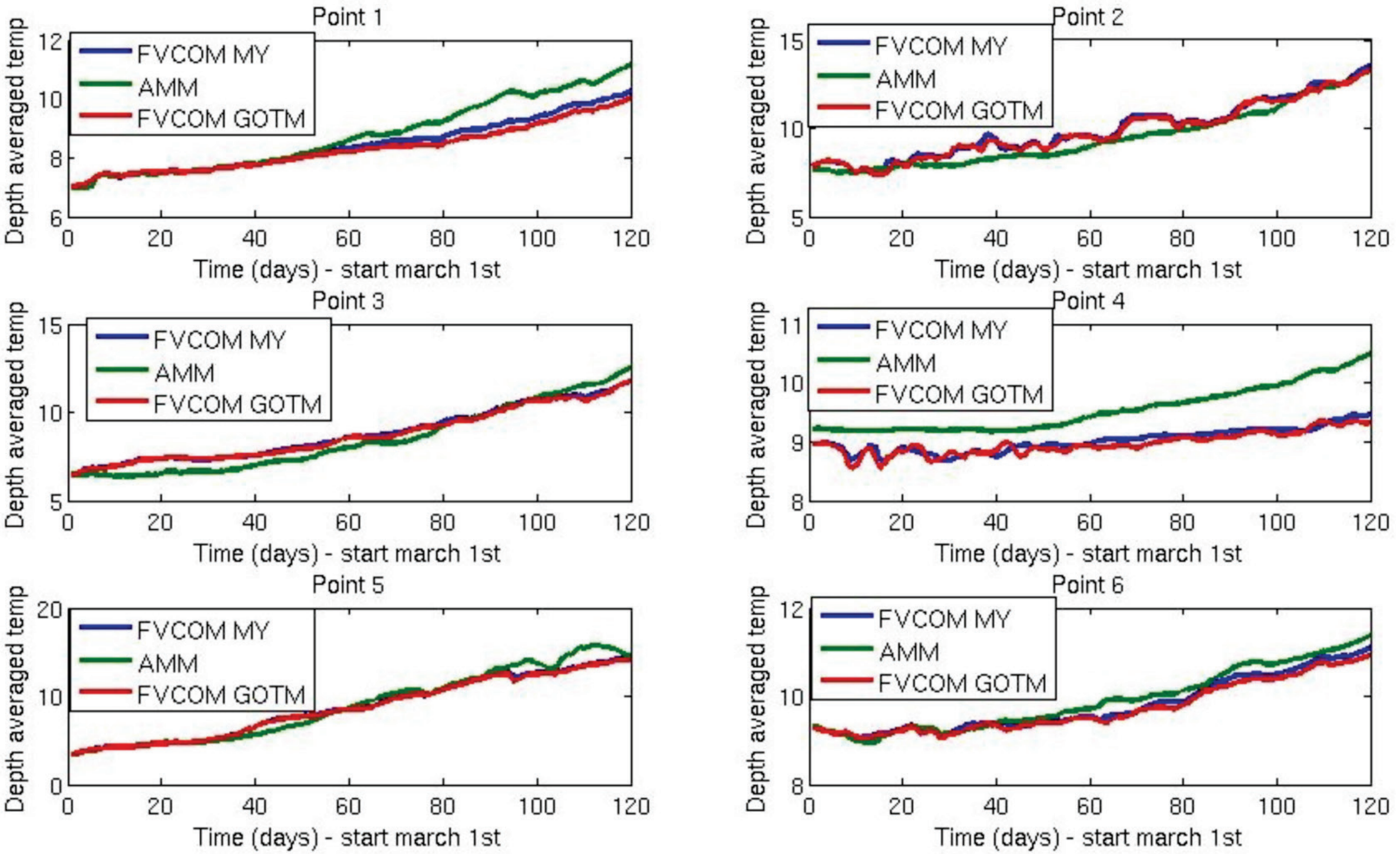


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-26		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Surface-bottom temperature difference (degC) June 2009: Left – FVCOM, right - AMM**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014

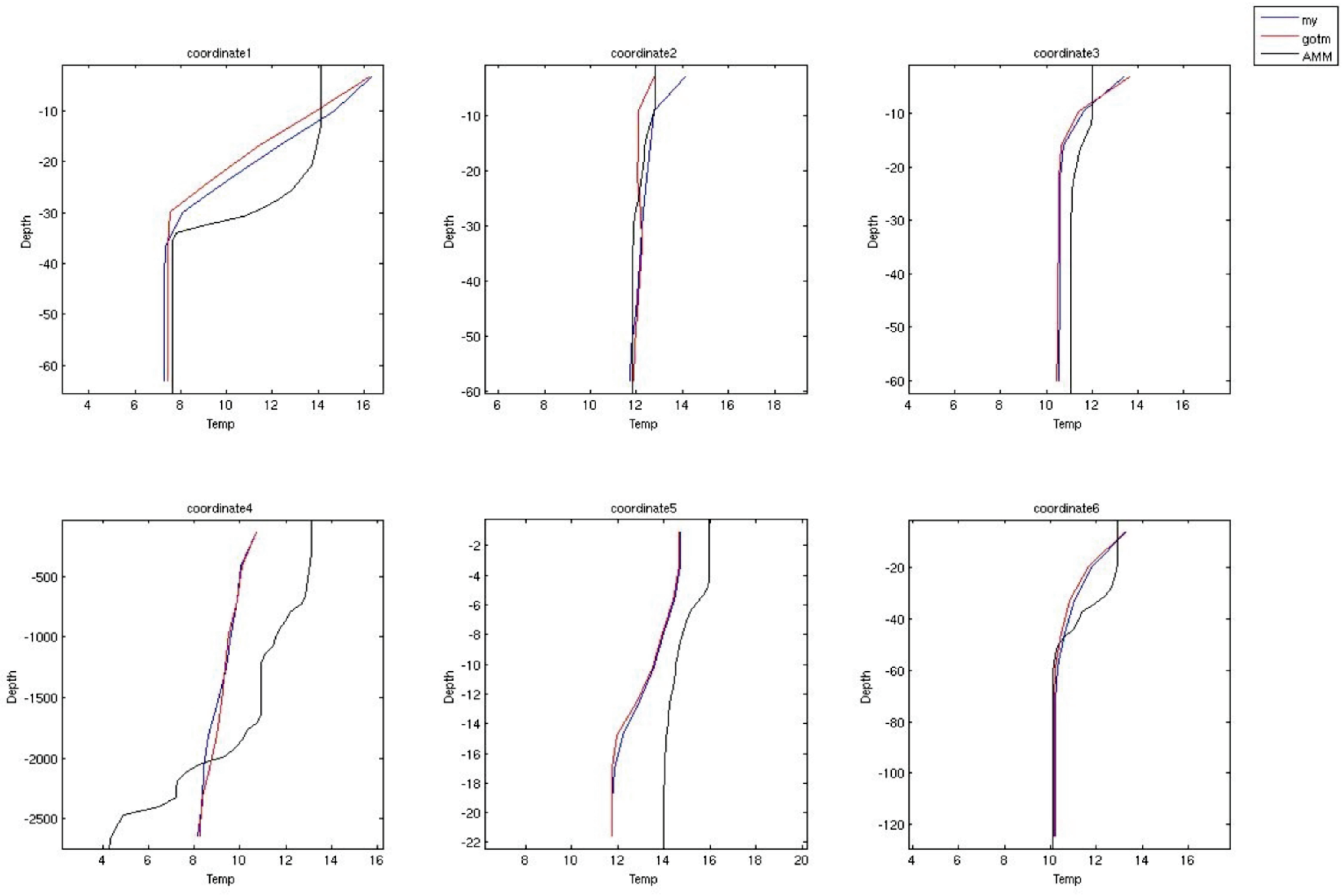
ch2m



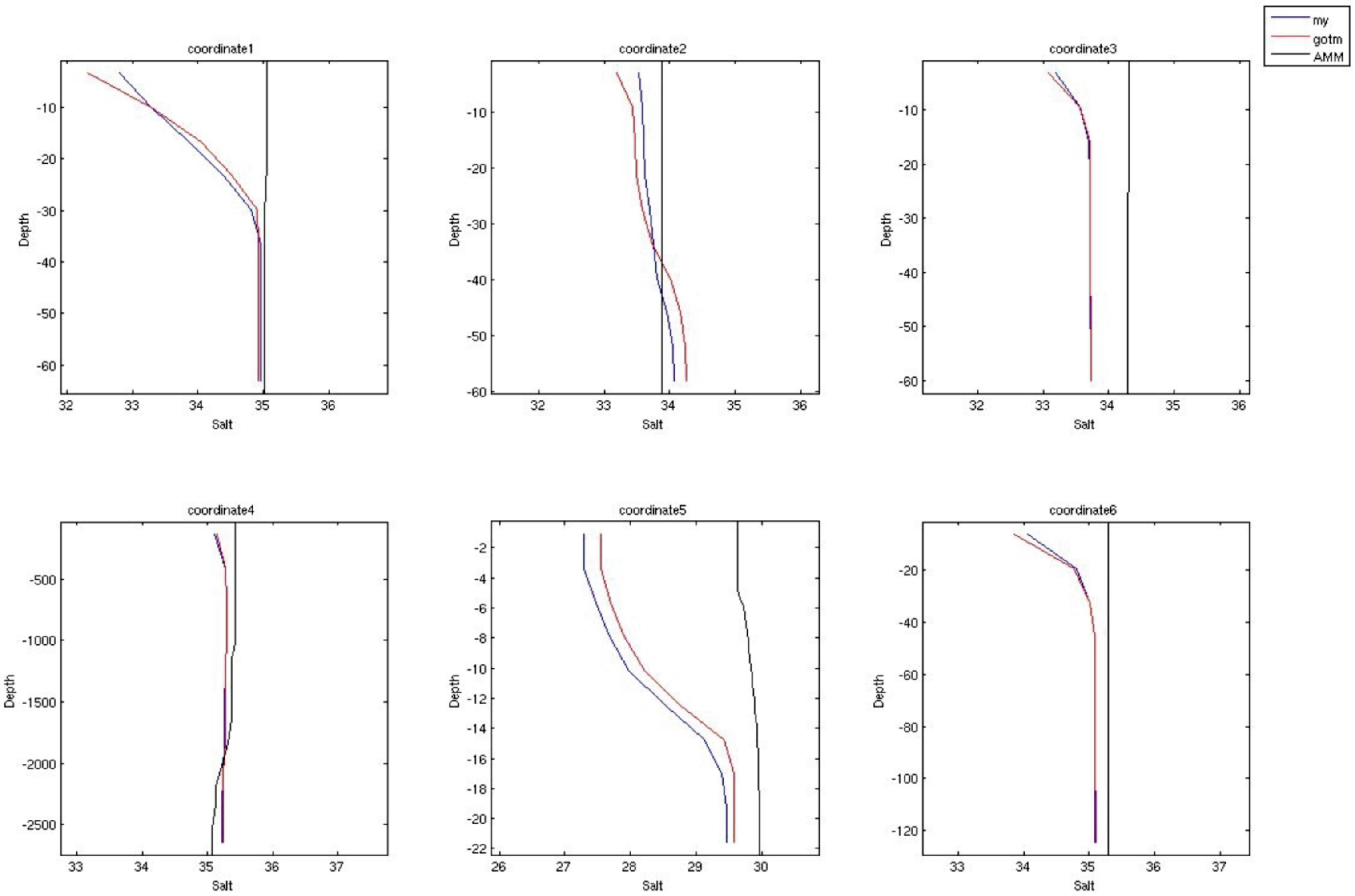
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-27		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Sea surface temperature difference (degC) May 2009: FVCOM-AMM, with selected profile stations	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



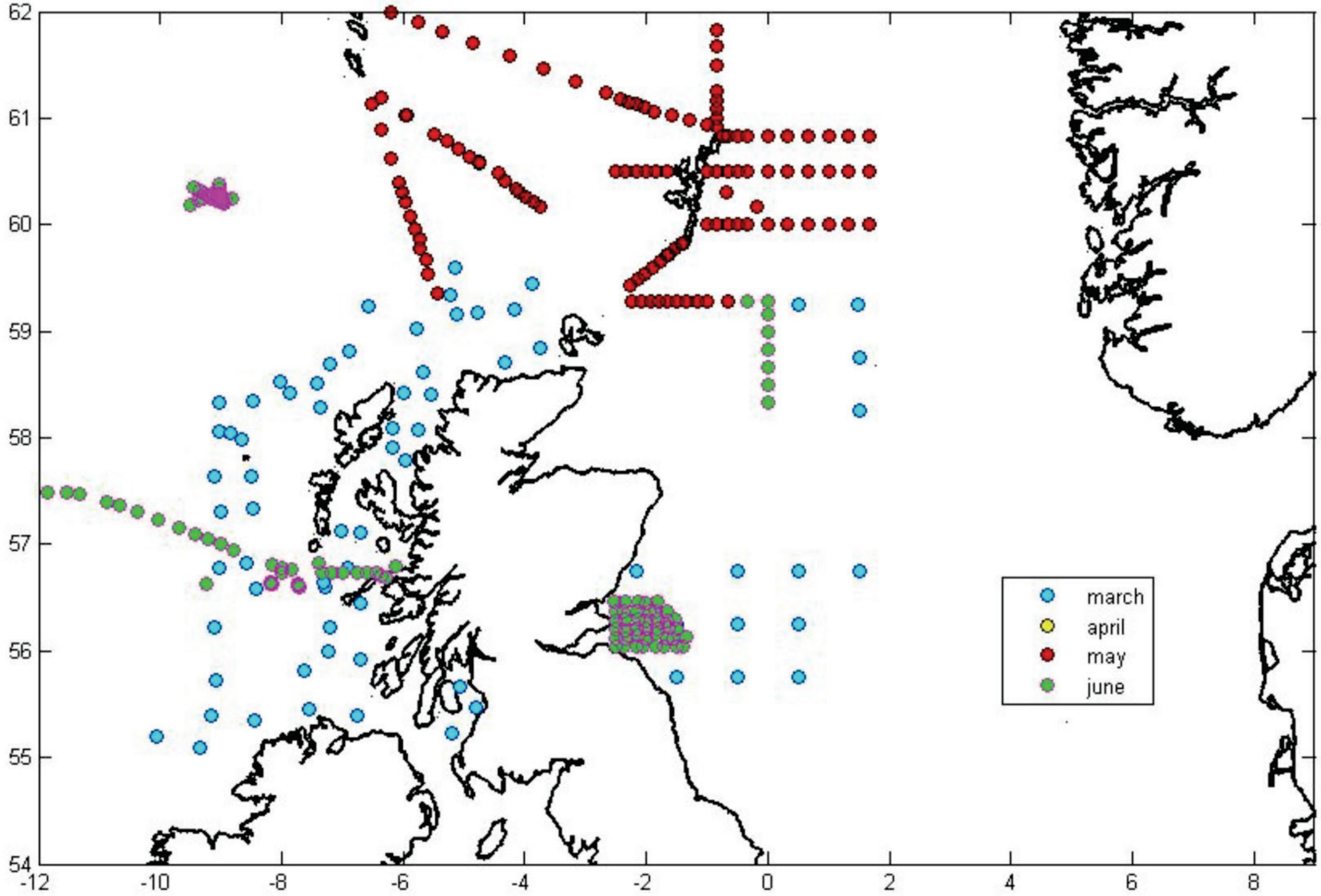
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-28		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Depth-averaged temperature temporal evolution (degC) March-June 2009, at selected stations	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



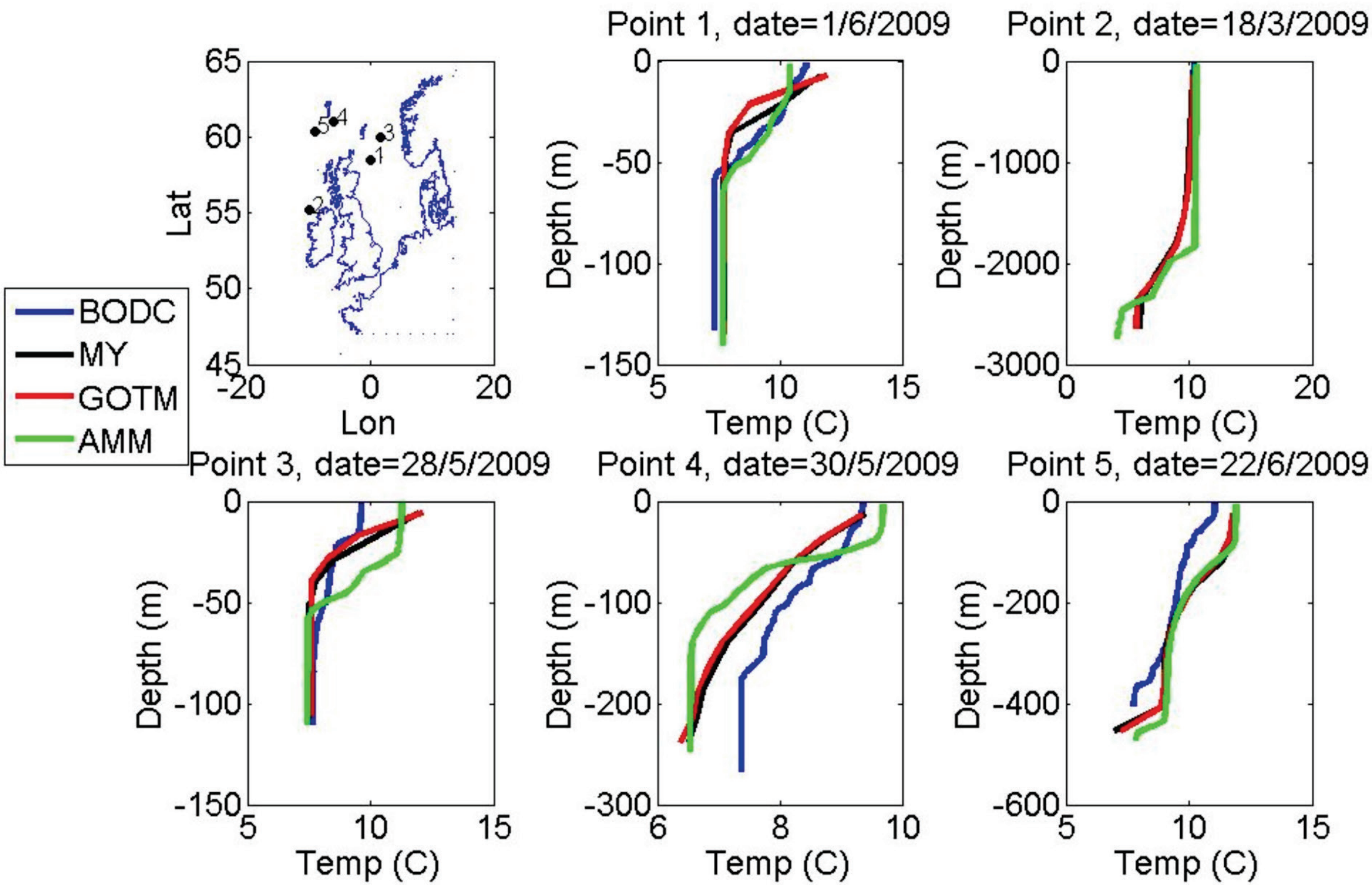
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-29		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Temperature profiles (degC) June 2009	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-30		
Marine Scotland		Scottish Shelf Waters Model	**Salinity profiles (psu) June 2009**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-31		
Marine Scotland	ch2m	Scottish Shelf Waters Model	CTD locations used to compare observed temperature profiles with model calculated ones	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-32		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Temperature profiles at selected locations and times, March – June 2009	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

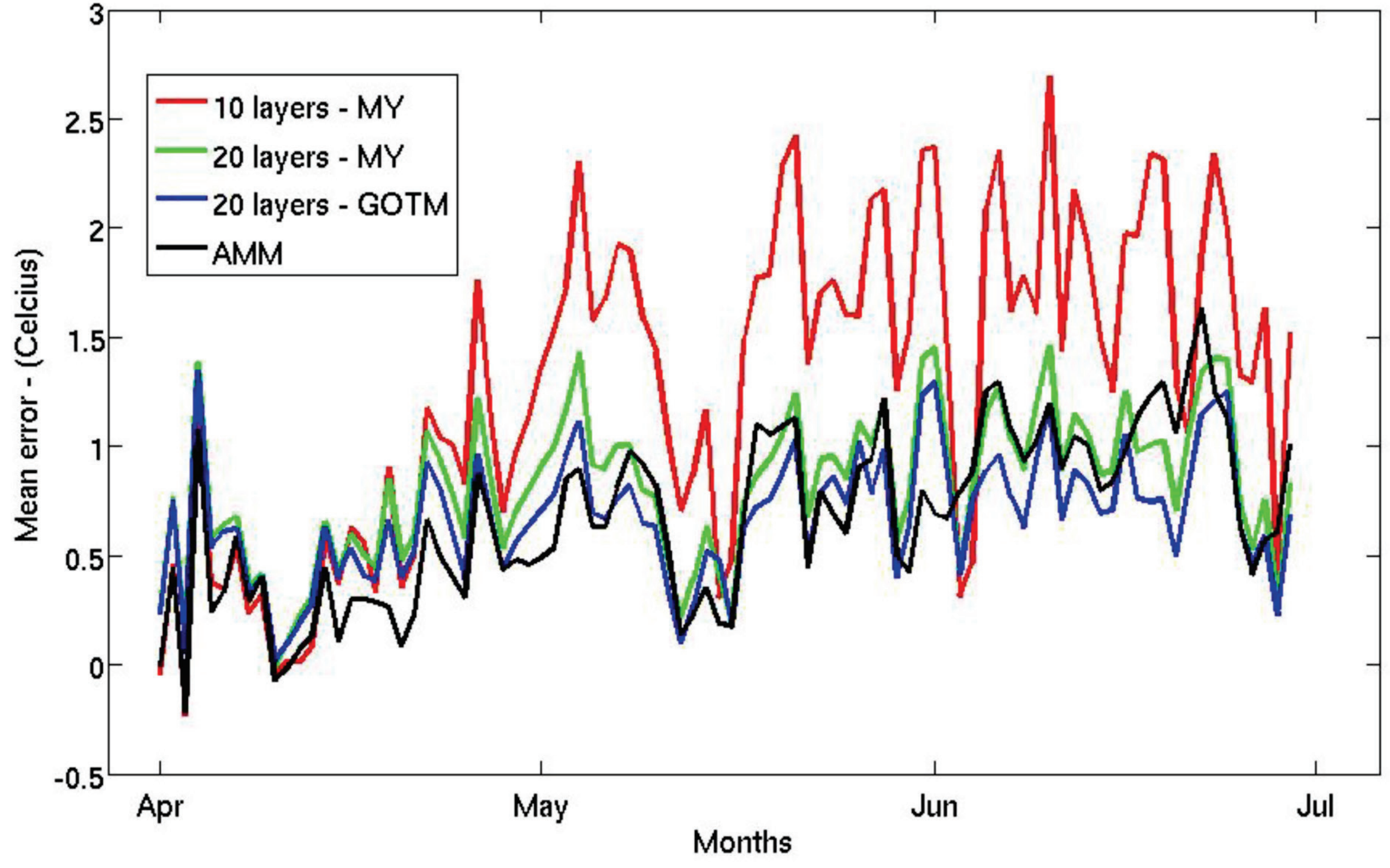
In this case it is interesting to note that in many cases the FVCOM model is in better agreement with the observations than AMM, which may have a too well-mixed surface layer. There is very little difference between MY and GOTM.

Increasing the vertical resolution to use 20 layers proved to make a great improvement in the surface temperature. Further validation data in the form of AVHRR (Advanced Very High Resolution Radiometer) SST daily composite data were obtained from the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for the period of March-June 2009 Figures 3-33 and 3-34 show the evolution of the mean and RMS error respectively, comparing the FVCOM MY10, MY20, GOTM20 and AMM datasets. The time series were averaged across the available data for the whole domain (defined to be 54-62N, 12W-9E). Although these data are high precision, the distribution of data is spatially variable due to gaps caused by cloud cover and at some times there is more data coverage than at others.

Comparing the three simulations, it is abundantly clear that having 20 layers gives better results than 10 layers, so the extra computational time needed for the 20 sigma-layer simulations should ideally be provided. This also indicates that the depth resolution of the grid needs to be sufficient for heat to be mixed to deeper waters as the surface temperature is much warmer in the 10 layer model. There is also a slight improvement (0.1-0.2 degrees) using the GOTM turbulence closure scheme.

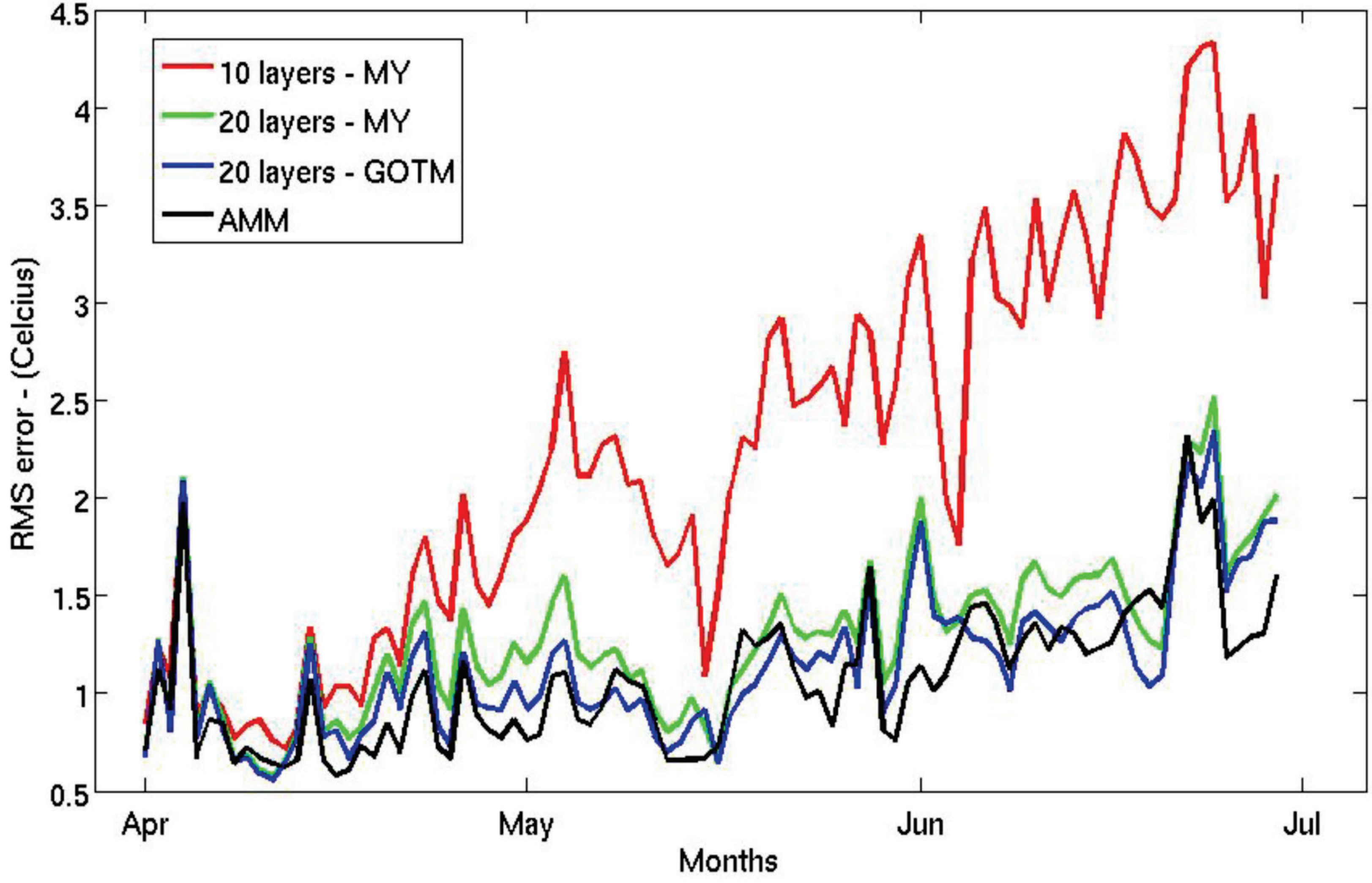
Comparing the best of the three simulations, namely the 20 sigma-layer GOTM simulation, to the AMM model, there is a very similar mean error. AMM looks better in agreement near the start but diverges as time goes on. This shows that the FVCOM model mean error is more consistent and does not suffer from the drifting error which was found in AMM. The RMS error between both models is fairly indistinguishable.

Overall, the model simulations are too warm near the surface (this is also true in comparison with the AMM model – which has 40 layers) and so prescribing more layers could achieve even better results by allowing heat to percolate more readily through the surface mixed layer. However the computational time would increase further.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-33		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Mean error over Scottish Waters domain, model versus AVHRR SST data**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-34		
Marine Scotland	ch2m	Scottish Shelf Waters Model	RMS error over Scottish Waters domain, model versus AVHRR SST data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.3.9 Summary

The calibration exercise led to adjustments of horizontal mixing and bottom friction and selection of the heating-calculated option for the baroclinic forcing. A further mesh refinement was also carried out to remove any rogue points. It was found that using 20 levels in the vertical was a big improvement over 10 levels and that the GOTM vertical mixing option performs marginally better than Mellor-Yamada so these options were selected for the rest of the modelling work (see Table 3-3 for friction and horizontal mixing settings for optimised model).

3.4 Full shelf model simulations and validation

3.4.1 Introduction

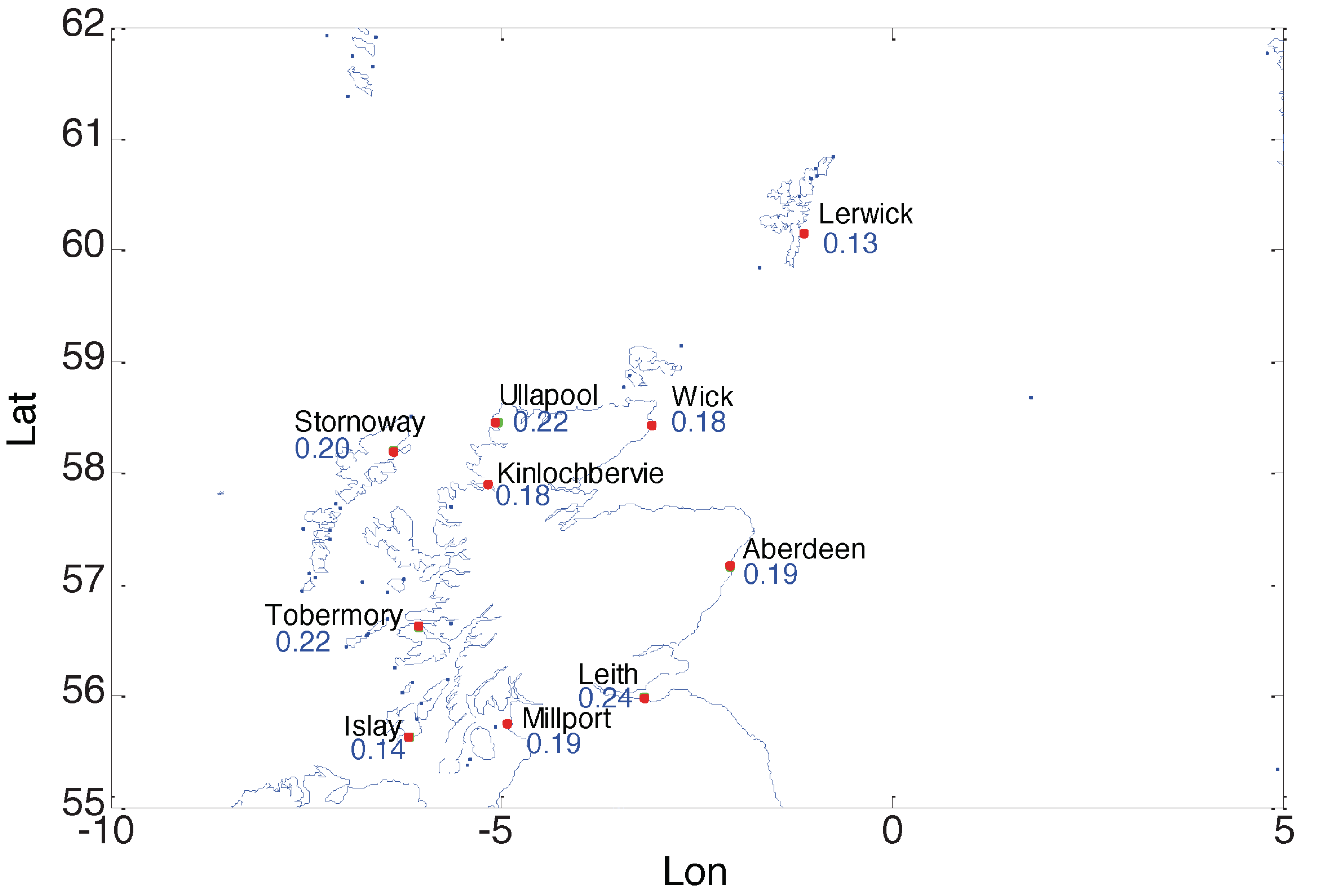
In order to carry out a validation exercise against observational data for different seasons of the year the final version of the model was run for a 10-month period from May 2008 until March 2009, complete with all tidal, met and river forcing. This was therefore complementary to the calibration run from March 2009 - June 2009 and thus covered the onset and breakdown of seasonal stratification as well as the winter of 2008-2009 with various wind-driven mixing events. During the winter period the largest storms in Scottish Waters were identified in October 2008 (23rd -24th) and January 2009 (18th).

A set of plots and statistics (mean error or bias, RMS error, etc.) was used to compare model results with observations for tidal elevation, currents, temperature and salinity. A simple cost function was used to systematically compare the accuracy of different variables.

3.4.2 Observed Data

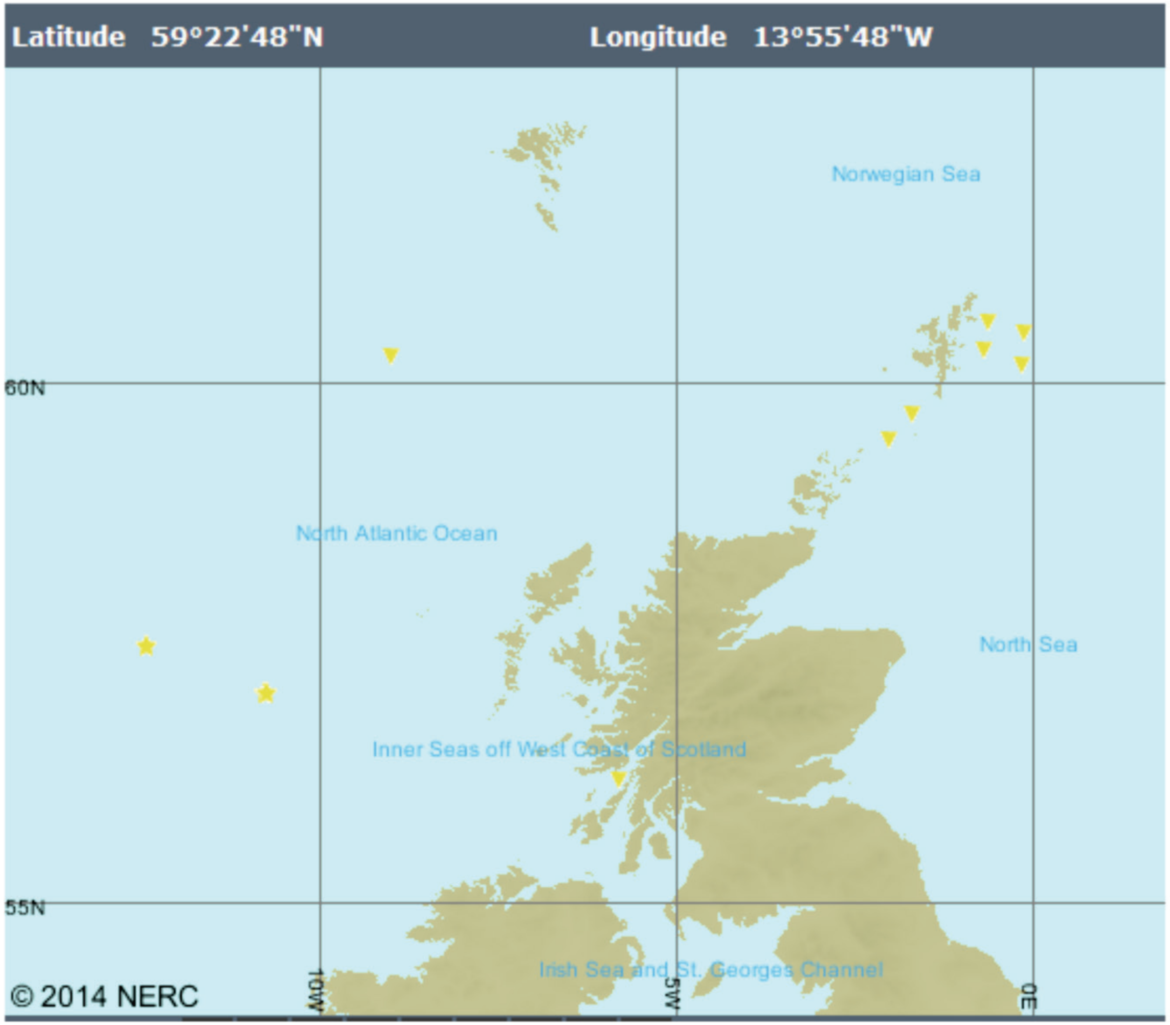
Observed data were obtained from BODC, but also other surveys and field campaigns as reviewed in the Data Review report. The area selected was 54-62 N, 12W-9E and less than 200m water depth, for the period June 2008 to June 2009.

We used the 15 standard ports in Scottish Waters for water level comparisons (Figure 3-35). The available current meter observations from BODC for our area and period of interest are shown in Figure 3-36. The CTD stations available from the ICES dataset are likewise shown in Figure 3-37.

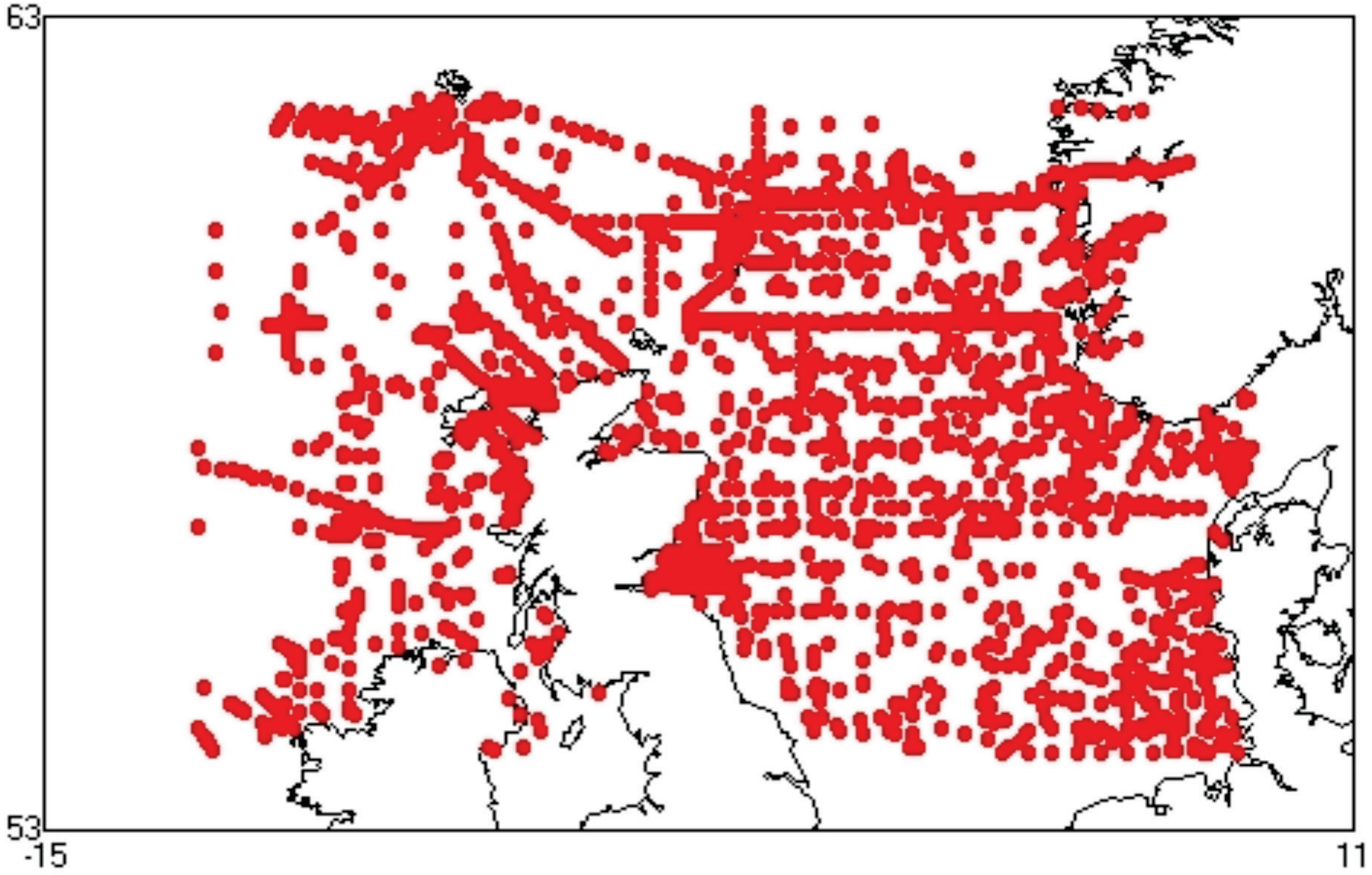


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-35		
Marine Scotland	ch2m:	Scottish Shelf Waters Model	Tide gauges at standard ports in Scottish Waters	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m:



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-36		
Marine Scotland	ch2m	Scottish Shelf Waters Model	BODC current data 2008-2009 for Scottish Waters	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-37		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**ICES CTD data 2008-2009 for Scottish Waters: 54-62N, 12W-9E**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.4.3 Error statistics

The following metrics were used to provide a quantitative measure of the model accuracy:

Mean absolute error (*mae*) = $\frac{1}{N}\sum \text{abs}\ (y_m - y_o)$; where y_o refers to observed variable and y_m is model, N is number of data points.

Mean bias (*bias*)= $\frac{1}{N}\sum(y_m - y_o)$;

RMS error (*rms*) = $\sqrt{\frac{1}{N}\sum (y_m - y_o)^2}$;

Correlation coefficient (r) = $\frac{N\sum y_m y_o - \sum y_m \sum y_o}{\sqrt{N\sum {y_m}^2 - (\sum y_m)^2}\sqrt{N\sum {y_o}^2 - (\sum y_o)^2}}$;

Coefficient of determination (r^2) = r^2;

Cost function (*CF*) = RMS error divided by the standard deviation of the observations.

3.4.4 Water level

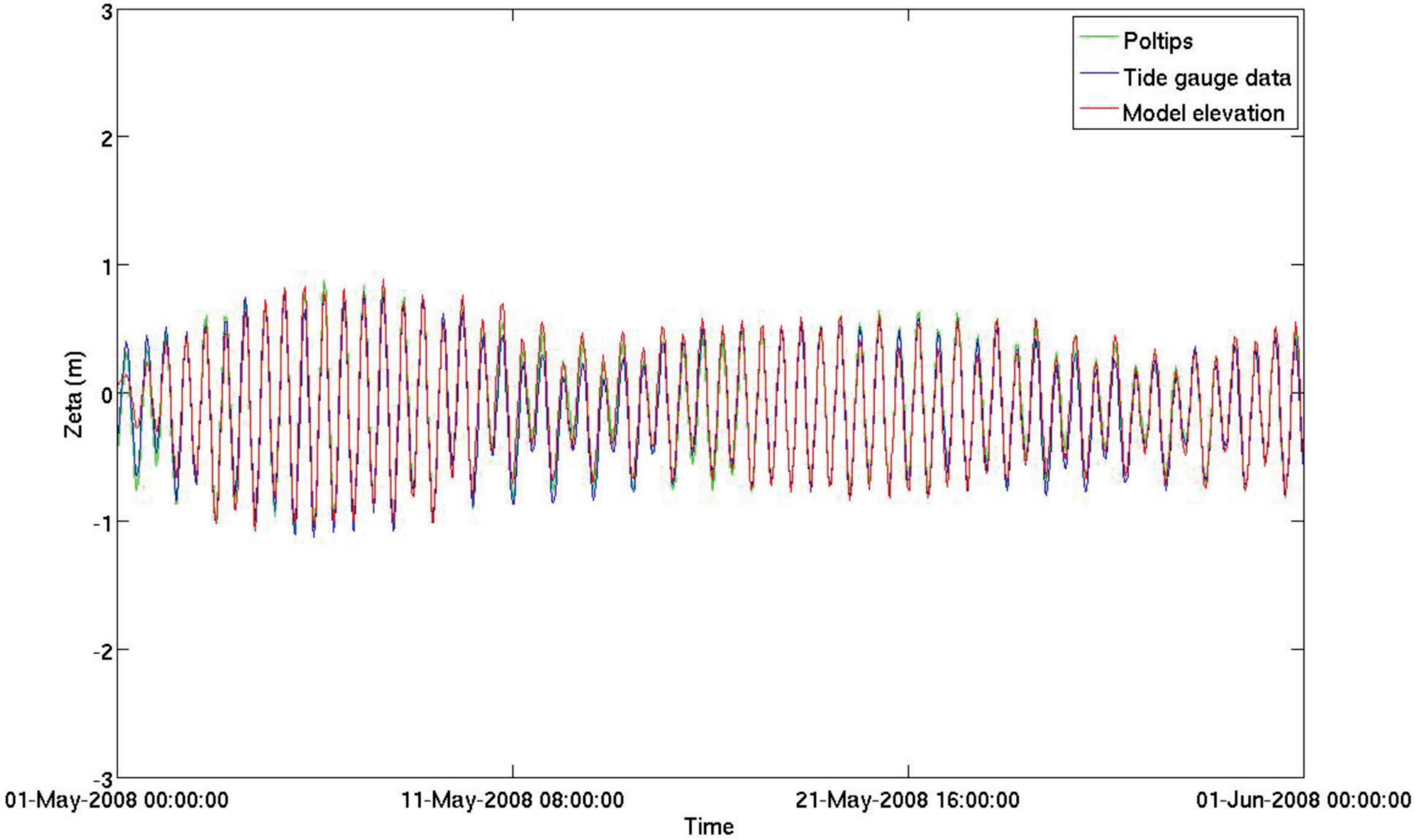
Tidal constituents are available from harmonic analysis for most standard and secondary ports and the NOC in-house tidal prediction software, POLTIPS, has been run for standard ports to generate water level time series from the tidal constituents for any specified time (past or future). The total water level recorded allows us to compare the model for tide plus surge (which may also be affected by rainfall) with POLTIPS in order to estimate the surge component. In order to properly quantify the accuracy of the model surge it is necessary to run the model with tide only for the period of interest and subtract this from the total water level (as done in the UK operational surge model). This has not yet been done so the comparison of surge events with the observed surge residuals is only qualitative. However the surge events identified correspond to those in the archive of the operational surge model (http://www.ntslf.org/storm-surges/storm-surge-model).

Figures 3-38, 3-39, 3-40 and 3-41 show examples of the water level comparisons, for different months, at Lerwick, Aberdeen, Kinlochbervie and Millport, respectively. In these plots the observed water level at the tide gauge is given (in blue) as well as the model water level (in red) at the nearest wet point, together with the POLTIPS tide-only curve (in green). The first three show summer months of May and June 2008 and the three curves are in close agreement. For the Lerwick plot in May 2008 it can be seen that the model is spinning up for the first couple of days. In Figure 3-41 for Millport in October to November 2008 we can see the effect of the surge on 23-24 October and a negative surge in early November. The model follows the observed water level well, diverging from the tidal prediction.

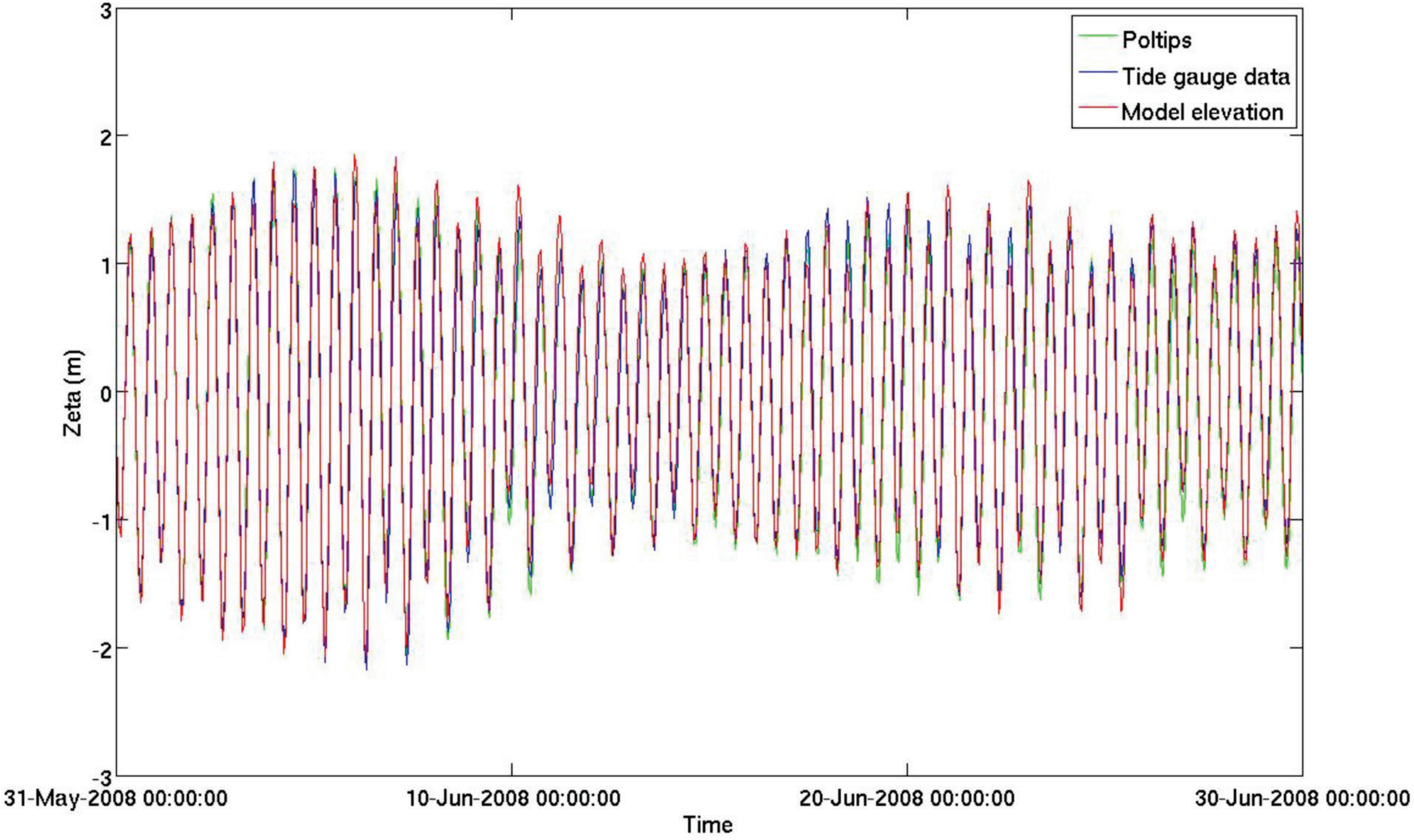
Table 3-6 shows the overall metrics for 10 of the tide gauge stations, calculated for the full length of the validation run. The individual time series have been corrected for any discrepancies in the datum being removing the long-term mean, hence the bias is zero in each case. The *rms* error is around 20cm in most cases. The coefficient of determination (correlation squared) is close to or >0.9 in nearly every case. The cost factor is quite low, around 0.2, except for Islay. At Islay there is an issue with the model point drying out for part of the tidal cycle which spoils the correlation and error statistics.

Table 3-6: Validation metrics for water level

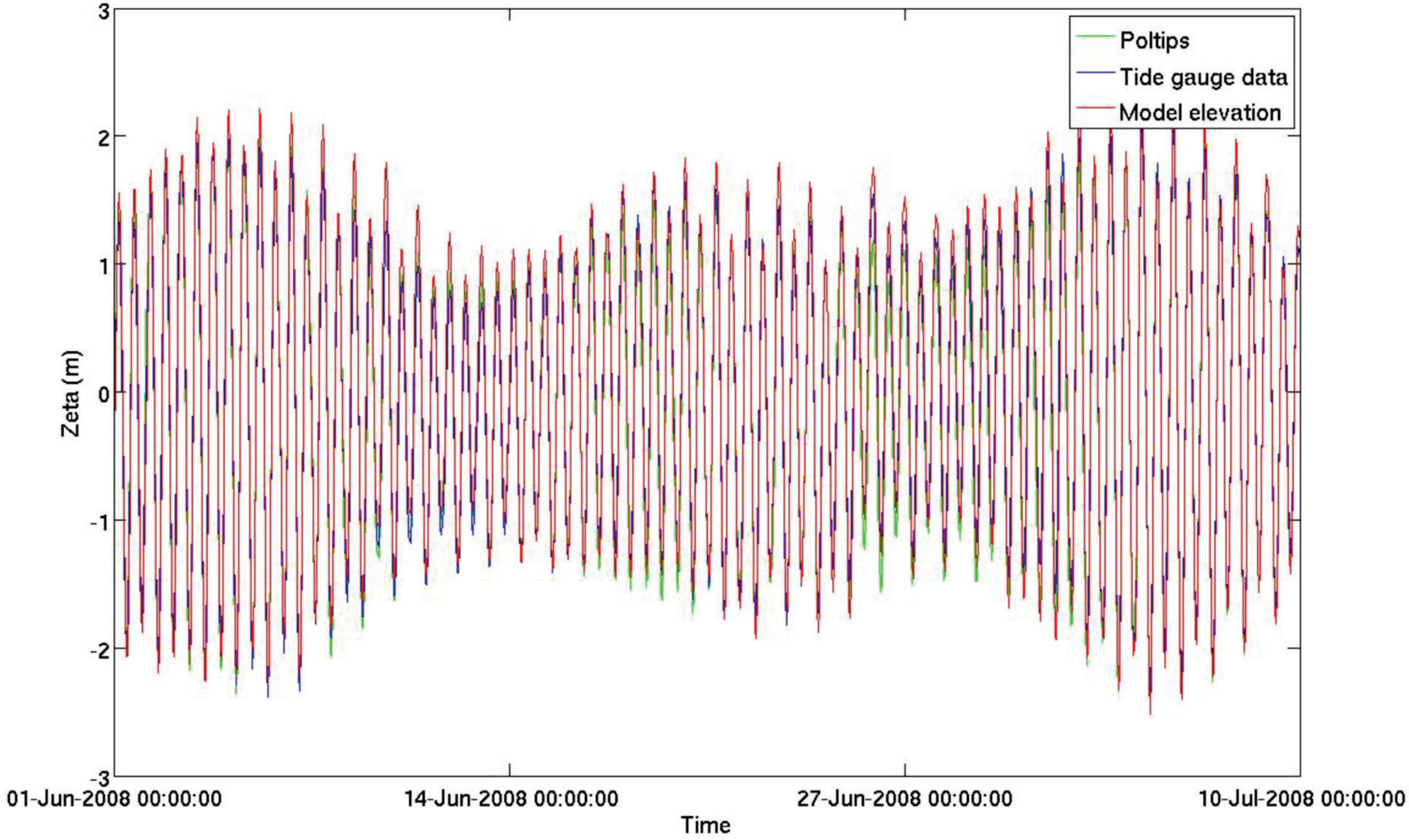
Metric	Leith	Aberdeen	Wick	Lerwick	Ullapool	Kinlochbervie	Stornoway	Tobermory	Islay	Millport
mae	0.189	0.149	0.1434	0.105	0.179	0.141	0.160	0.179	0.110	0.155
rms	0.244	0.191	0.180	0.132	0.225	0.178	0.200	0.220	0.138	0.192
r^2	0.939	0.929	0.913	0.852	0.938	0.954	0.943	0.930	0.482	0.895
CF	0.179	0.193	0.228	0.281	0.195	0.162	0.188	0.220	0.547	0.224
bias	0	0	0	0	0	0	0	0	0	0



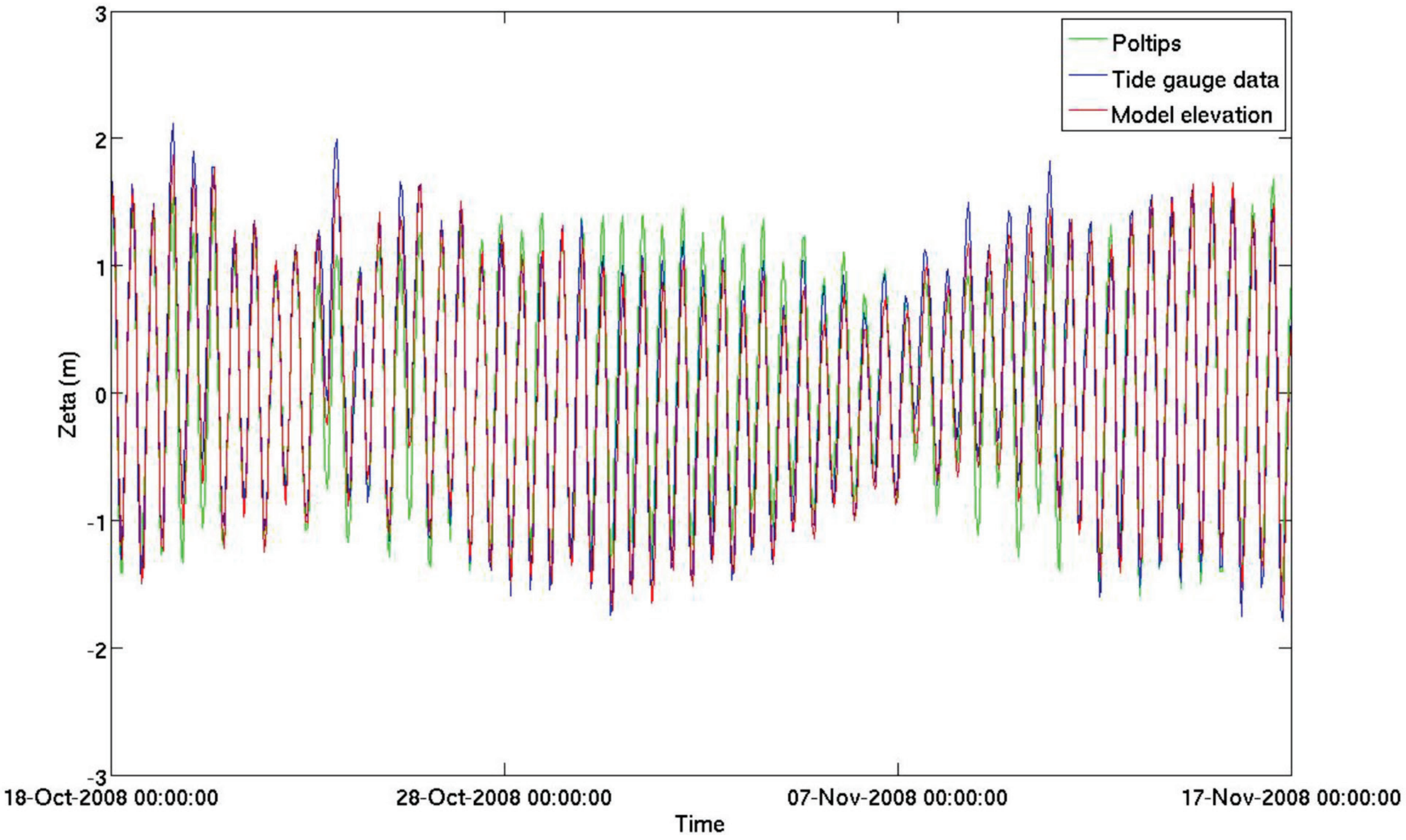
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-38		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Water level comparison at Lerwick, May 2008	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-39		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Water level comparison at Aberdeen, June 2008	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-40		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Water level comparison at Kinlochbervie, June 2008	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-41		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Water level comparison at Millport, Oct-Nov 2008	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

3.4.5 Currents

Current meters on moorings only record the currents at a few levels, often near-surface, mid-depth and near-bed. They are typically deployed for at least a month which allows a basic harmonic tidal analysis to be carried out.

There are some ADCP data – these give profiles of current through the water column at resolution O(2m) in the vertical. They may be deployed as upward-looking on a bottom mooring or downward-looking from a ship underway. However they were all in deep water off the shelf and not utilised.

There are 18 data series in all, which come from 8 individual moored stations (see Table 3-7), plus 2 underway datasets. Some stations have more than one current meter in the vertical and some have repeat deployments. The instruments have been identified with individual stations (numbered arbitrarily) and T, M or B according to which third of the water column they are in. Most of the instruments were recording current speed, current direction, salinity and temperature but in some cases no salinity record was available and 1039256 had only salinity and temperature but no current data. There are 3 ADCP deployments – the first is a sub-surface mooring, the last 2 are underway data. The moored data end on 18 May 2008, which is still in the spin-up period of the model and therefore discarded. An investigation of the underway ADCP data shows poor agreement in direction. These data are all in the deep Atlantic and not considered further.

For some instruments the logging of good data ended early so they were not available for the validation period (series 896261, 896285). Series 896273 ends on 9 May 2008, again early in model spin-up and is discarded. The remainder of the data (11 data series) were used for model validation for currents.

Figure 3-42 shows the comparison of model and observed currents at two levels at stations 3 and 4 for the month of June 2008.

3.4.6 Temperature and salinity

Temperature and salinity data from CTD stations provide profiles of temperature, conductivity and depth, usually made from a ship station, but possibly also a continuous time series on a mooring. We have used

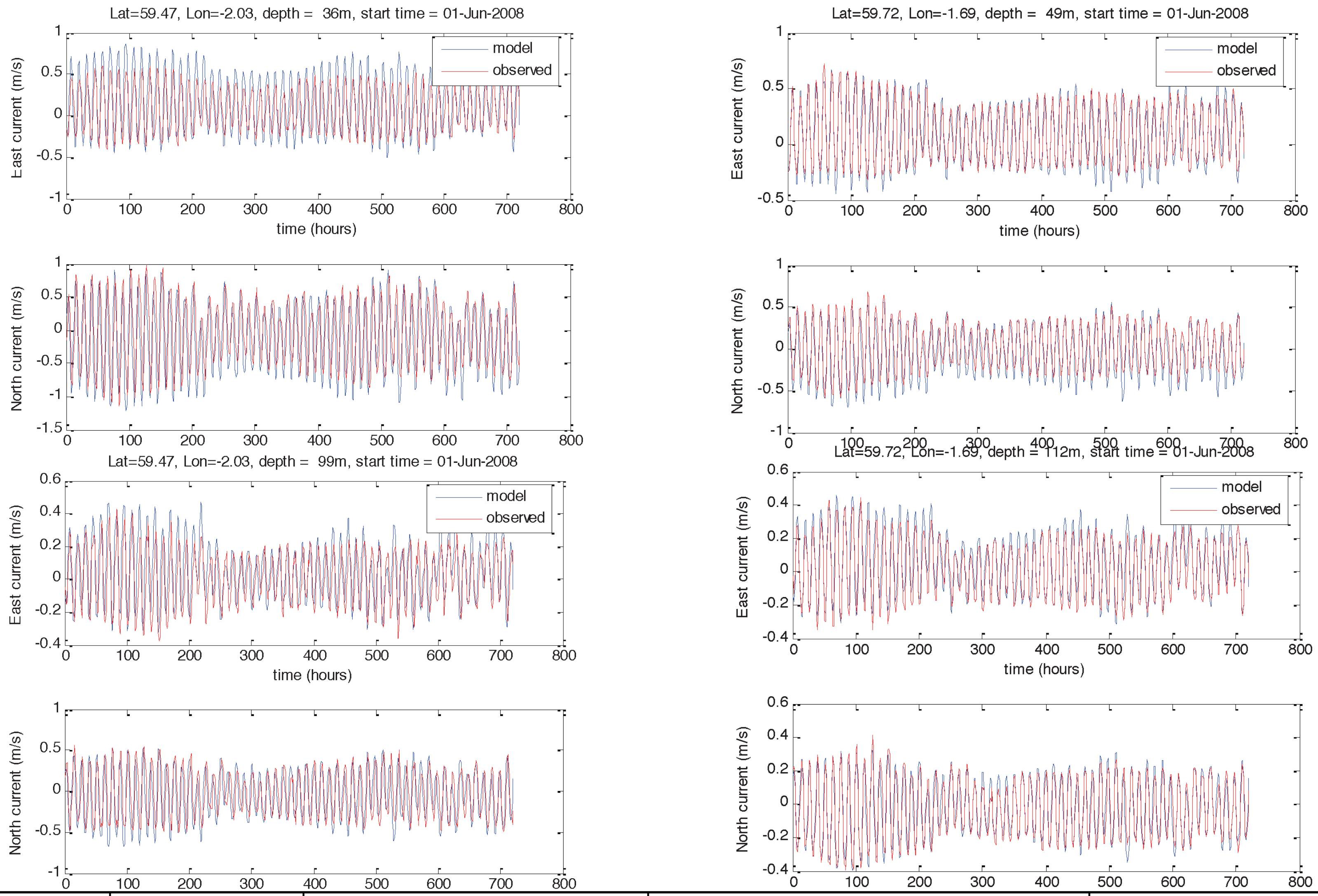
the ICES dataset
http://ocean.ices.dk/HydChem/HydChem.aspx?plot=yes.

Figure 3-43 shows a selected subset of CTD stations to represent different sea areas (similar to those selected for Figure 3-32). Figures 3-44 and 3-45 show the temperature and salinity profile comparisons between model and observations for these stations. A further set of stations in the nearshore zone is selected in Figure 3-46, with profiles in Figures 3-47 and 3-48.

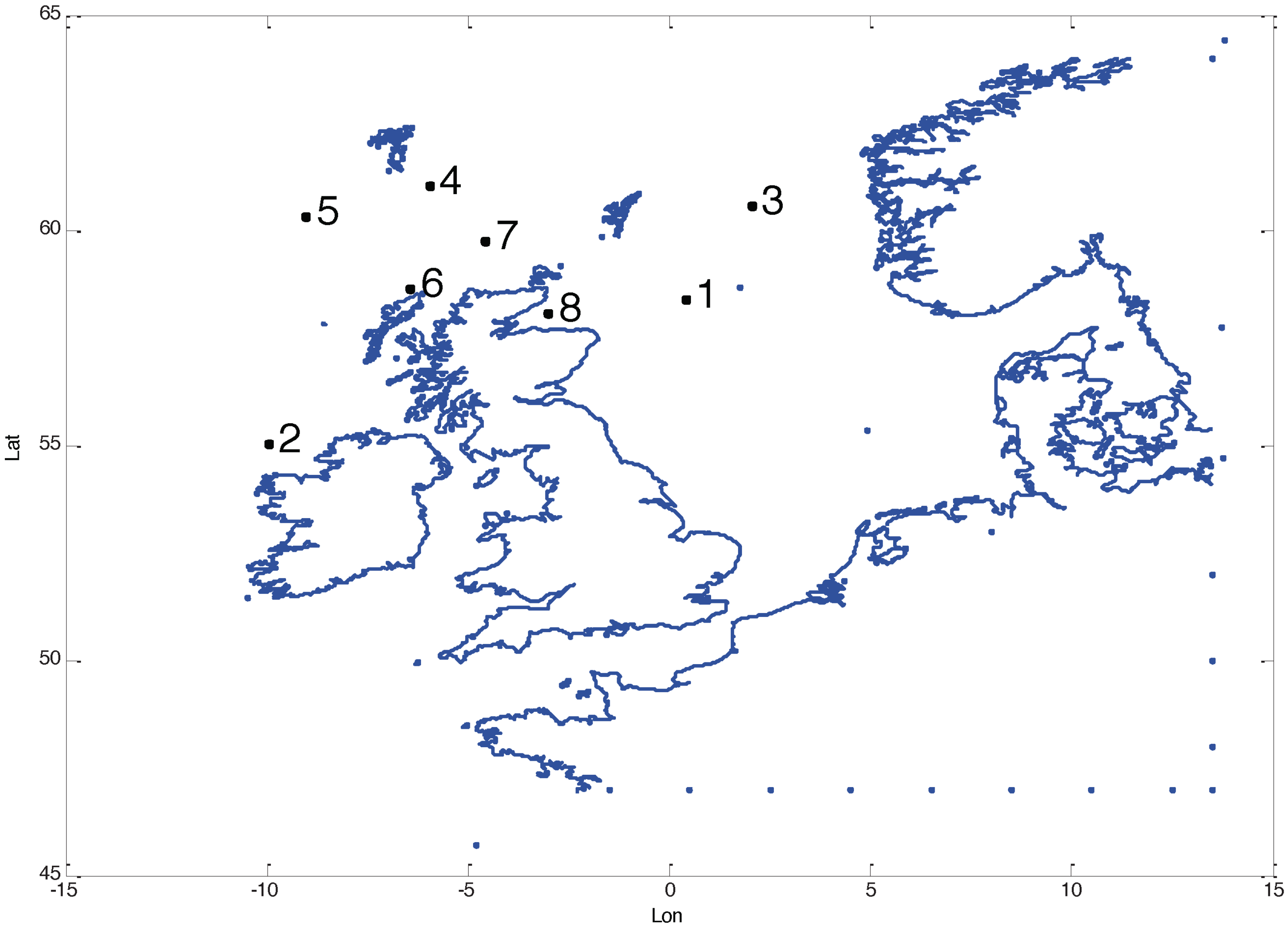
Table 3-7: Current meter data May 2008-June 2009

BODC ref	Instrument	Lat (°N)	Lon (°E)	Station	Water depth (m)	Meter depth (m)	Start date	End date	Parameters	Comments
896261	Paddle wheel c/m	60.48	-0.14	1(T)	116	34	08/10/2007	09/05/2008	Current dirn, speed, S, T	Ended 25/03/2008
896273	Acoustic c/m	60.48	-0.14	1(B)	116	109	08/10/2007	09/05/2008	Current dirn, speed, S, T	Too short
896285	Paddle wheel c/m	60.57	-0.63	2(T)	147	35	08/10/2007	09/05/2008	Current dirn, speed, S, T	Ended 25/04/2008
896304	Paddle wheel c/m	59.47	-2.03	3(M)	104	36	07/05/2008	27/09/2008	Current dirn, speed, S, T	Complete, 2 flags for
896316	Paddle wheel c/m	59.47	-2.03	3(B)	104	99	07/05/2008	27/09/2008	Current dirn, speed, T	Complete, no flags
896328	Paddle wheel c/m	59.72	-1.69	4(M)	117	49	07/05/2008	27/09/2008	Current dirn, speed, S, T	
896341	Acoustic c/m	59.73	-1.69	4(B)	117	112	07/05/2008	27/09/2008	Current dirn, speed, T	54 flagged gaps
103924	Paddle wheel c/m	59.47	-2.03	3(B)	102	89	27/09/2008	08/05/2009	Current dirn, speed, S, T	Ends 9/02/2009
103926	Acoustic c/m	59.72	-1.69	4(B)	115	102	28/09/2008	08/05/2009	Current dirn, speed, T	Complete, no flags
103925	Paddle wheel c/m	59.72	-1.69	4(M)	115	9	28/09/2008	08/05/2009	S, T only	Complete, no flags
103928	Paddle wheel c/m	56.21	-5.82	5(B)	28	27	11/12/2008	21/01/2009	Current dirn, speed, T	Complete, no flags
103929	Acoustic c/m	60.31	-0.70	6(M)	94	42	24/05/2009	11/07/2009	Current dirn, speed, T	Complete, no flags
103931	Paddle wheel c/m	60.31	-0.70	6(B)	94	85	24/05/2009	05/10/2009	Current dirn, speed, S, T	Complete, no flags,

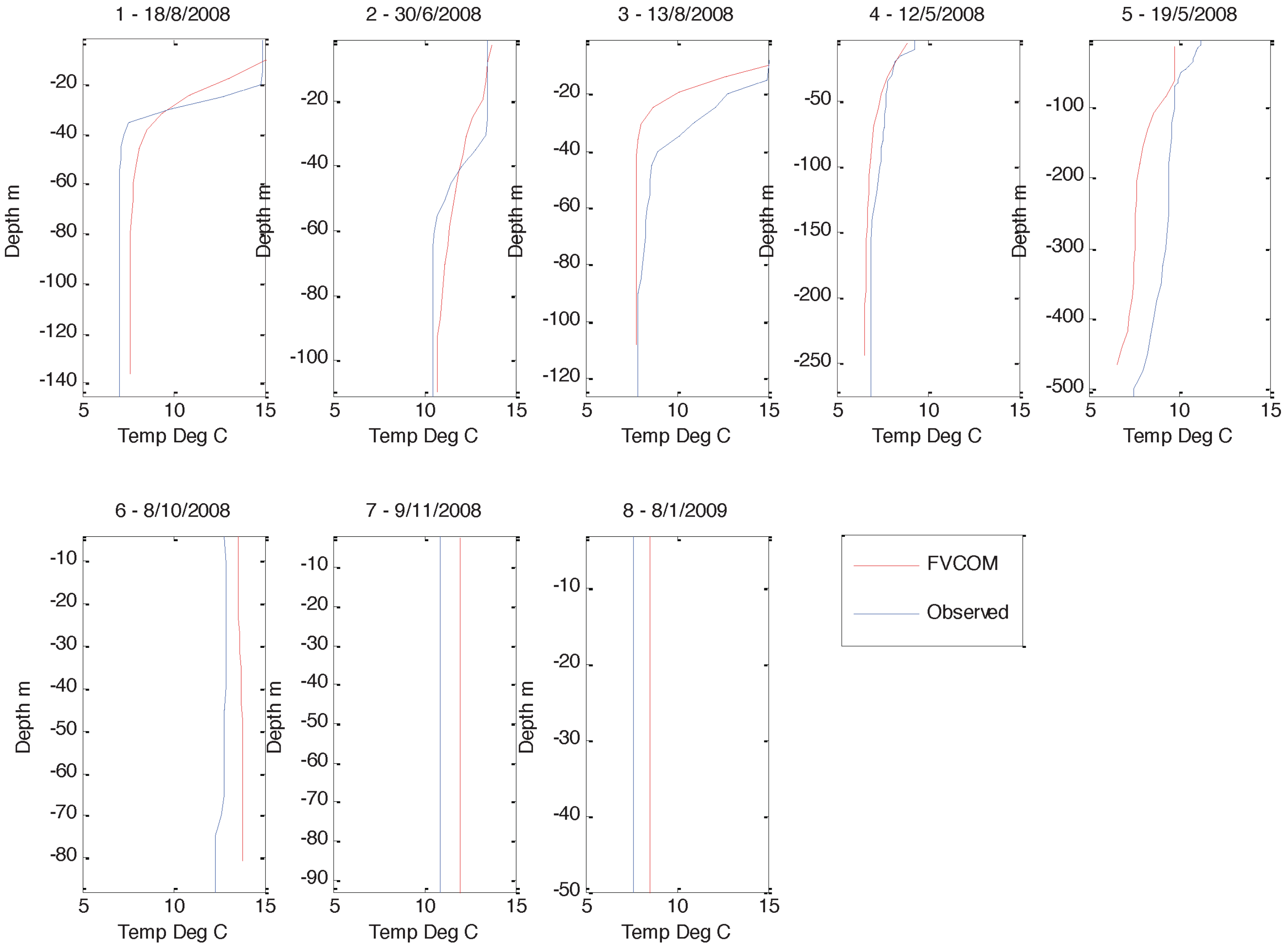
BODC ref	Instrument	Lat (°N)	Lon (°E)	Station	Water depth (m)	Meter depth (m)	Start date	End date	Parameters	Comments
103933	Acoustic c/m	60.17	-0.17	7(M)	124	42	24/05/2009	05/10/2009	Current dirn, speed, S, T	Complete, no flags,
103934	Paddle wheel c/m	60.17	-0.17	7(B)	24	115	24/05/2009	05/10/2009	Current dirn, speed, S, T	Complete, no flags,
101448	ADCP moored	60.25	-9.01	8	1310	4	02/09/2007	18/05/2008	Current dirn, speed, S, T	Deep Atlantic
102408 5	ADCP ship-mounted	57.53 – 57.08	-12.44 - -10.78		2370	11-407	22/09/2008	23/09/2008	Current dirn, speed, S, T	Deep Atlantic, discard
102928 6	ADCP ship-mounted	57.53 – 57.08	-12.44 – -10.78		2370	17-809	22/09/2008	23/09/2008	Current dirn, speed, S, T	Deep Atlantic, discard



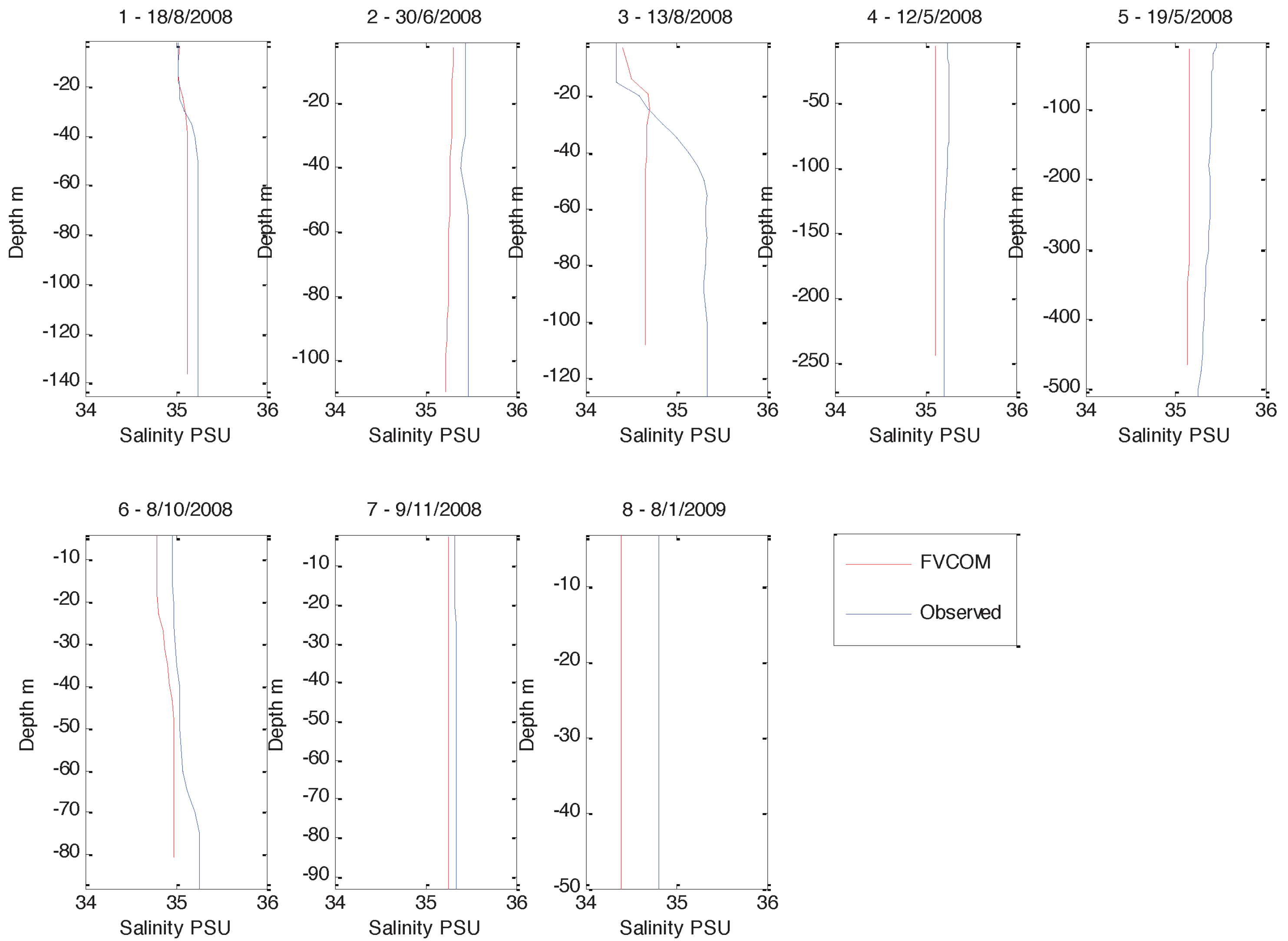
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-42		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Current data comparisons at 2 stations	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-43		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Selected offshore CTD stations 2008-2009	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-44		
Marine Scotland		Scottish Shelf Waters Model	**Offshore temperature profiles**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-45		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Offshore salinity profiles	Checked DMP	Scale Not to scale	Rev. 0
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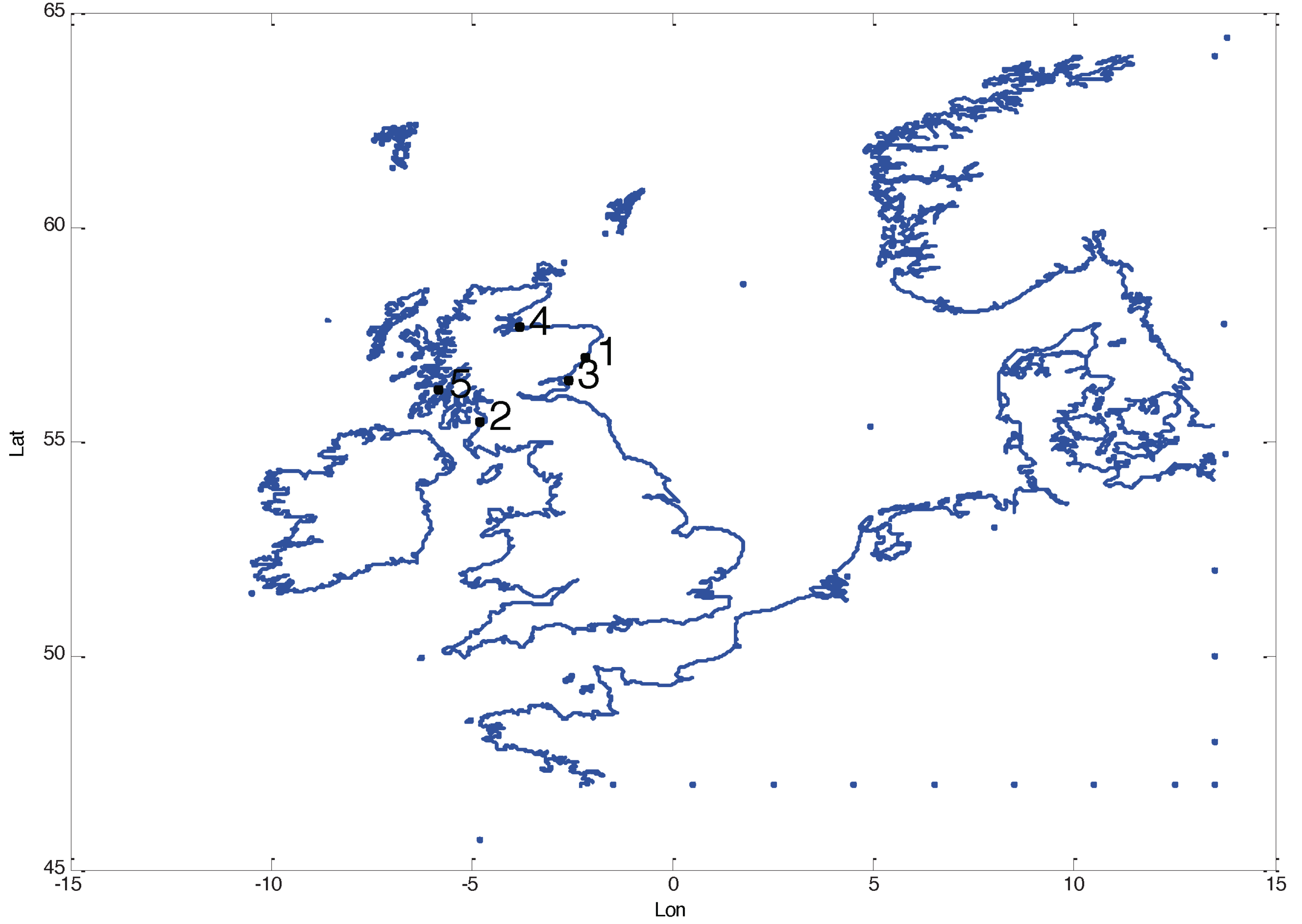
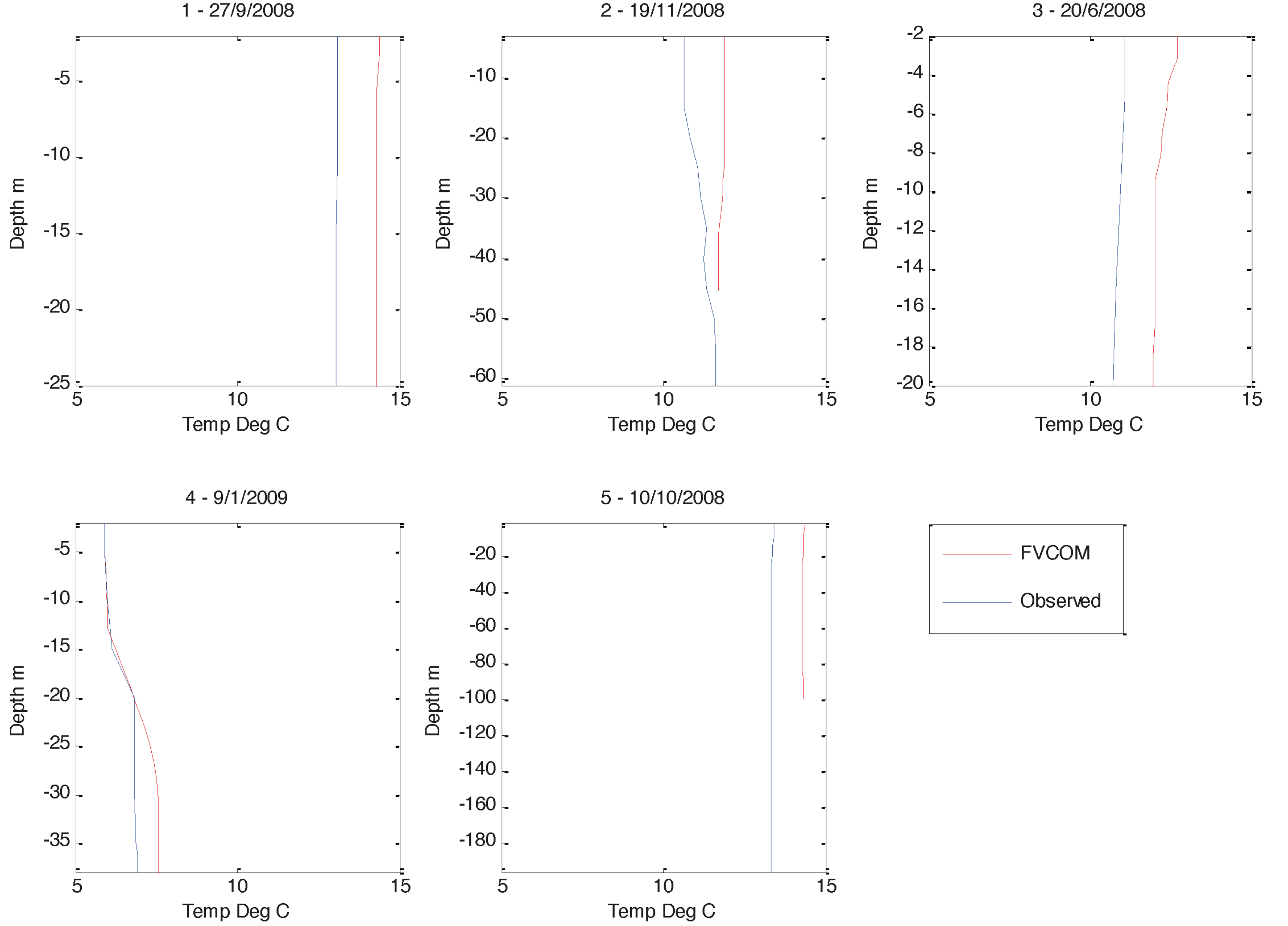
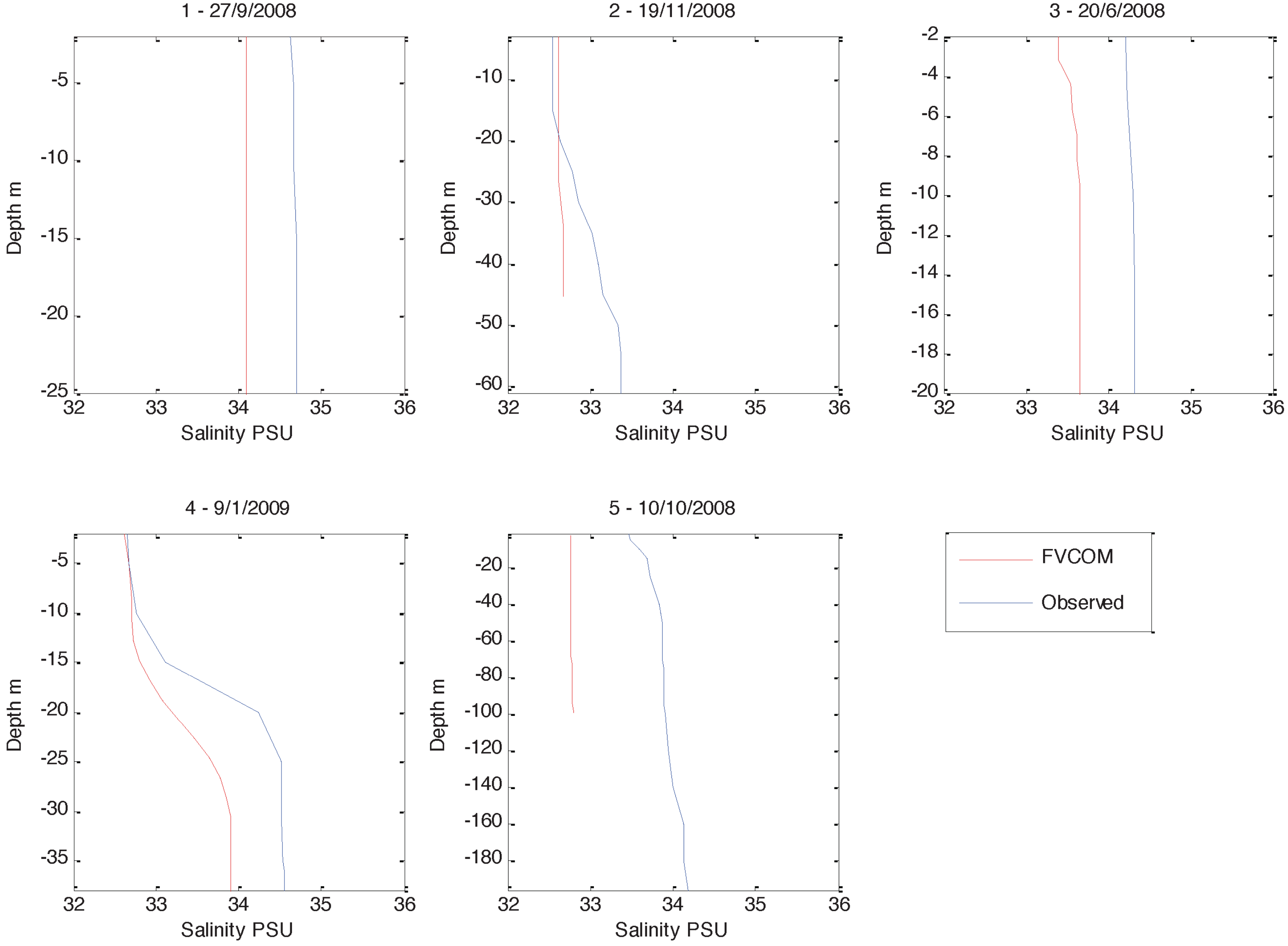


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-46		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Selected nearshore CTD stations, 2008-2009	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-47		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Nearshore temperature profiles**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-48		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Nearshore salinity profiles	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

4 Marine Energy Resources

4.1 Introduction

The requirement is to make an assessment of the tidal energy resources. This was to include standard parameters of energy resources, for example, mean peak spring tidal current and mean power density for tidal stream areas. Marine Scotland intends to use the data generated for these plots within ArcGIS.

4.2 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).

In this exercise, it was decided to follow the second approach, performing harmonic analysis of a longer time series. It is difficult to select an "average" tide that is representative, as these will vary throughout the year and between years and may not give representative currents across the whole Scottish Shelf.

Having decided on the methodology, FVCOM was run for a whole year. The tidal forcing used was derived from the TOPEX satellite data as in previous runs, but with nodal factors excluded to give an average tidal year. The results from this run were then analysed, and this analysis is described in more detail below.

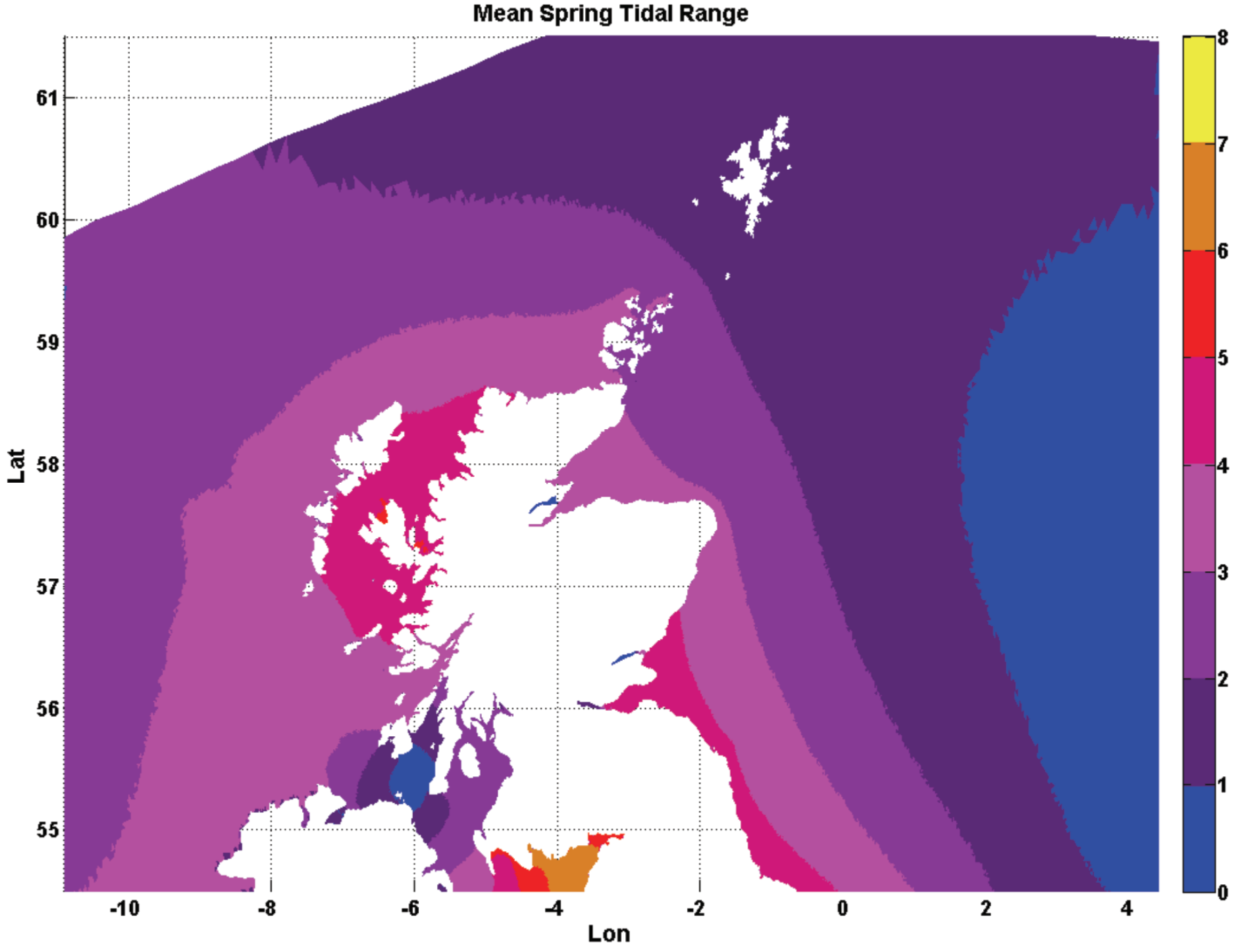
The software package T_TIDE was once again used to analyse time series to obtain harmonic constituents, given FVCOM contains no in-built code to perform this function. Due to the amount of processing needed, harmonic constituents were only computed for relevant Scottish Waters.

The data for the maps of tidal energy resources has been prepared using Matlab to manipulate FVCOM output in NETCDF files. ArcGIS shape files can be produced by importing xyz files of this data into ArcCatalog, from whence it can be transformed to shape file format.

4.2.1 Mean Spring / Neap Tidal Range

Mean spring tidal ranges were computed directly from the two principal semi-diurnal components M_2 and S_2 using the formula 2 x (Amplitude M_2 + Amplitude S_2). Values for these constituents were obtained from a harmonic analysis of one year's worth of data using tidal forcing without nodal corrections (considered to be an average tidal year). 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 were also used to calculate the mean neap tidal range as 2 x (Amplitude M_2 - Amplitude S_2). A map of the mean spring results is shown in Figure 4-1, and by way of comparison, the equivalent tidal range from the ABPMer / NOC Atlas of Marine Energy Resources (http://www.renewables-atlas.info/) is shown in Figure 4-2. The corresponding plots for mean neap tidal range are shown in Figures 4-3 and 4-4.

As can been seen from Figure 4-1 and 4-2, there is good agreement between the two sets of mean spring tidal range results. There are some minor differences around the amphidromic point to the NE of Ireland. This is perhaps to be expected given that we are comparing results from a structured grid at 1.8km resolution with an unstructured grid with a typical mesh resolution of 750m in the vicinity of north-east Ireland, and that the amphidromic points are likely to be sensitive to the model setup. Some of the difference may also be due to differences in the projections used for the two plots. Also apparent is the difference in tidal range in the upper Solway Estuary and this is likely to be due to bathymetry differences between the two models. The structured model for the ABPMer / NOC Atlas uses a minimum depth throughout the upper estuary, in order to avoid drying out, whereas the FVCOM model uses more accurate bathymetry data. This identifies the main channel but is typically shallower in the upper estuary, leading to the differences in model results. The same feature is seen in the mean neap tidal range plots (Figures 4-3 and 4-4), which otherwise show excellent agreement.



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-1		
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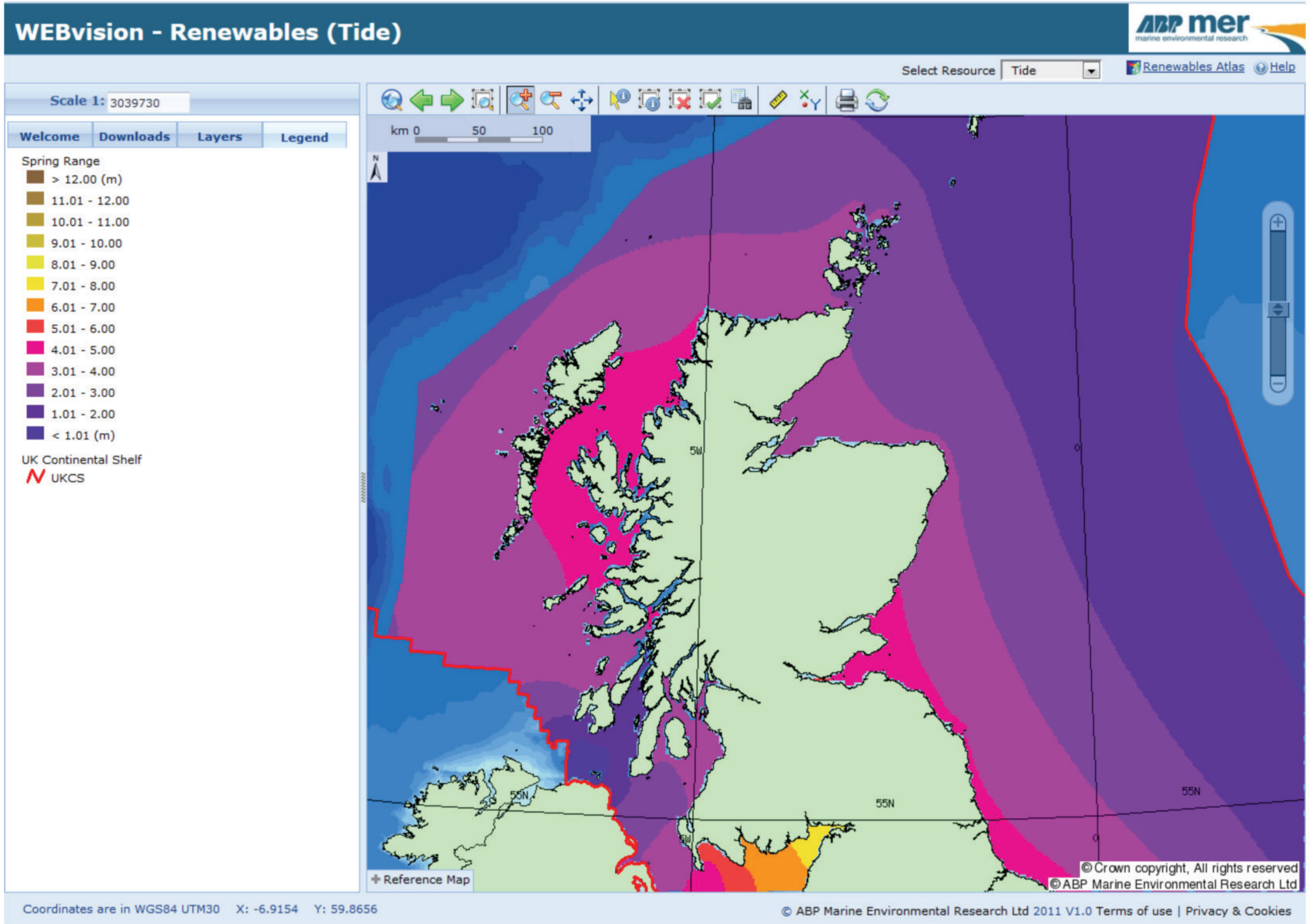
				Designed	Drawn	Date 26/03/2014



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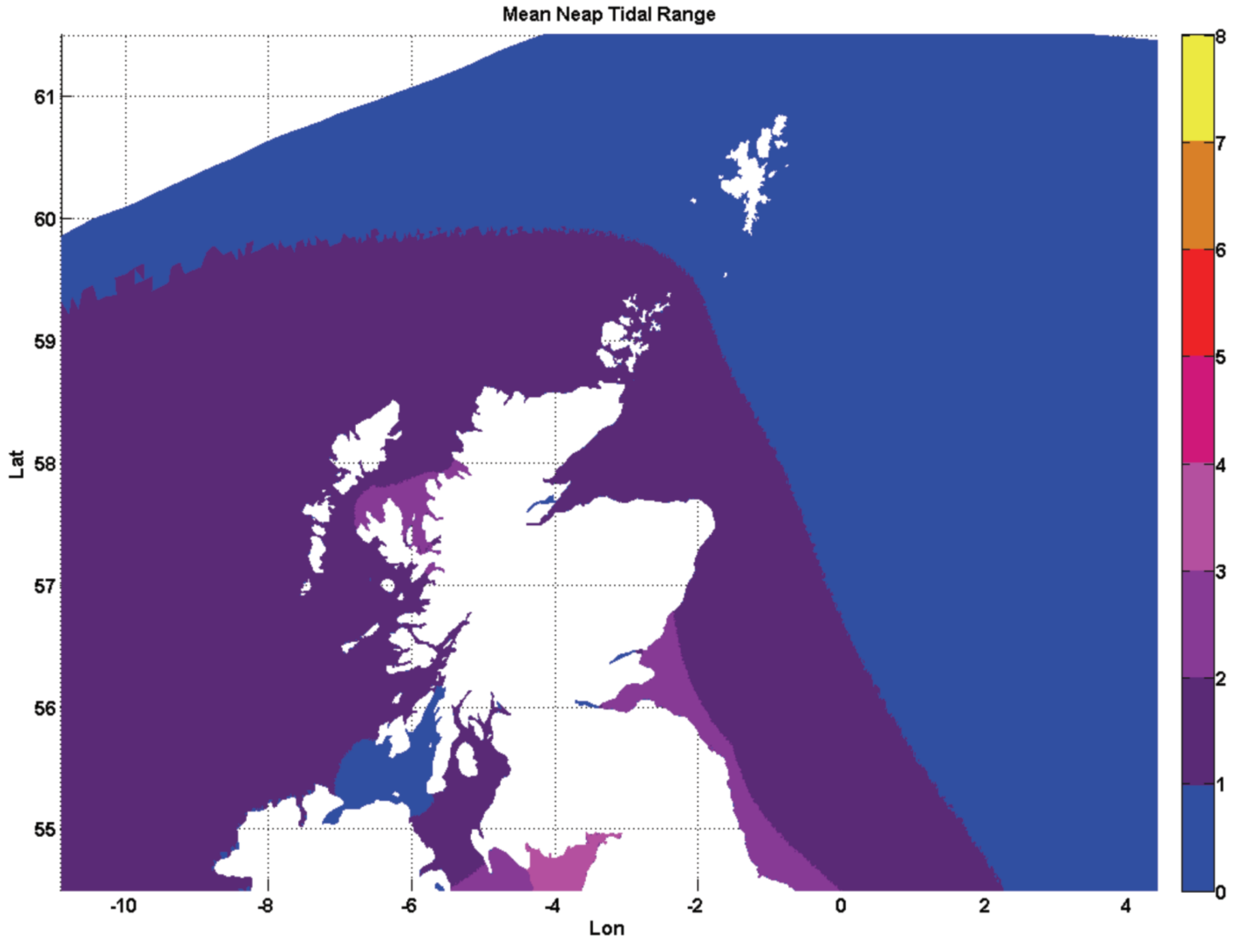
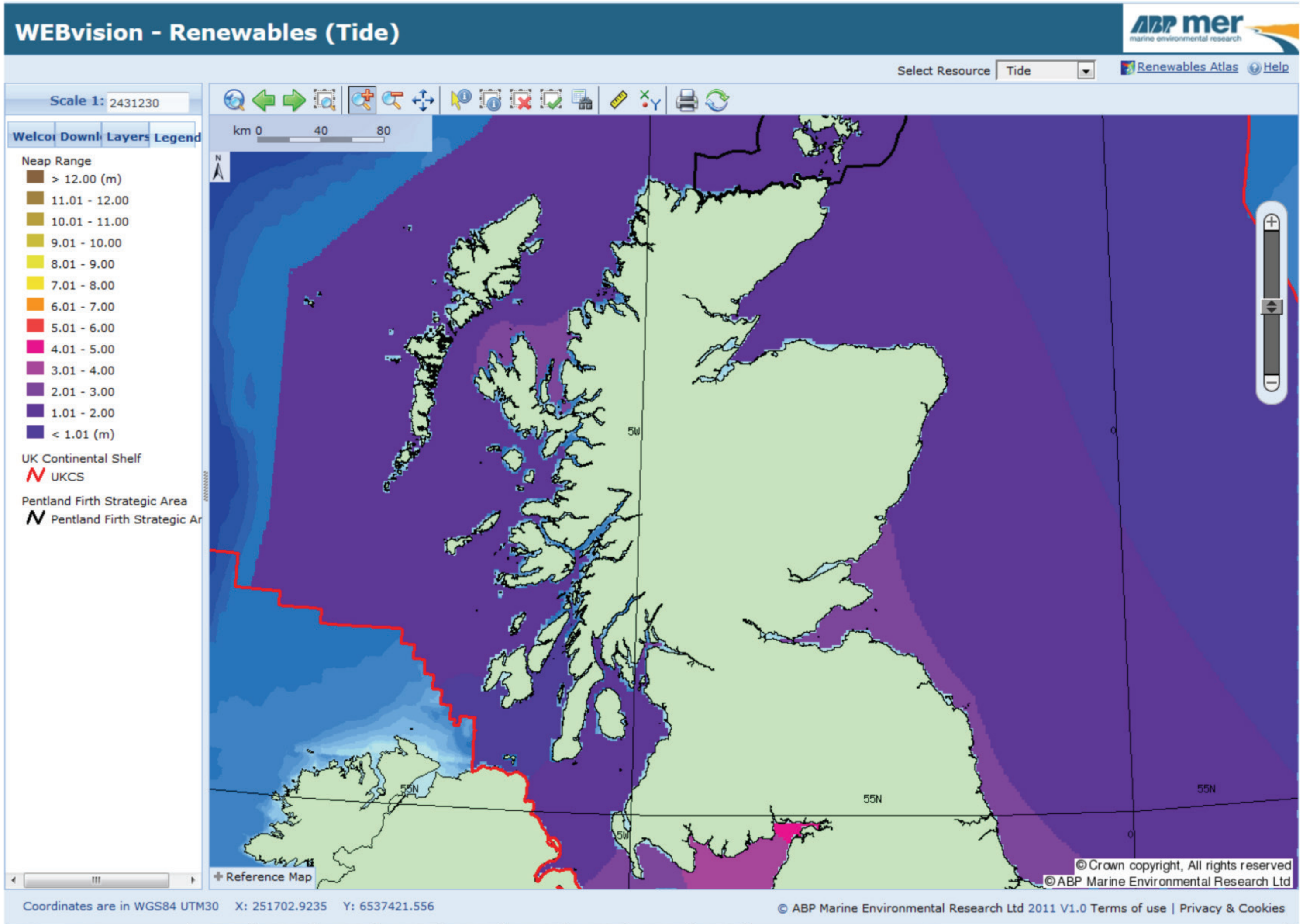
Marine Scotland	ch2m:	Scottish Shelf Waters Model	Mean spring tidal range from ABPMer / NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-3		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Mean Neap Tidal Range from FVCOM model**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



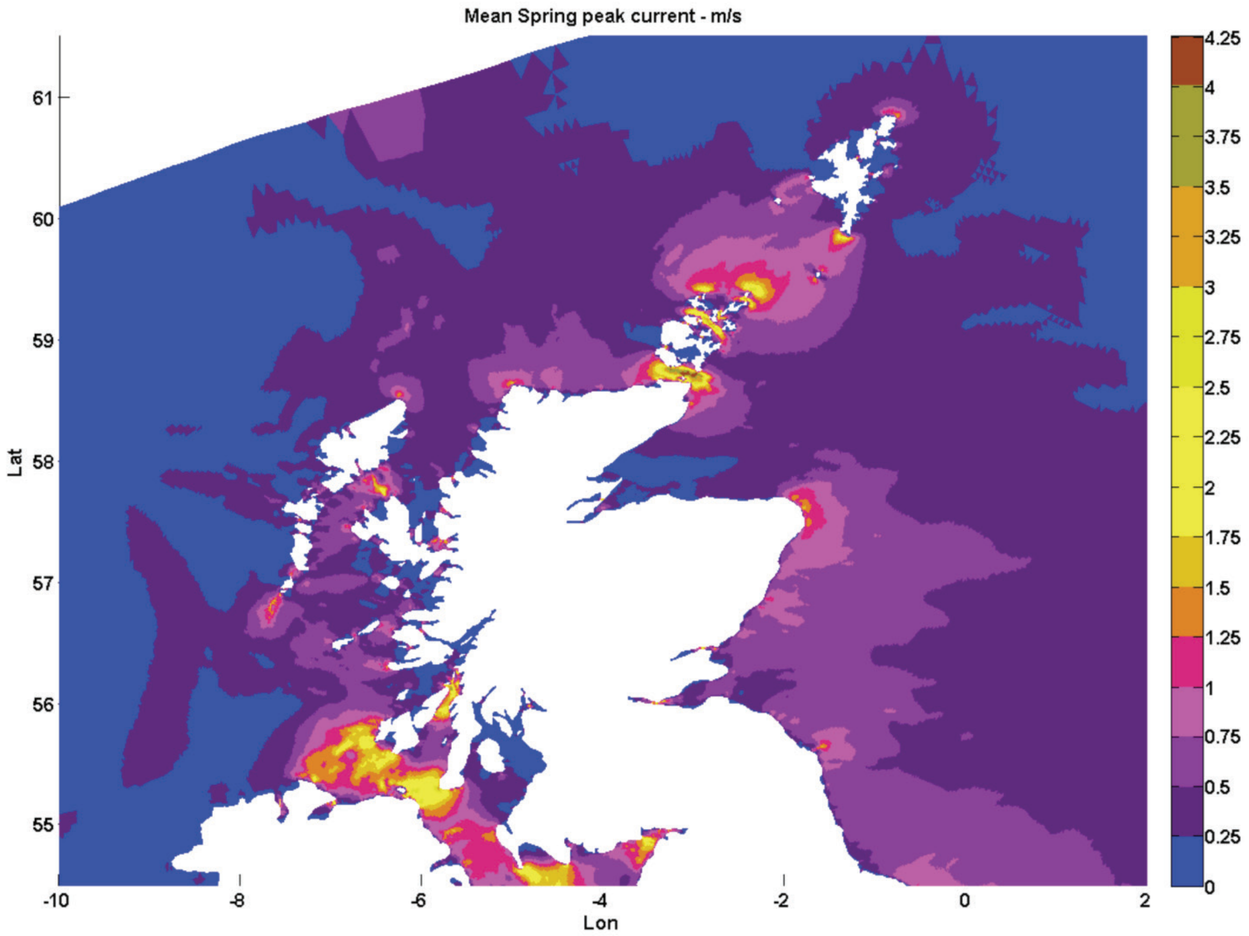
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-4		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Mean neap tidal range from ABPMer / NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m

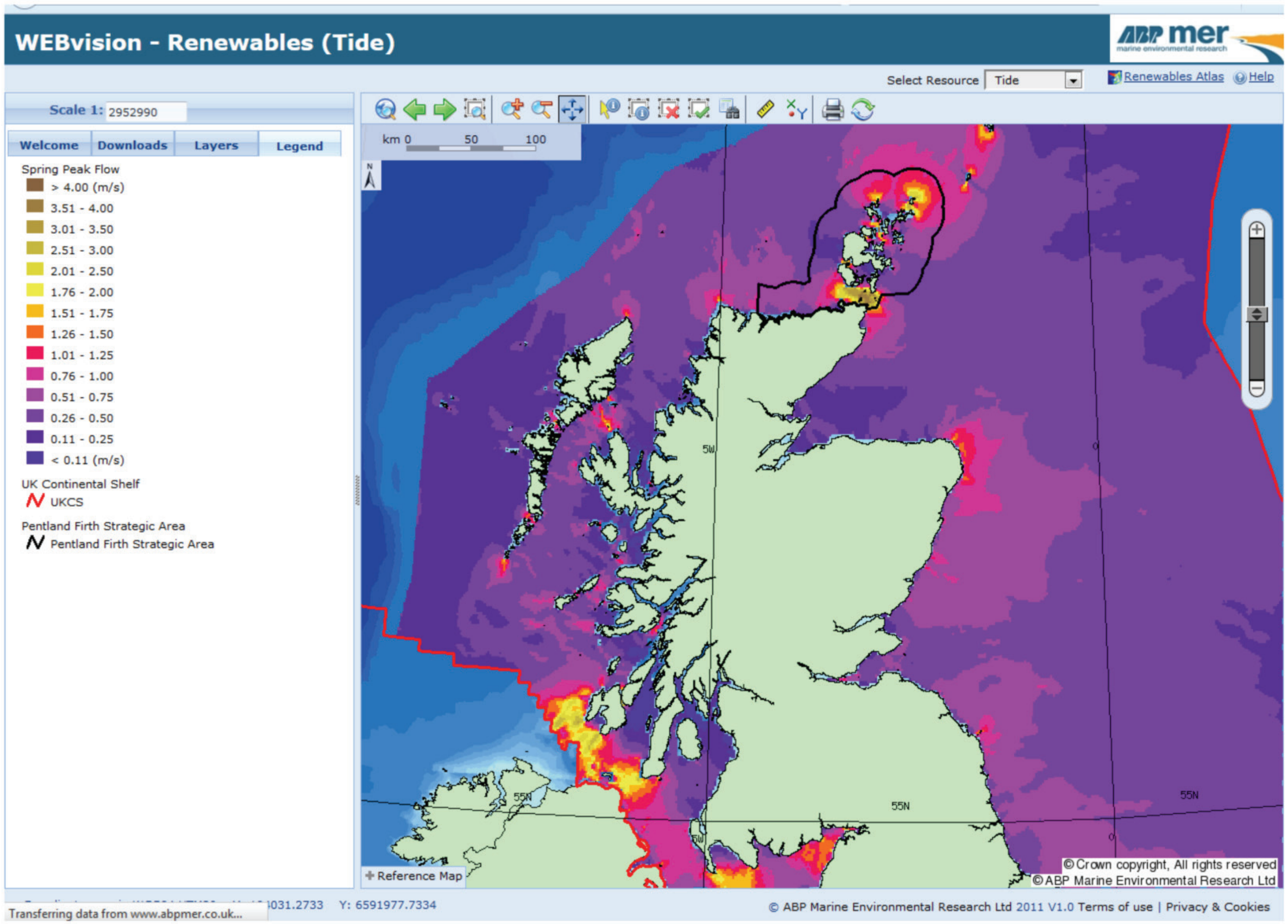
4.2.2 Mean Peak Spring / Neap Current

Mean peak current speeds have been calculated from a harmonic analysis of a year's worth of tidal velocities. In line with the methodology used for the ABPMer / NOC Atlas, a mid-depth velocity was used for the calculations. The east and north 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 (amplitude semi-major axis M_2 + amplitude semi-major axis S_2). The mean neap spring current was computed as (amplitude semi-major axis M_2 - amplitude semi-major axis S_2). A map of the results for mean spring current is shown in Figure 4-5, and by way of comparison, the equivalent tidal range from the ABPMer / NOC Atlas of Marine Energy Resources is shown in Figure 4-6. Corresponding plots for the mean neap current are shown in Figures 4-7 and 4-8.

As can been seen from Figures 4-5 and 4-6, there is good agreement between the two sets of results for mean peak spring current, particularly in the important Pentland Firth Strategic Area. There are some minor differences apparent in the Solway Firth, but these probably follow from the bathymetry (and hence tidal range) differences between the two models discussed in the previous section. The increased spatial resolution of the FVCOM model (~750m compared to 1.8km for the ABPMer / NOC model) can be seen to resolve more current detail in some coastal areas, especially around Jura, correlating well with observations. The plots for mean neap current (Figures 4-7 and 4-8) also show a similar pattern (for the same reasons), with additional being apparent around Jura in the FVCOM model results.

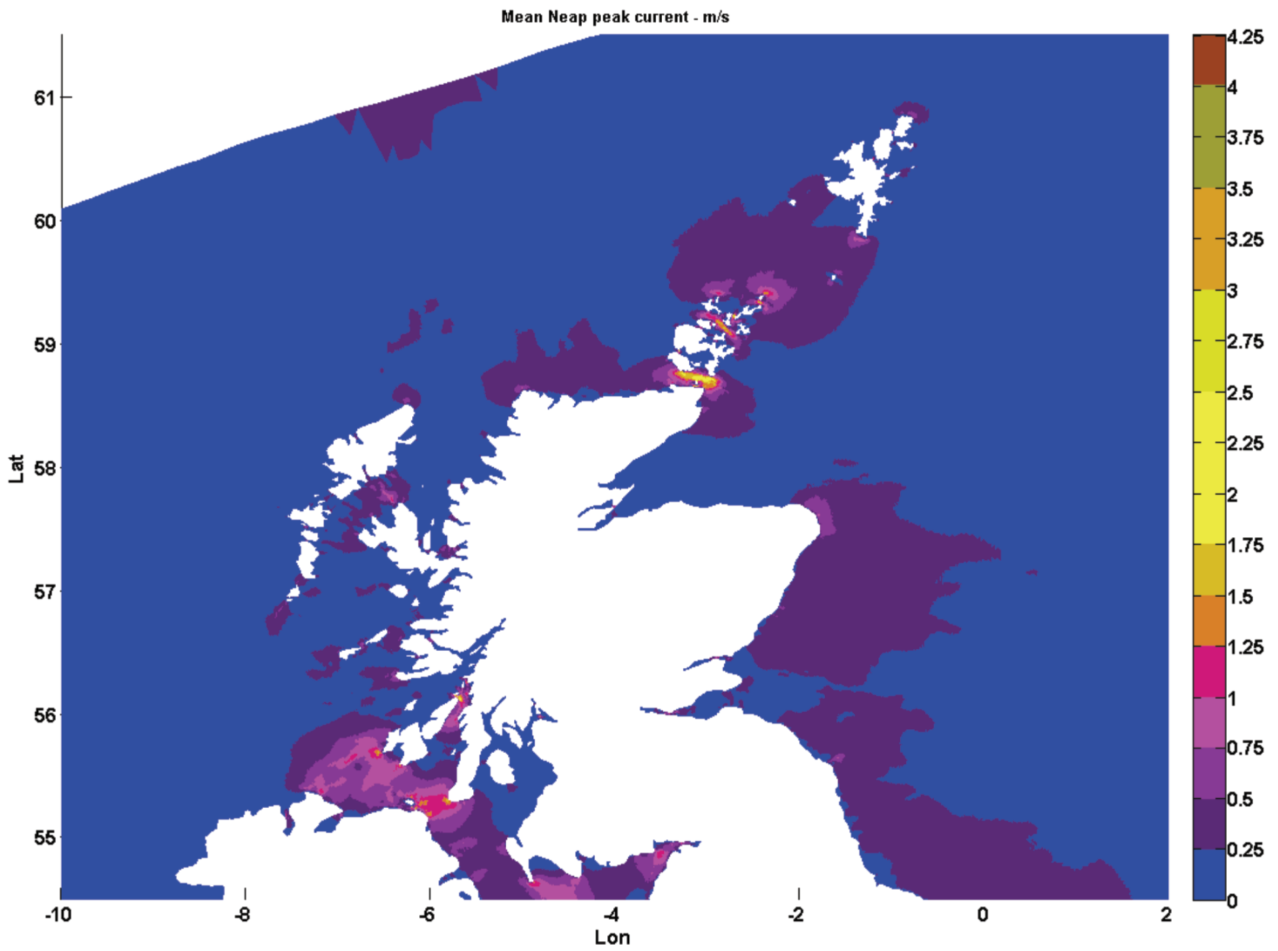


Client	Consulting Engineer	Project:	Figure Title:	Figure 4-5		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Mean peak spring current from FVCOM model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

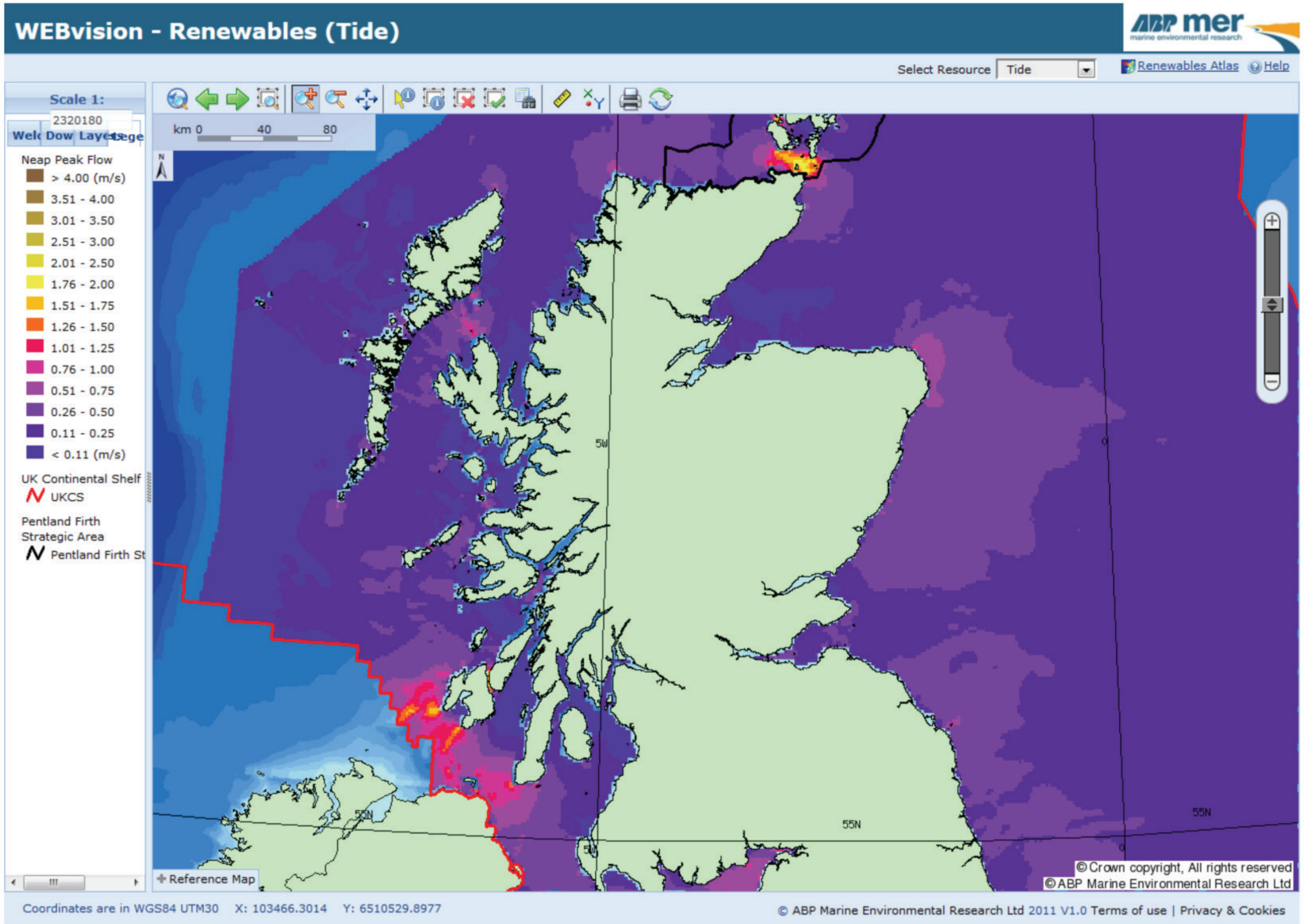


Client	Consulting Engineer	Project:	Figure Title:	Figure 4-6		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Mean peak spring current from ABPMer / NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-7		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Mean peak neap current from FVCOM model**	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014



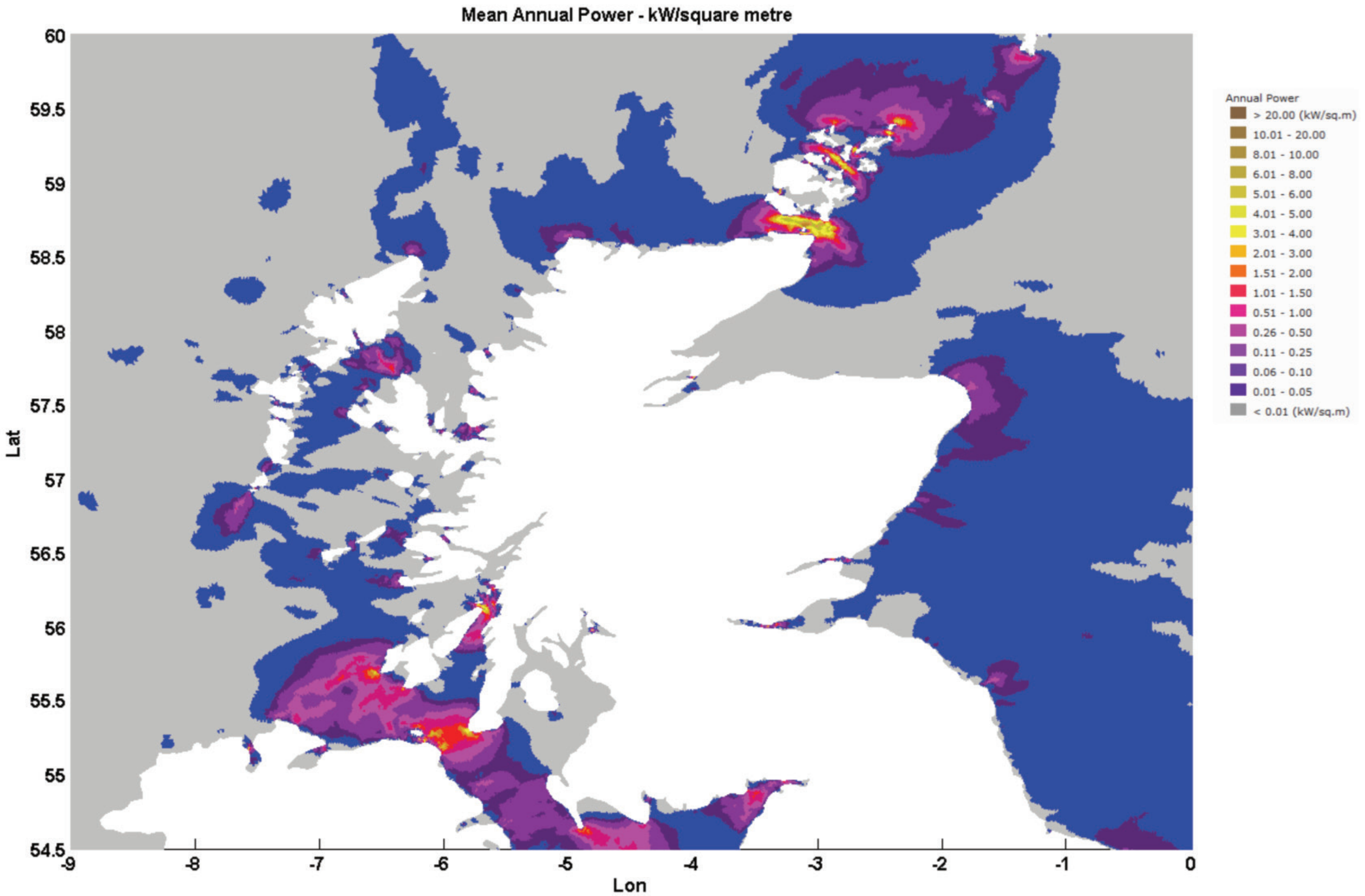
Client	Consulting Engineer	Project:	Figure Title:	Figure 4-8		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Mean peak neap current from ABPMer / NOC Atlas of Marine Energy Resources**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed:	Drawn:	Date: 26/03/2014

4.2.3 Mean Tidal Stream Power Density

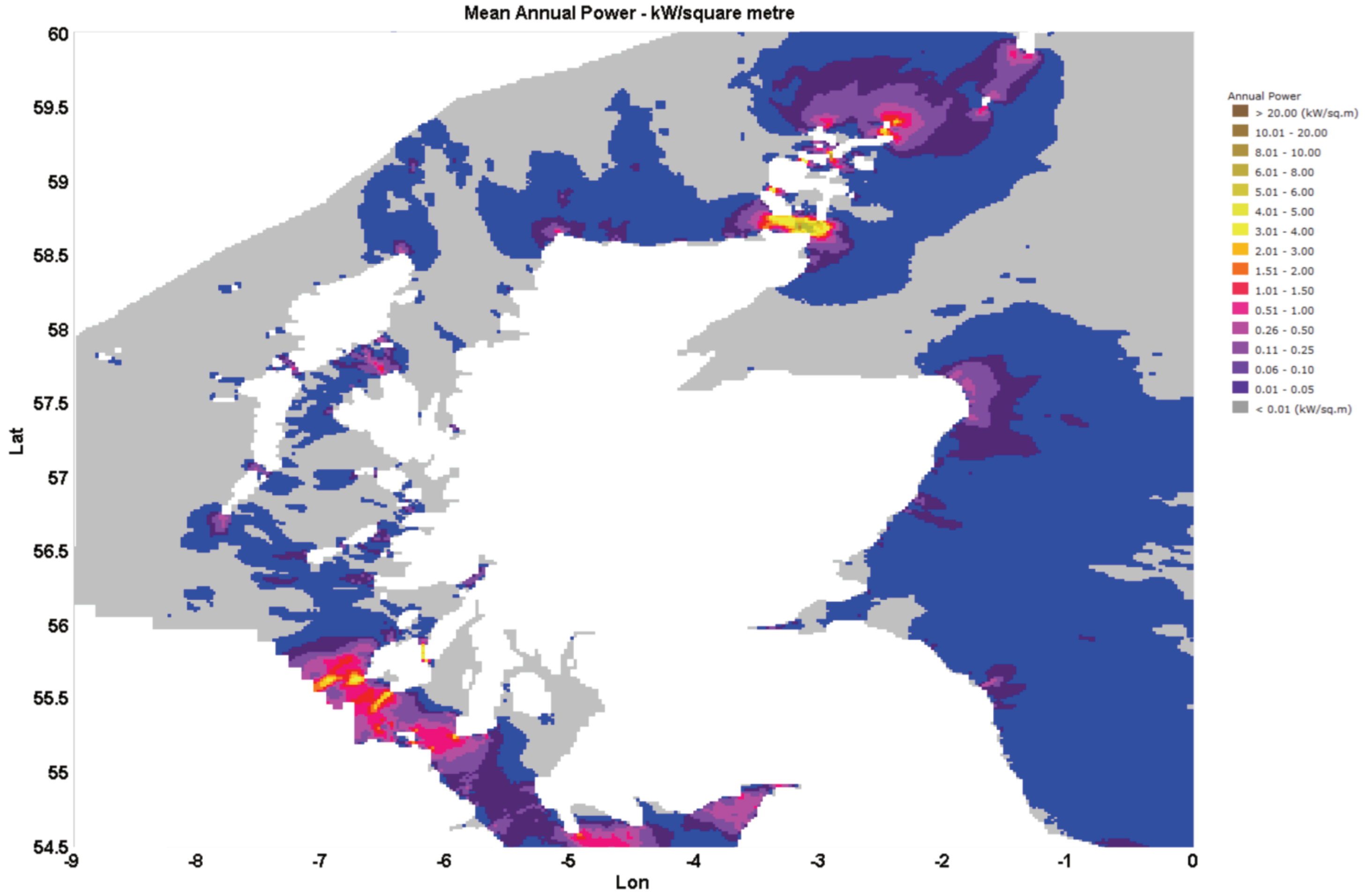
The mean tidal stream power density is the kinetic energy in the tidal flows (per unit cross-sectional area) averaged over the time period, which in this exercise was a whole year. As tidal energy results were computed by harmonic analysis of long time series (as discussed earlier), only the mean annual power density was calculated.

A mid-depth velocity was used as in the previous section, with the mean power density being given by $0.5 \times \rho \times <U^3>$. The density ρ was taken as 1027 kg/m^3, and the chevrons indicate that it is the cube of the mid-depth speed that is averaged over the whole year. A map of the results is shown in Figure 4-9, and by way of comparison, the equivalent tidal range from the ABPMer / NOC Atlas of Marine Energy Resources is shown in Figure 4-10.

As can be seen from the plots, the FVCOM model is correctly identifying both the location and magnitude of the maximum annual average power. The unstructured grid mesh with a minimum resolution of 750m has resolved additional detail around Jura, and around headlands between the Mull of Kintyre and Ireland. There is a slight difference observed off the tip of Islay which is probably due to differences in model resolution and bathymetry.



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-9		
Marine Scotland	ch2m	Scottish Shelf Waters Model	**Mean annual power density from FVCOM model**	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 26/03/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 4-10		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Mean annual power density from ABPMer / NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 26/03/2014

ch2m

4.3 Approaches for assessing impacts of extracting tidal stream energy

There are a number of stakeholders requiring detail on the impacts of extracting tidal stream energy. Developers, for example, need to know how much energy their device will actually generate, as this is crucial to the viability of their business. Regulators, by contrast, want to understand the impacts of tidal devices on waves, sediment transport, tidal currents, mixing in the water column and marine animals. Regulators also need to know the total impact of multiple farms of devices, and potentially the conjunctive impact of different categories of (farms of) devices such as wave and tidal stream energy convertors.

These differing and complex needs cannot be met by simple analytical (mathematical) models, and so there is a need to represent devices in either 2-D or 3-D numerical models. Only tidal stream devices are considered here. Whilst (3-D) FVCOM will ultimately be used to model the impact of tidal stream devices on marine physics, it is still worth reviewing the approaches used with 2-D models.

The simplest method of representing devices in 2-D model is by locally enhancing the bed stress to represent (typically) a farm of devices. For example, Sutherland et al (2007) modelled the Johnstone Strait in Canada, Karsten et al (2008) the Minas Passage in the Bay of Fundy, and Walkington and Burrows (2009) the West Coast of the UK, all using 2D finite element modelling.

All of these studies suffer from the problem of defining the value of the friction associated with the farm. In addition, it is not clear if such gross averaging of the effects of a tidal stream farm is a realistic parameterisation. The 2-D modelling is also not capturing the sharp changes in velocity and water level likely to be associated with a farm, nor differential effects through the water column. What such modelling does allow is the simulation of tidal stream farms outside of channels, partial closure of channels, and a more detailed exploration of hydrodynamic and far field effects. For example, in Walkington and Burrows (2009), flow diversion (acceleration and deceleration) can be clearly seen around the small tidal stream farms modelled, and this is a potentially significant result for the economics of such schemes.

Instead of representing the devices as enhanced bed stress, other approaches have been to represent them as momentum sinks (e.g. Ahmadian and Falconer 2012), or to parameterise the turbine blades using actuator disk theory (e.g. Draper et al 2010, building on the work of Whelan et al 2009).

In 2-D modelling, the models calculate a depth averaged flow velocity, and the turbine parameterisation is then applied to the whole vertical water column. To address the more realistic case of submerged turbines that do not extend throughout the vertical water column, 3-D modelling will be required, and this is a developing and complex area of research.

In order to accurately represent tidal stream devices in 3-D, model parameterisations would ideally need to capture –

- the correct placement of the device in the water column
- the effect of a rotating turbulent wake structure
- sharp changes in water velocity and level
- interactions between the wakes of multiple devices in a farm
- different levels of drag between a structure and turbine blades

CFD modelling is starting to address some of these issues for single devices (though rotation has been a particularly difficult problem), but the computing power needed for these calculations means that CFD models are limited in physical and temporal extent.

Given these limitation (though CFD should deliver useful insights), there is thus still need for adequate tidal stream parameterisation to allow assessment of the impacts of farms of devices over large areas and timescales. One of the earliest approaches was to transfer the momentum sink approach used in 2-D modelling to 3-D (e.g. Shapiro 2011), but this is still a relatively crude approximation to the complexity of device and farm flows. Research is ongoing to refine the parameterisation used for tidal stream devices in 3-D models. Approaches in the literature include using blade element momentum theory to improve the device representation (e.g. Masters et al 2011), or to include tide and depth varying parameters for bed stress and turbine drag.

5 Model Climatology

5.1 Introduction

The requirement is to produce a one-year climatology run based on climatological forcing, including climatological river forcing, which will represent a typical annual cycle.

The results from the climatology run have been compared with climatological atlas information for temperature, salinity and currents. This has provided a distribution of the typical tidal and residual currents over Scottish Waters which has then been used for particle tracking and to calculate connectivity indices.

In order to derive representative residual flows (driven by tide, wind, density gradients and river discharges) for the model connectivity calculations we wish to look at monthly mean rather than synoptic scale forcing. This includes the prevailing wind, tides, mean river flow and monthly mean boundary and surface forcing for temperature and salinity, which allows the water temperature and salinity to follow the seasonal cycle.

An interesting question which is not explored fully here is to understand how much winter storm events affect the residual flows. It would be of interest to examine the model results using monthly mean forcing for a stormy winter month compared with the mean forcing for the same month. It may be possible to select a representative year to explore storminess, in the same way as has been done for the PFOW wave modelling. However (after some detailed discussion with Marine Scotland) in this case it was decided to ignore the effect of storms. The monthly mean wind-stress was used over a climatological period (typically 30 years), which, while larger than the monthly mean wind speed, will thus underestimate the effect of wind-driven mixing.

5.2 Data

Forcing data

1. AMM daily mean boundary forcing (plus initial conditions) for temperature and salinity were taken from the long-term hindcast carried out by Sarah Wakelin and Jason Holt, over the period 1960-2004.
2. Met forcing data for climatological simulations of the models were obtained 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.

3. River climatology were obtained from 2 sources: (i) a reconstructed river climatology derived by reference to the E-HYPE model (126 Scottish rivers, 1980-2012 provided by the Swedish Meteorological and Hydrological Institute, SMHI), distributed across the 508 G2G river discharge locations for the Scottish mainland, as originally provided by CEH for March 2007 – Sep 2010 (see below) (ii) G2G river climatology (1962-2011, 577 rivers) recently provided by CEH in August 2014 and updated in October 2014.

Validation data: Temperature and salinity climatology

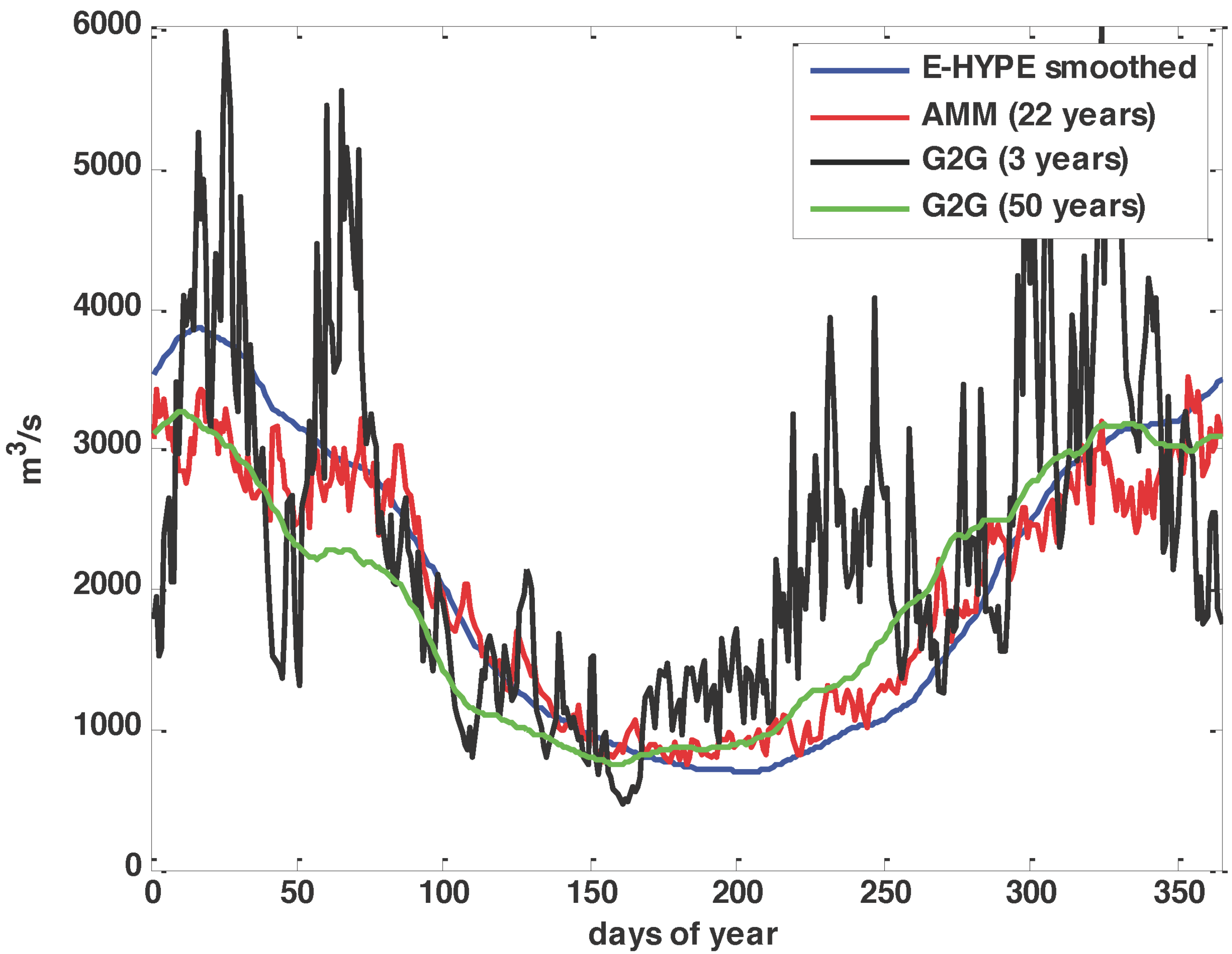
1. Temperature and salinity observations are available from the ICES dataset (http://www.ices.dk/marine-data/data-portals/Pages/ocean.aspx) gridded and averaged for 1960-2004 (45 years) by Jason Holt. Note that this is not identical to Berx and Hughes (2009) who presented a 30-year climatology. Temperature and salinity data are also available from the NOAA/NDBC World Ocean Atlas (2013; http://www.nodc.noaa.gov/OC5/woa13/) based on over 100 years of observations. These data have been interpolated onto grids with varying resolution. Here we used 0.25° resolution temperature and salinity for the Greenland and Nordic Seas for qualitative comparisons, referred to as WOA.
2. The AMM model results (1960-2004; Holt et al., 2009) have also been used for comparison (see above).

5.3 Methodology

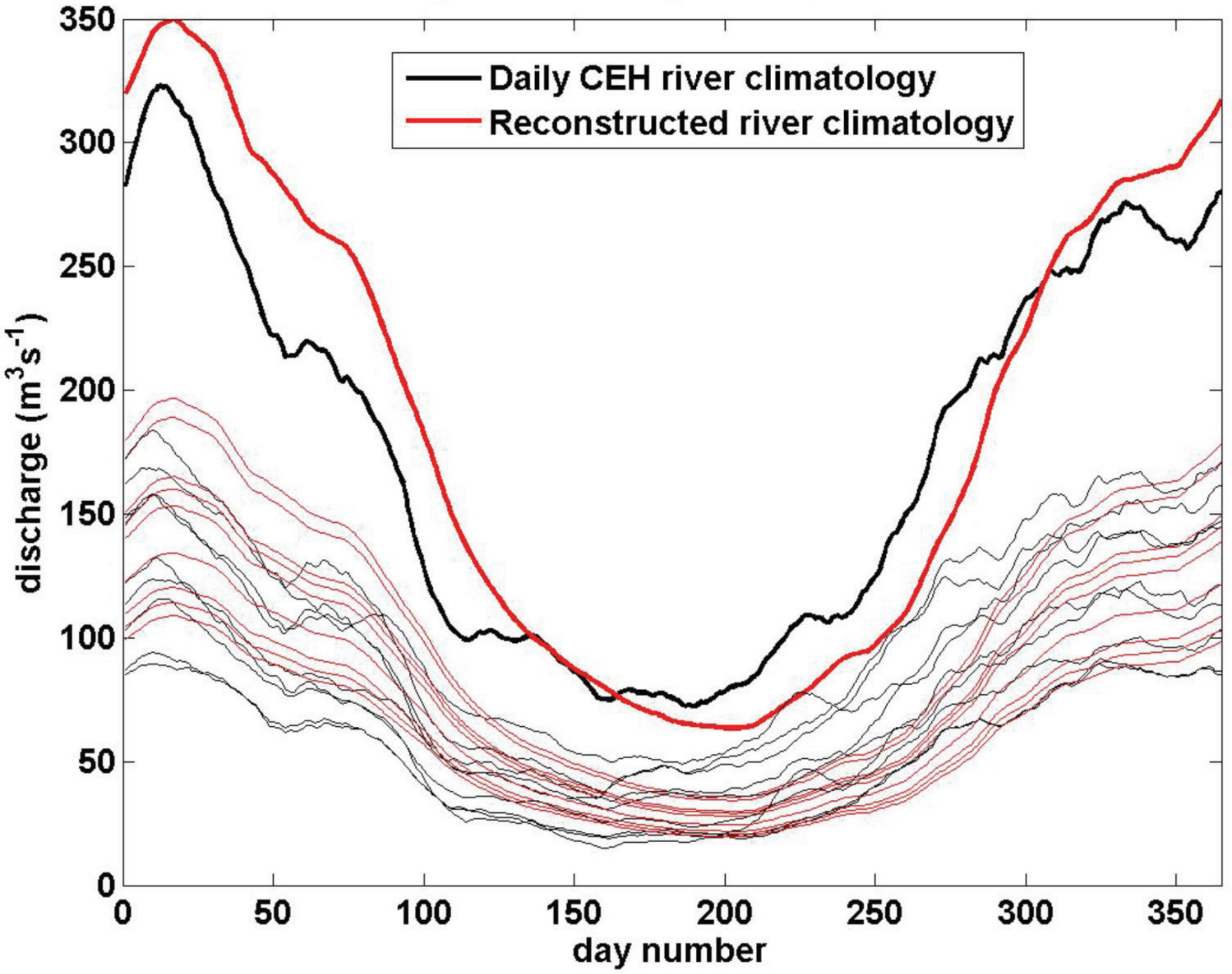
1. ERA-Interim data were accessed from BADC for derivation of the climatological forcing. Met Office UM data were not available for an extended period, thus were not suitable.
2. Initially CEH river data were only available for the Scottish mainland and there was no climatology provided, so for the initial climatology run, a reconstructed river climatology was used. Later, data were provided for the extra rivers in Northern Ireland and Shetland and a 50-year river climatology was also provided. The method for deriving the reconstructed climatology for the 508 G2G rivers was to apply a climatological mean to each river, scaled by its fraction of the mean discharge, taken from the 2007-2010 dataset. The climatological mean was taken from the E-HYPE data for 1981-2010 i.e. summing all the rivers in the E-HYPE database. The seasonal cycle was retained by taking the daily mean for each day in the year across the 30 years. Although the distribution between east-, north- and west-flowing rivers may vary somewhat from year to year the inter-annual

variability appears to be only O(10%). The daily data were de-trended before averaging. Further smoothing was carried out in the time domain (using a 31-day running mean), as there is a lot of variability at the daily to monthly time-scale. The total daily climatological discharge for each river dataset is shown in Figure 5-1. It may be seen that the climatology for AMM and E-HYPE is rather similar, whereas the 3-year-averaged G2G data retain more variability due to the shorter duration. The resultant daily discharges, for the top 10 G2G rivers (all on the Scottish mainland), are shown in Figure 5-2, comparing the reconstructed (red) with CEH-provided climatology discharges (black). The largest discharge (shown as heavier lines) is for the Tay, being almost twice the magnitude of the next largest river. The Tay is the longest river in Scotland, with the largest catchment area. It is interesting to note that the CEH climatology is quite similar to the reconstruction, with a slight phase shift.

3. A 1-year climatological model run of the shelf model was carried out using the following forcing:
    a. Initial and boundary conditions were taken from a mean of the AMM climatology run.
    b. The tides were included as a mean tidal year.
    c. The met forcing was 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. The spatial interpolation was carried out by FVCOM in a similar way to the use of UM data for the model hindcast of 2008-2009.
    d. The first run of climatology used the reconstructed river data. A second run used the CEH-provided river climatology. The results were very similar except that the nearshore freshwater due the inclusion of the Northern Ireland rivers can be seen.



Client	Consulting Engineer	Project:	Figure Title:	Figure 5.1		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Mean daily discharge for each river dataset	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 10/12/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-2		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Daily river discharge climatology for top 10 Scottish rivers	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 10/12/2014

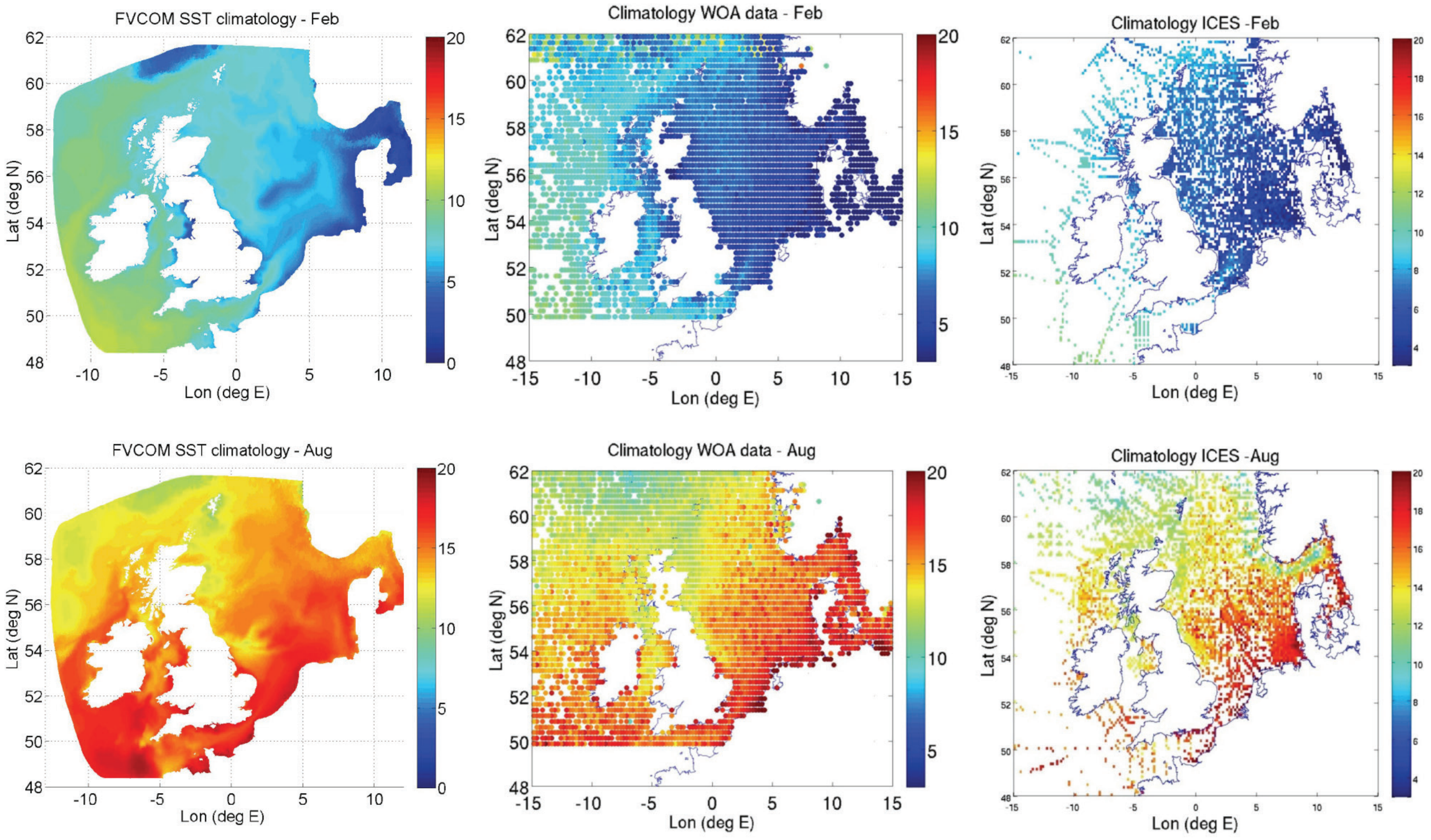
ch2m

5.4 Results and qualitative comparison with ocean atlas data

It can be seen e.g. from Berx and Hughes (2009) that the maximum and minimum of the SST occur in February and August so these months have been used (Figures 5-3 and 5-4) to show the range of the seasonal cycle. The SST shows good agreement with the World Ocean Atlas (2013) data and the ICES data sets. As well as agreement on SST values, local spatial variations and patterns in SST are correctly predicted by FVCOM, such as the warm SST line North of Scotland in February and the localised cooler patch of SST in East Scottish Waters for August.

Surface salinity comparisons are shown in Figure 5-4 for the three climatology representations. Good agreement is shown for salinity with the World Ocean Atlas and ICES data sets and all three give higher salinity in August compared to February for the North Sea region. FVCOM gives slightly lower salinity compared with the atlas data along the shelf edge, however this difference is marginal.

Mean residual currents are shown in Figure 5-5. In Figure 5-6 some comparative data are shown from OSPAR (2000) and Holt and Proctor (2008). These show general agreement for the magnitude and patterns of the residual circulation.



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-3		
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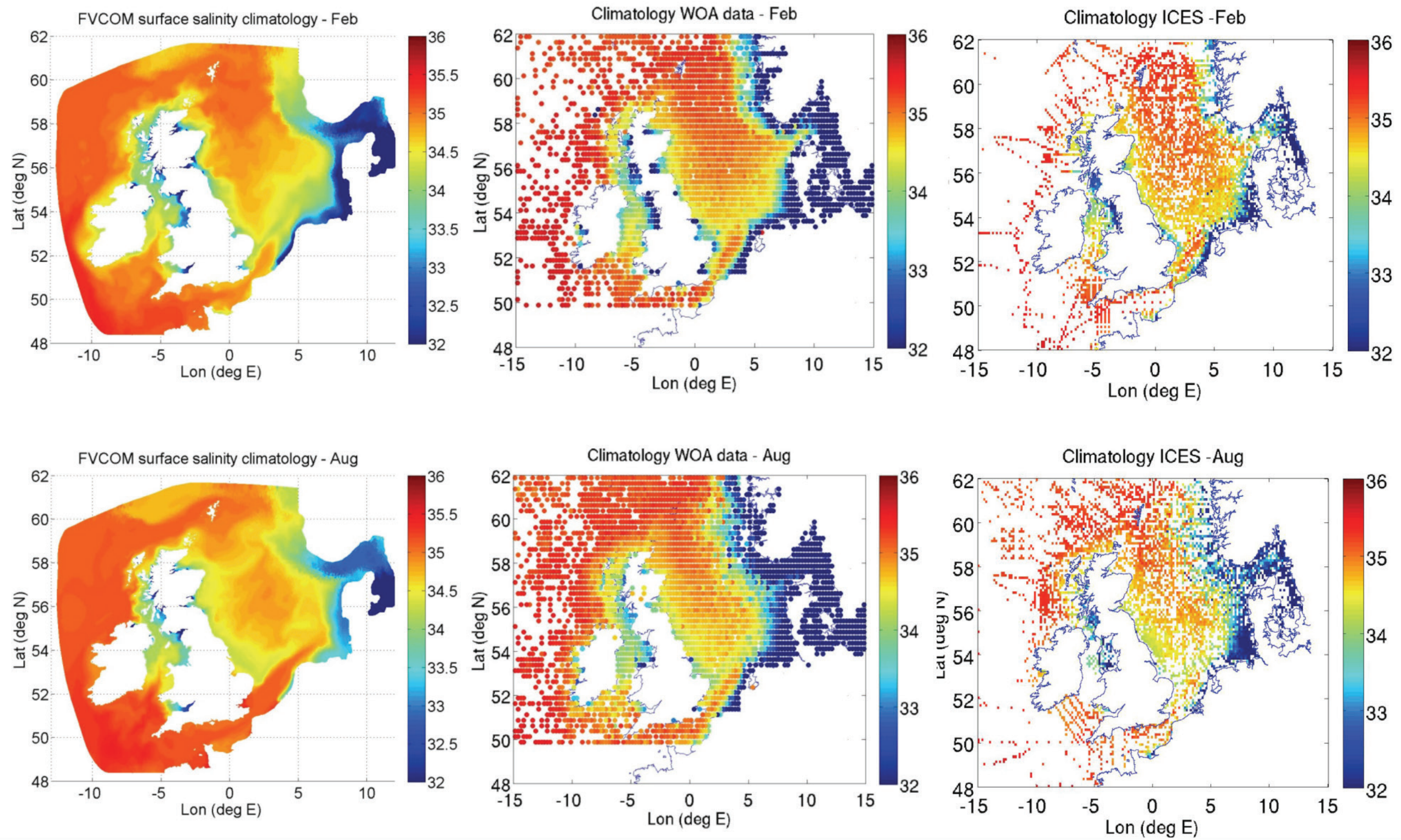
				Designed	Drawn	Date 10/12/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-4		
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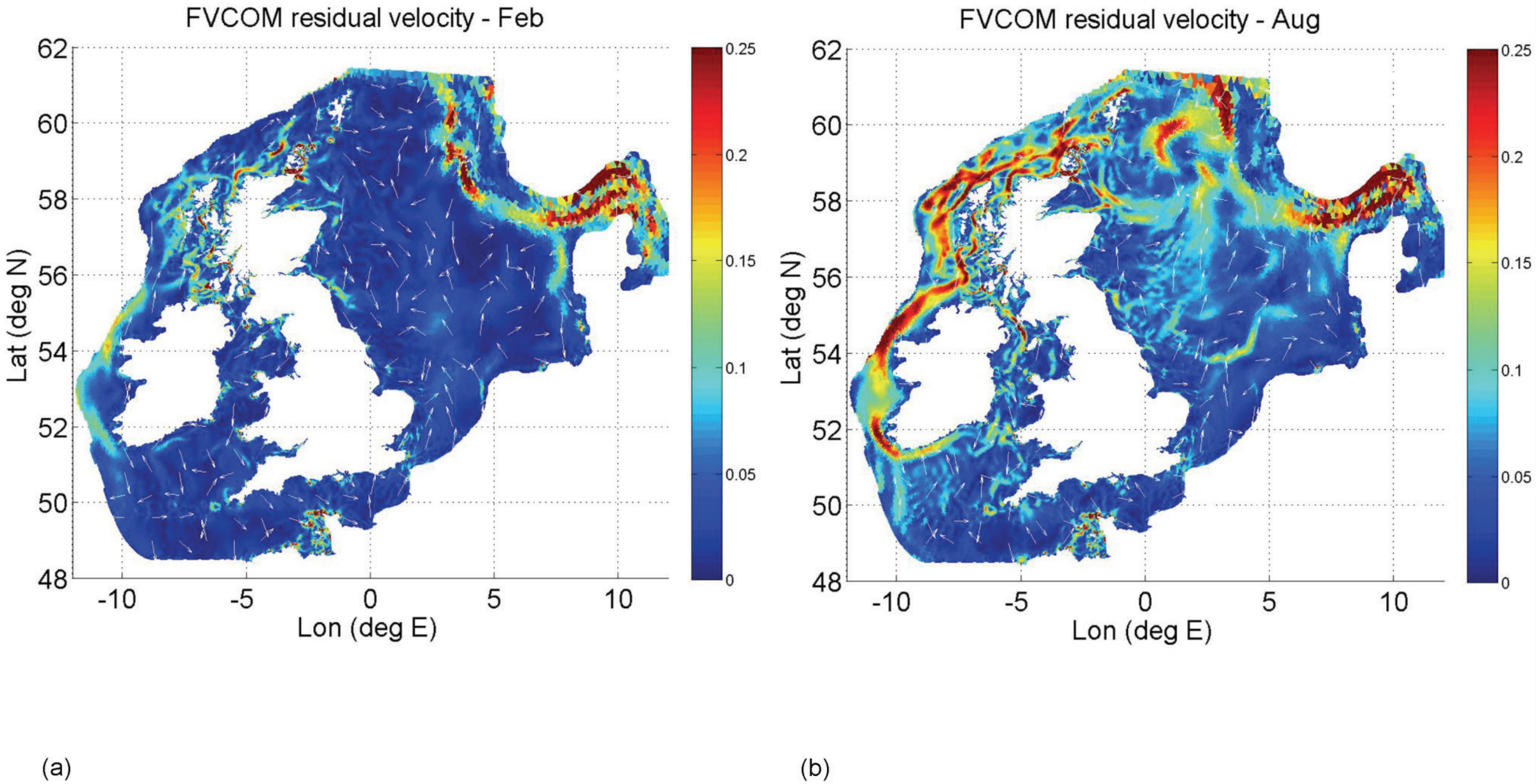
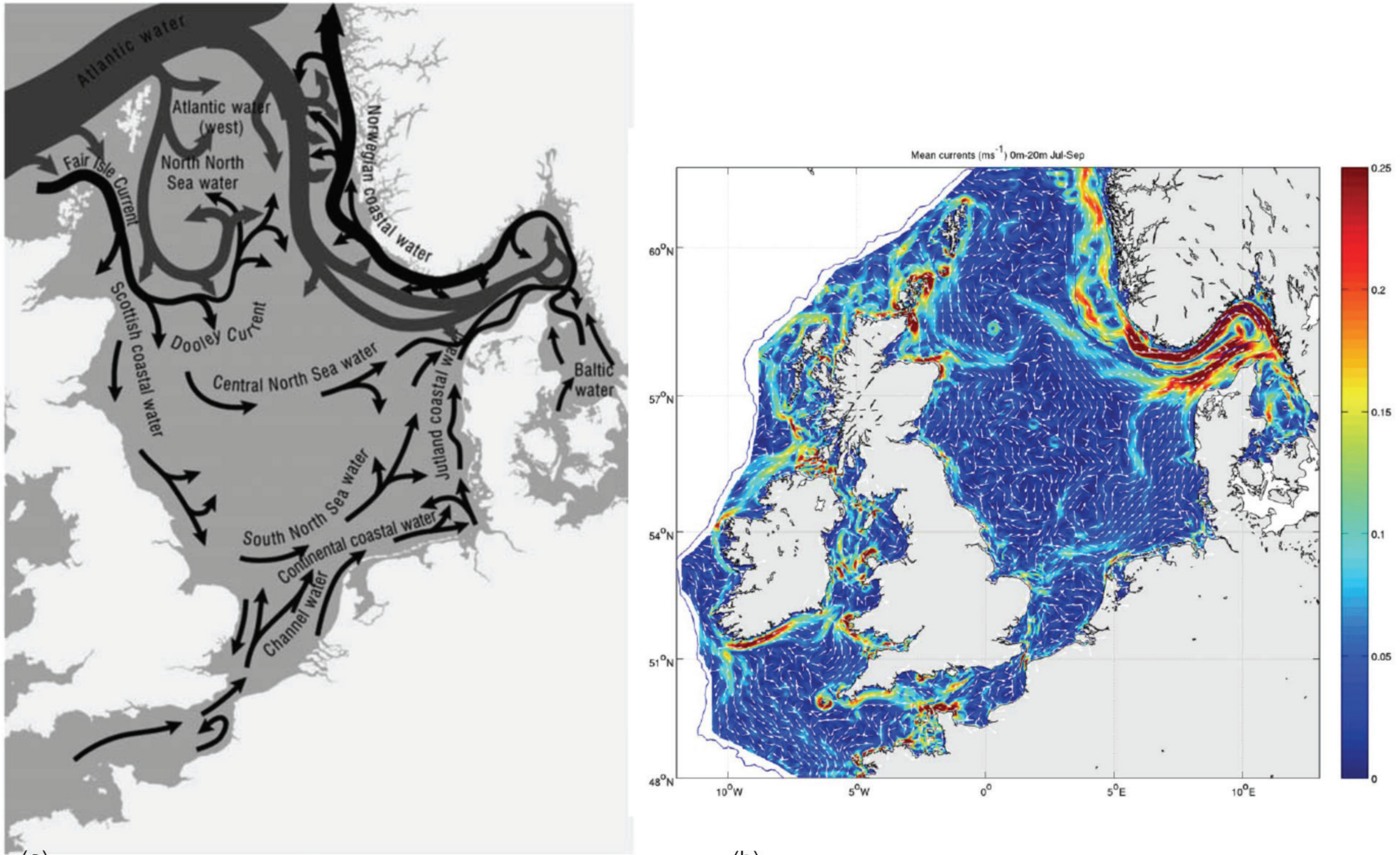
				Designed	Drawn	Date 10/12/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 5-5		
Marine Scotland	ch2m	Scottish Shelf Waters Model	Residual currents from climatology run (a) February (b) August	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 10/12/2014



(a) (b)

Client	Consulting Engineer	Project:	Figure Title:	Figure 5-6		
Marine Scotland	ch2m	Scottish Shelf Waters Model	(a) Canonical circulation on NW European shelf (from OSPAR 2010) (b) Results from Holt and Proctor (2008), July-September	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 10/12/2014

6 Summary and Conclusions

This report describes the process of setting up the Scottish Shelf Waters FVCOM model from the assembling of data sets, through development of a stable grid, implementation of forcing (tidal, meteorological and river discharge), calibration and validation. The calibration period was March - June 2009 inclusive, while the validation has been carried out over the period May 2008 - March 2009.

The model grid has been set up to provide at least 1km resolution around the Scottish coast. The model extends over the whole NW European continental shelf and into the North Atlantic in order to properly represent the tidal regime.

It was found necessary to use the HEATING_CALCULATED option rather than HEATING_ON, within the FVCOM model, in order to get a reasonable evolution of the SST. The sources of met forcing data have been explored, including which variables to download from the Met Office Unified Model output and ERA40/ERA-Interim reanalysis datasets.

The model has then been used to assess the tidal energy resource and, using climatological forcing, the monthly mean circulation pattern. These results have been assessed qualitatively against previously published work and found to be in good agreement.

The most difficult part of the model implementation was to develop a stable grid. In the end, by trial and error and also advice from various sources, including Prof Chen, via CH2M Hill, it was found that the model was sensitive to the connectivity of the mesh (no more than 8 elements must be connected to a single node), steep gradients in bathymetry and issues related to the river forcing. Some smoothing of bathymetry was necessary, near the shelf edge and the Norwegian Trench. At river nodes it was necessary to ensure that the depth was at least 5m in order to ensure that the river inflow could be accepted and propagated into the main body of the model grid.

The model was calibrated by adjusting the number of vertical layers, the bottom friction and the turbulent closure scheme. Validation was carried out by comparison with water surface elevation data, from coastal and offshore tide gauges, current meter data and CTD profiles.

7 Acknowledgements

Thanks are due to members of the FVCOM UK Users Group for sharing their experiences and expertise. In particular we are indebted to Pierre Cazenave at PML for contributing to and sharing the FVCOM toolbox for pre- and post-processing of the model input and output datasets.

8 References

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