The Scottish Shelf Model. Part 4: East Coast of Lewis and Harris Sub-Domain

Scottish Marine and Freshwater Science Vol 7 No 6

D Price, C Stuiver, H Johnson, A Gallego, R O' Hara Murray

The Scottish Shelf Model. Part 4: East Coast of Lewis and Harris Sub-Domain

Scottish Marine and Freshwater Science Vol 7 No 6

D Price, C Stuiver, H Johnson, A Gallego, R O' Hara Murray

Published by Marine Scotland Science

ISSN: 2043-7722
DOI: 10.7489/1695-1

Marine Scotland is the directorate of the Scottish Government responsible for the integrated management of Scotland's seas. Marine Scotland Science (formerly Fisheries Research Services) provides expert scientific and technical advice on marine and fisheries issues. Scottish Marine and Freshwater Science is a series of reports that publishes results of research and monitoring carried out by Marine Scotland Science. It also publishes the results of marine and freshwater scientific work that has been carried out for Marine Scotland under external commission. These reports are not subject to formal external peer-review.

The Scottish Shelf Model. Part 4: East Coast of Lewis and Harris sub-domain

Marine Scotland

04 Sep 2015

City Park, 368 Alexandra Parade, Glasgow, G31 3AU
tel 0141 552 2000
fax 0141 552 2525

Document history

The Scottish Shelf Model. Part 4: East Coast of Lewis and Harris sub-domain

Marine Scotland

This document has been issued and amended as follows:

Version	Date	Description	Created by	Verified by	Approved by
1.0	15/03/2013	Draft report including only data review section.	Maurice McCabe, Fiona McLay, Darren Price		
1.1	19/03/2014	Extra calibration data added	Caroline Stuiver		
1.2	20/10/2014	Model calibration section added	Darren Price		
1.3	25/02/2015	Climatology set up and results section added	Caroline Stuiver		
1.4	17/4/2015	Summary and Conclusions	Darren Price		
1.5	30/6/2015	Final version Includes general editorial changes	Caroline Stuiver	Hakeem Johnson	John Debenham
1.6	04/09/2015	Minor changes based on comments from Marine Scotland.	Caroline Stuiver	Hakeem Johnson	John Debenham

The Scottish Shelf Model. Part 4: East Coast of Lewis and Harris sub-domain.

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

Acknowledgements:

The Scottish Shelf Model (SSM) contract was funded by the Scottish Government.

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 Fiona McLay, Maurice McCabe, Ilektra Apostololidou and Elysia Ward (CH2M HILL).

The Grid2Grid freshwater runoff data were supplied under contract by the Centre for Ecology and Hydrography. We would like to thank Robert Moore and his colleagues at CEH for those data.

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

Contents

Abbreviations

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

Abbreviation	Meaning
MRV	Marine Research Vessel
MS	Marine Scotland
MSL	Mean sea level
NGDC	National Geophysical Data Centre
NOAA	US National Oceanic and Atmospheric Administration
NOC-L	National Oceanography Centre - Liverpool
NODB	National Oceanographic Database
NOOS	Northwest European Shelf Operational Oceanographic System
NTSLF	National Tide and Sea Level Facility
ODYSSEA	Ocean Data analYsis System for SEA
OS	Ordnance Survey
PFOW	Pentland Firth and Orkney Waters
SEPA	Scottish Environment Protection Agency
SSS	Sea surface salinity
SST	Sea surface temperature
UKHO	United Kingdom Hydrographic Office
WOA	World Ocean Atlas
WVS	World Vector Shoreline

1 Introduction

1.1 Background

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

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

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

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

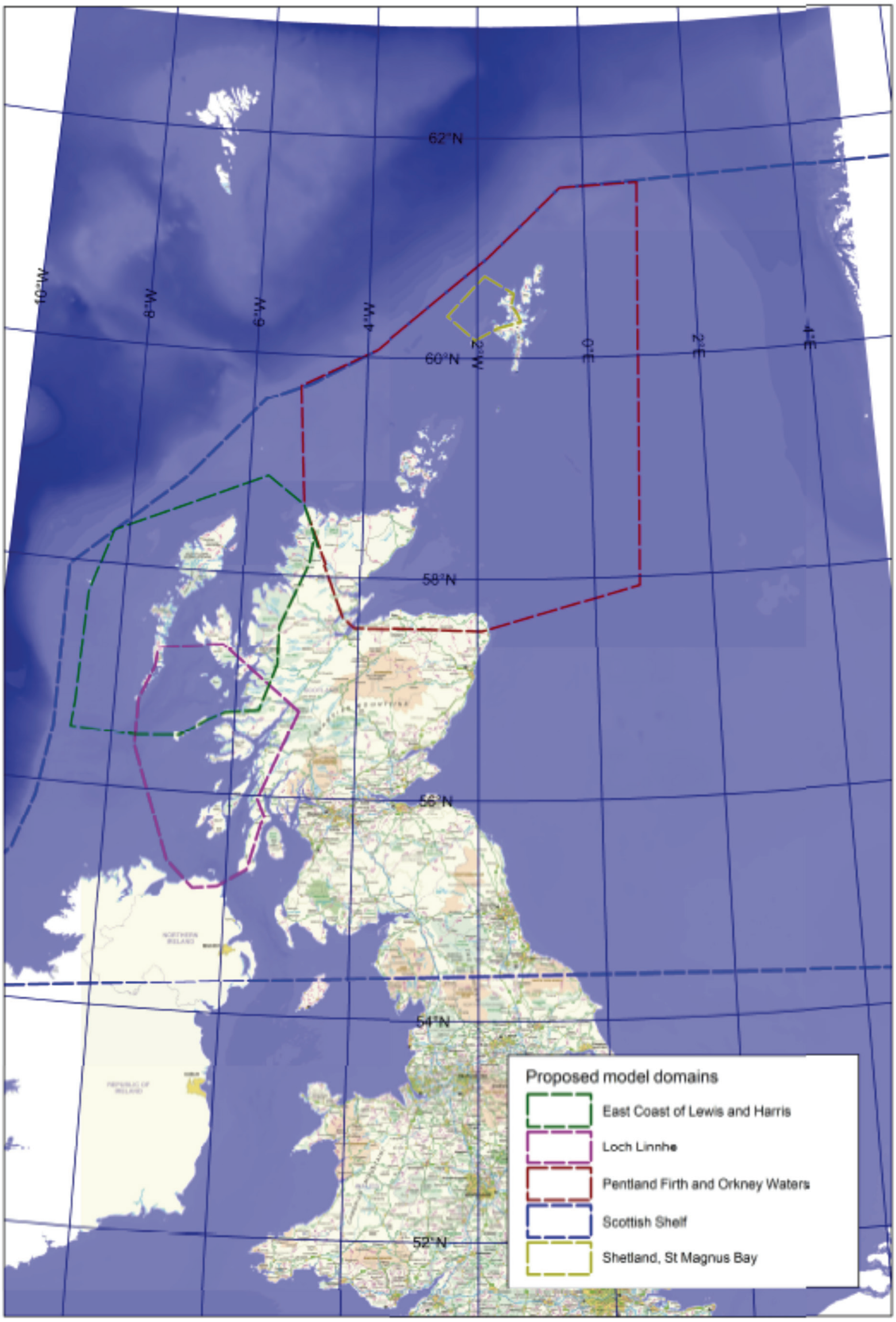
1.2 Study areas

The overall study area includes all of the Scottish shelf waters out to the 200m depth contour at the edge of the continental shelf. A Scottish shelf waters model covering this study area was 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 were 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
Case Study 2:	Wider Loch Linnhe System
Case Study 3:	East Coast of Lewis and Harris (ECLH)
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	East Coast Lewis and Harris Model	Location of the Shelf and individual case study model domains

1.3 Aims and scope of numerical modelling works

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

The modelling 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 (only in the Pentland Firth and Orkney Waters). It also includes 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., 2013). One of the reasons behind the choice of this modelling software is that the models developed in this project will be freely available to others at the end of the Project. Marine Scotland have a vision that the models will be used and developed further by Marine Scotland staff and the marine modelling community as more data becomes available and/or other needs are identified.

1.4 Project Team

The project team for 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 sea lice and the development of connectivity indices.

1.5 This Report

This report documents the work carried out in developing the East Coast of Lewis and Harris (ECLH) 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 ECLH area.

This report is Volume 1 of the ECLH model report. A companion volume (Volume 2 – Model Documentation Report for ECLH) 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 are used in this study:

- All horizontal co-ordinates are referenced to latitude and longitude.
- All vertical levels are relative to MSL.

1.7 Acknowledgments

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

- Marine Scotland (Alejandro Gallego, Rory O'Hara Murray and George Slesser) for providing, requesting and collecting available data.
- UKHO for the bathymetry datasets
- 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 was 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.
- 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) was 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 East Coast of Lewis and Harris (ECLH), the following data have been collated:

- 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 for the East Coast of Lewis and Harris (ECLH) 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 have been obtained for use in this study the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) distributed by National Geophysical Data Centre (NGDC) in the US, and Ordnance Survey Mapping.

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

The Ordnance Survey (OS) Vector Map District contains tidal boundary polylines, which are at Mean High Water Spring level (MHWS) in Scotland and MHW in England and Wales. The GSHHS data is 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.

2.2.2 Global/Regional Gridded Data Sets

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

2.2.2.1 General Bathymetric Chart of the Oceans (GEBCO)

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

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

Figure 2-1 shows the GEBCO_08 bathymetry for the British Shelf and the source of the data. The discontinuity at 0°E and the grid pattern in the North Sea are clearly visible although this does not affect this model.

2.2.2.2 ETOPO-1

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

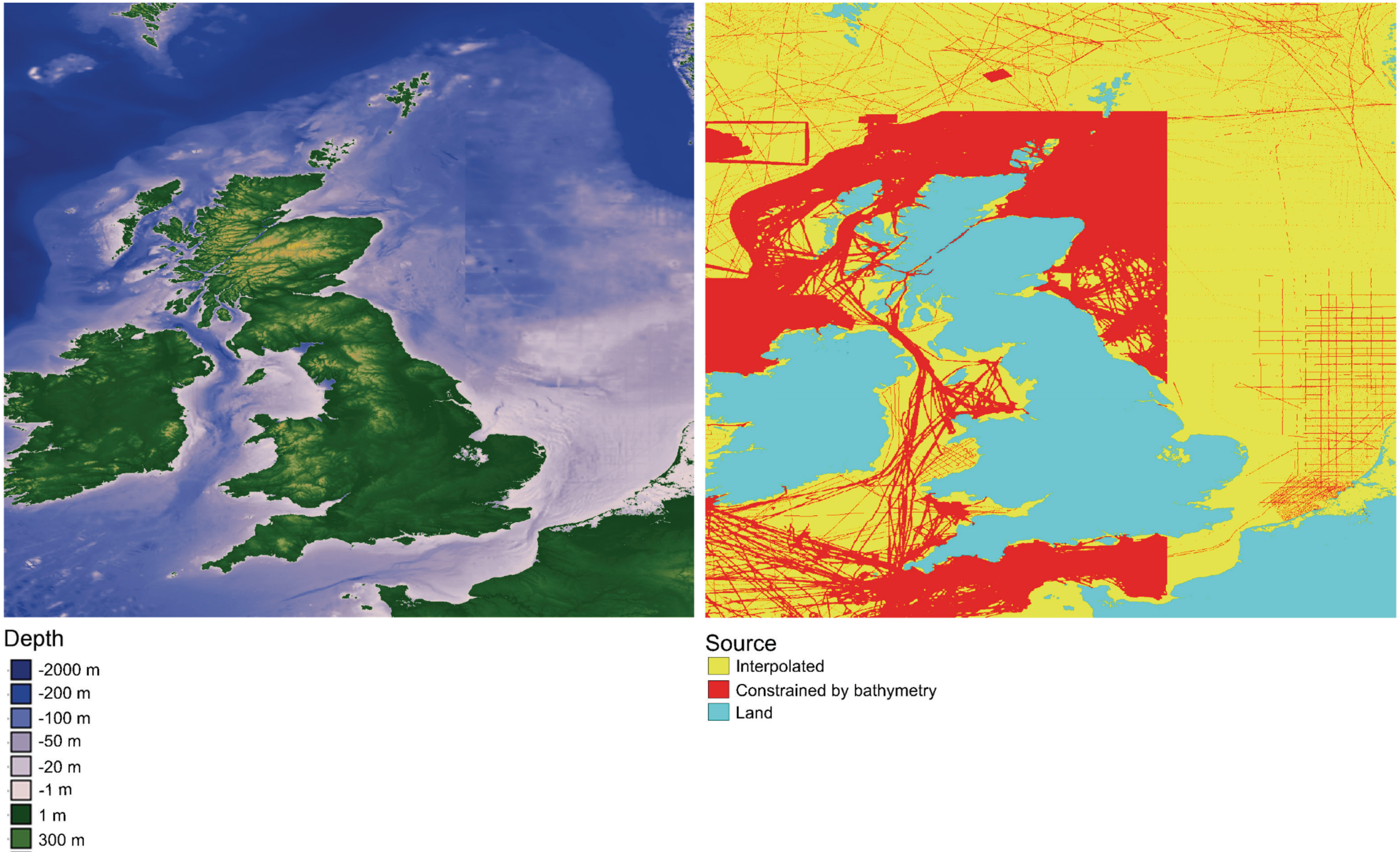
2.2.2.3 European Marine Observation and Data Network (EMODnet)

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

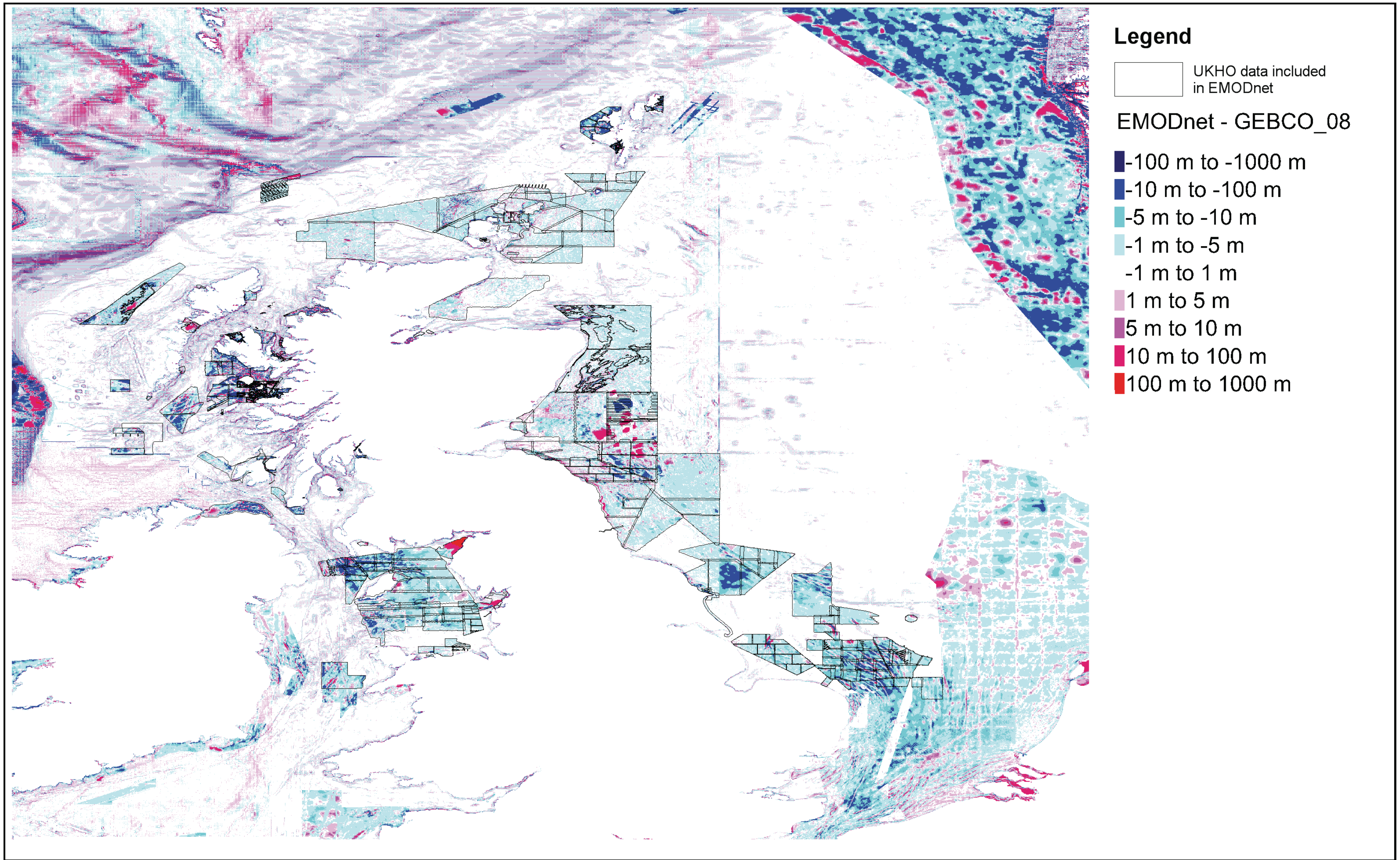
Further details of EMODnet are provided in Halcrow (2012).

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

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



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-1		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Data sources used in the GEBCO data set.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012



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

2.2.3 Hydrographic Data

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

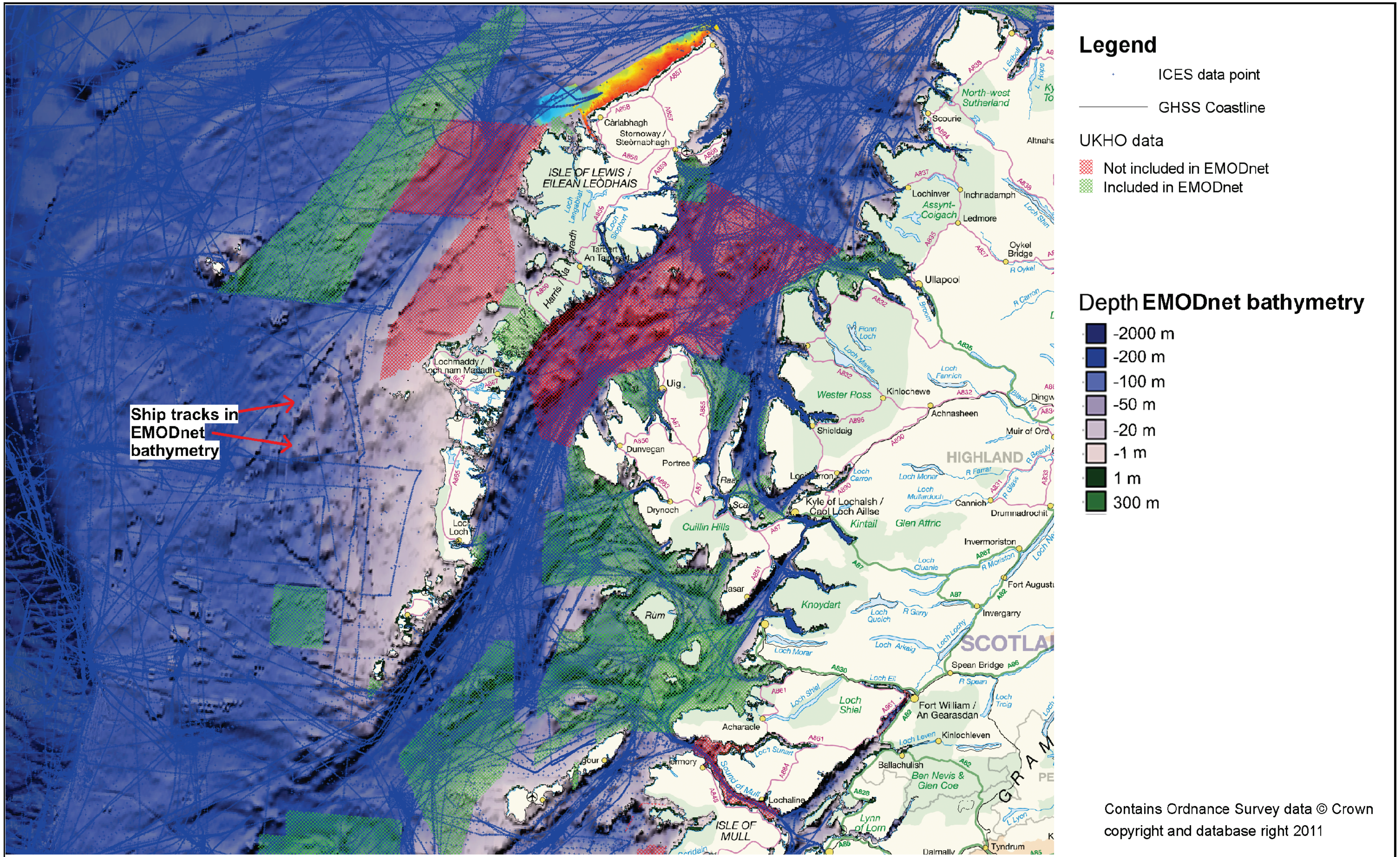
The UKHO have a memorandum of understanding with Marine Scotland making their high resolution bathymetric survey available. Most of these data have already been incorporated into the EMODnet bathymetry, however further data has since become available. The location of the UKHO data in the vicinity of the ECLH model domain is shown in Figure 2-3 where it has been indicated on top of the EMODnet data.

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

2.2.4 NOOS 1.0

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

After consideration of this data and comparison against other datasets (Halcrow, 2012) it was concluded that the NOOS bathymetry should not be used west of 0°E and has therefore not been used for the ECLH model.



Client	Consulting Engineer	Project:	Figure Title:	Figure 2-3		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Available bathymetry for the East Coast of Lewis and Harris.	Checked DMP	Scale Not to scale	Rev. 0
				Designed FML	Drawn	Date 14/112012

ch2m

2.2.5 Other data sources

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

2.2.6 Summary of bathymetry data availability for the East Coast of Lewis and Harris Area

Figure 2-3 shows data availability for the east coast of Lewis and Harris model. High resolution bathymetric survey is available for the east coast of the islands with the exception of the section between the Point of Ness and Stornoway. There are numerous soundings in the ICES database in this region, and the area is covered by Admiralty Charts. The GEBCO_08 bathymetry in this region is mainly derived from soundings, and is more likely to be accurate based on comparisons with other areas where UKHO data is available. ICES sounding data and Admiralty Charts should be used to increase the resolution between Point of Ness, Stornoway and the mainland above that in the EMODnet bathymetry.

For the wider model the UKHO data has not yet been incorporated in the EMODnet bathmetry for the area between Lewis and the mainland and the area between Lewis and the St Kilda and the bathymetry is largely GEBCO_08. West of Benbecula, South Uist, Barra and Mingulay few observations are incorporated into the GEBCO_08 bathymetry. Where ship soundings have been used ship tracks are clearly visible in the GEBCO_08/EMODnet bathymetry. As an example, the bathymetry is approximately 30m (50%) lower west of South Uist where the ship tracks are present than where the bathymetry is based on interpolation (compare with Figure 2-2). The planned Civil Hydrography programme survey of Barra should significantly improve accuracy of the bathymetry in this area, however these data were not available within our programme.

Use of the EMODnet bathymetry where it is derived from the GEBCO_08 grid is not appropriate for the area west of Noth Uist to Mingulay. Therefore digitised Admiralty Chart data were used and ICES depth soundings were used to adjust the GEBCO_08 data in this region.

To summarise, there appears to be reasonable coverage to the east of Lewis and Harris however this does not necessarily completely cover the shallower nearshore areas (UKHO and ship tracks). For example, ship tracks cover the lochs of interest (Lochs Erisort, Ouirn, Shell, Seaforth, Scalpay and East Loch Talbert) where Farm Management Areas (FMA) exist, but do not cover them in their entirety in shallower areas. There are little survey data to the west and southwest of Uist. Additional bathymetry data was digitised from Admiralty Charts in areas of interest and close to the shore where higher resolution was required and not available in the existing data.

2.3 Forcing Data

2.3.1 Introduction

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

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

2.3.2 Meteorological forcing

2.3.2.1 UK Met Office Model Data

Two data streams from the Met Office forecast models have been archived at NOC (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 Irish Sea Observatory operational modelling system, running the 3d baroclinic hydrodynamic model, POLCOMS, on (i) the Atlantic Margin Model (AMM, ~12km) and (ii) the nested Irish Sea model (IRS, ~2km). The data comprise the following, from 2004 to 2007 with some gaps, and continuously from 2007 to 2011, all at 12 km resolution:
    - Global model output for the Atlantic at 6-hour intervals – 10m wind (E and N components); sea level pressure; low, medium and high level cloud coverage; specific humidity at 1.5m, air temperature at 1.5m; total accumulated precipitation; sensible heat flux

- Mesoscale model output at 3-hour intervals – same variables

2.3.2.2 Climatological Forcing

Climatological forcing was derived from the ERA40 and ERA-Interim datasets, which were used to force the POLCOMS AMM (~12km) model for the 45 year hindcast (1960-2004). See Wakelin et al. (2012) and Holt et al., (2012). A licence to use these data has been provided by the European Centre for Medium range Weather Forecasting (ECMWF) for this study. A one-year climatological forcing for the temperature and salinity (i.e. heat flux and precipitation) has been derived. A detailed description of the methodology used to derive the climatology forcing is provided in the Scottish Shelf Waters Model report (Wolf et al. 2015).

2.3.3 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 output that CEH provided from the G2G model were:

1. Provision of river discharge data (time series data) at all coastal locations in Scottish waters with the G2G model. The data was 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 with the G2G model. The data was 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 with the G2G model. Daily averaged data was provided, the averaging period covered 1962-2011.

2.3.4 Tide

For the ECLH Model, the boundary data was derived from NOC-L's Atlantic Margin Model (AMM) with a 12km resolution. Water levels along with temperature and salinity timeseries were applied at the model boundaries for specific periods coincident with times that calibration data is available. Climatological runs were forced using shelf model climatology results whose boundary conditions were taken from the results of POLCOMS model hindcast from 1960-2004, which was run on the AMM 12km grid. This is 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 Calibration Data

2.4.1 Introduction

Model calibration was undertaken against observation datasets for periods of up to 1 month. Calibration is required for water level, currents, temperature and salinity. In addition validation is required for the 6 month 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 ECLH region. These come from three main sources: tide gauge data from the BODC National Oceanographic Database (NODB); bottom pressure data from the NODB, and analysed tidal data from NOC.

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 2-5. Because these data are based on harmonic analyses, water level estimates for any past or future date are obtainable, or via the use of constituents from the Admiralty tide tables. All available water level data available post year 2000 are shown in Figure 2-6.

2.4.3 Currents

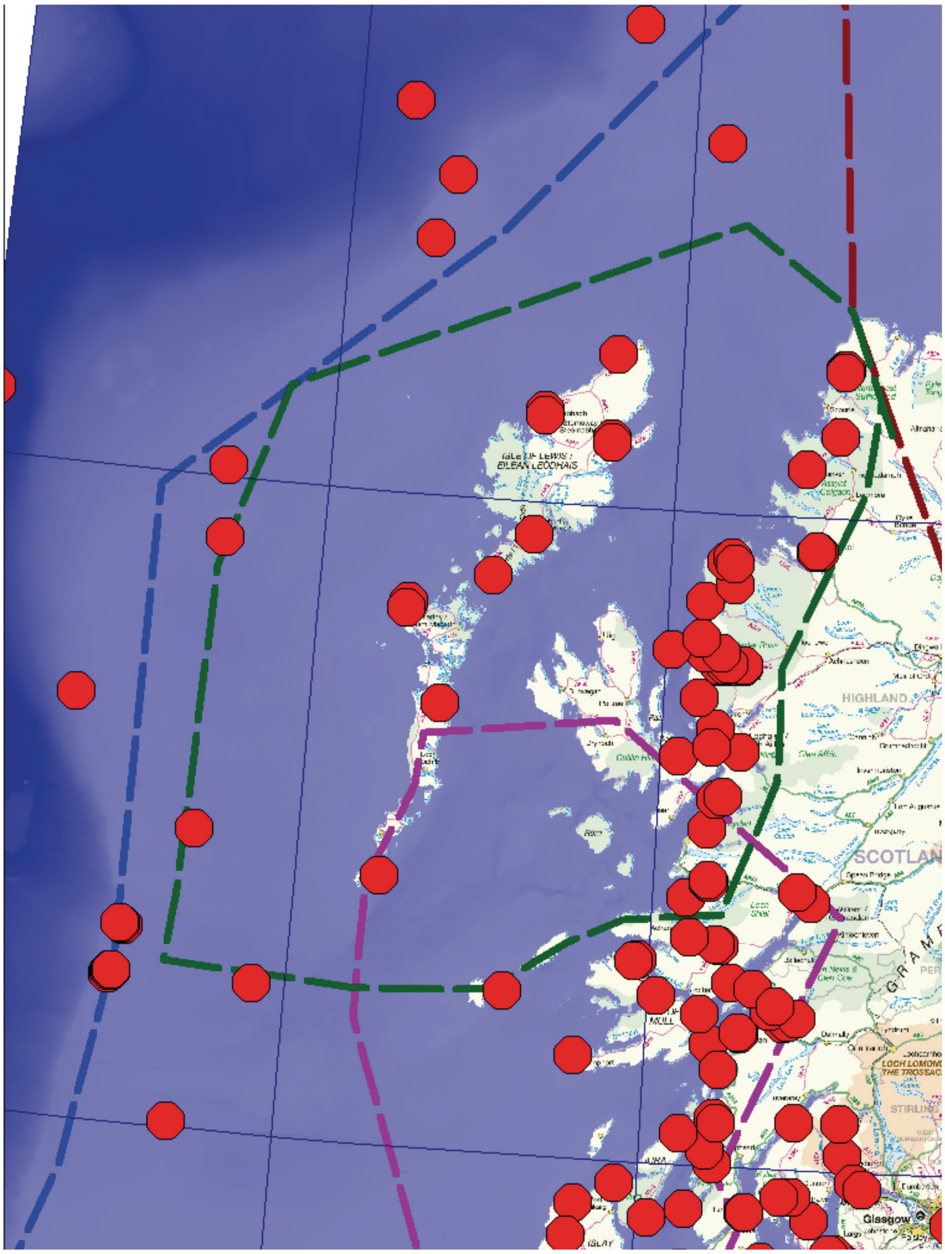
Datasets on currents have been found from a number of sources; all locations are shown in Figure 2-7. These come from the BODC National Oceanographic Database (NODB) and the TotalTide software, from UK Hydrographic Office. As Figure 2-8 shows, there are only a few datasets from the BODC National Oceanographic Database since year 2000. In some cases, vertical current profiles are available; these are shown in Figure 2-9.

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.

Direct measurements of current speed and direction at a number of fish farms are available within the area of interest, i.e. the east coast of

Lewis and Harris (Figure 2-11). Not all of these data set were suitable to use for calibration purposes, being in shallow water or outside of the calibration period. The data set selected for calibration purposes at 13 sites are shown in Figure 2-12 along with information on the sampling period and location. Two of the sites selected are not associated with fish farms and the measurements were made by Marine Scotland at the request of Halcrow, these are LMSL (Little Minch Seaforth Loch) and LMO (Little Minch Offshore), taken at the mouth of Seaforth Loch and Offshore of Seaforth Loch respectively.

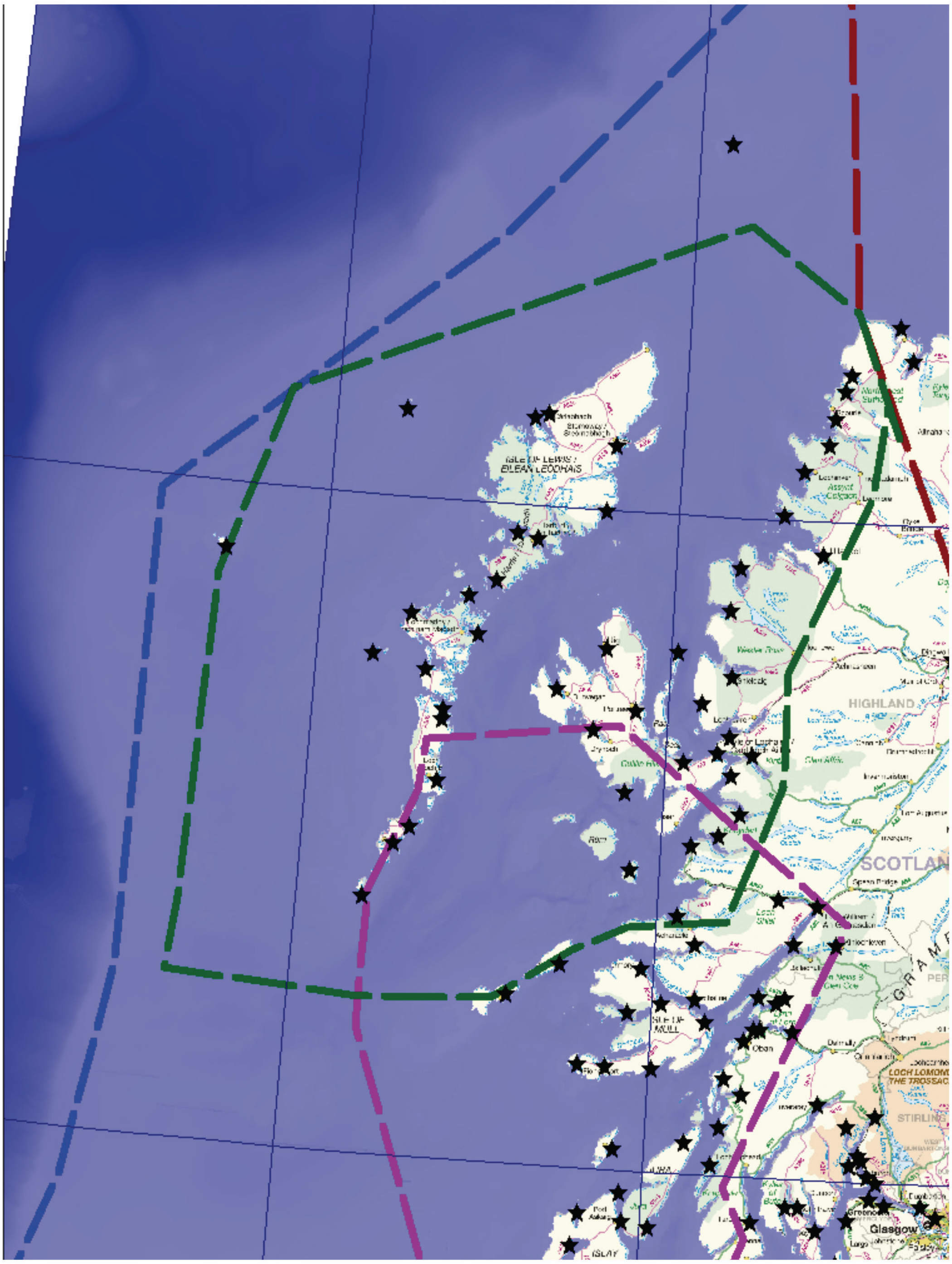


● Locations of water level observations

Proposed model domains

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

Client	Consulting Engineer	Project:	**Figure 2-4**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Water level observations within the ECLH model domain



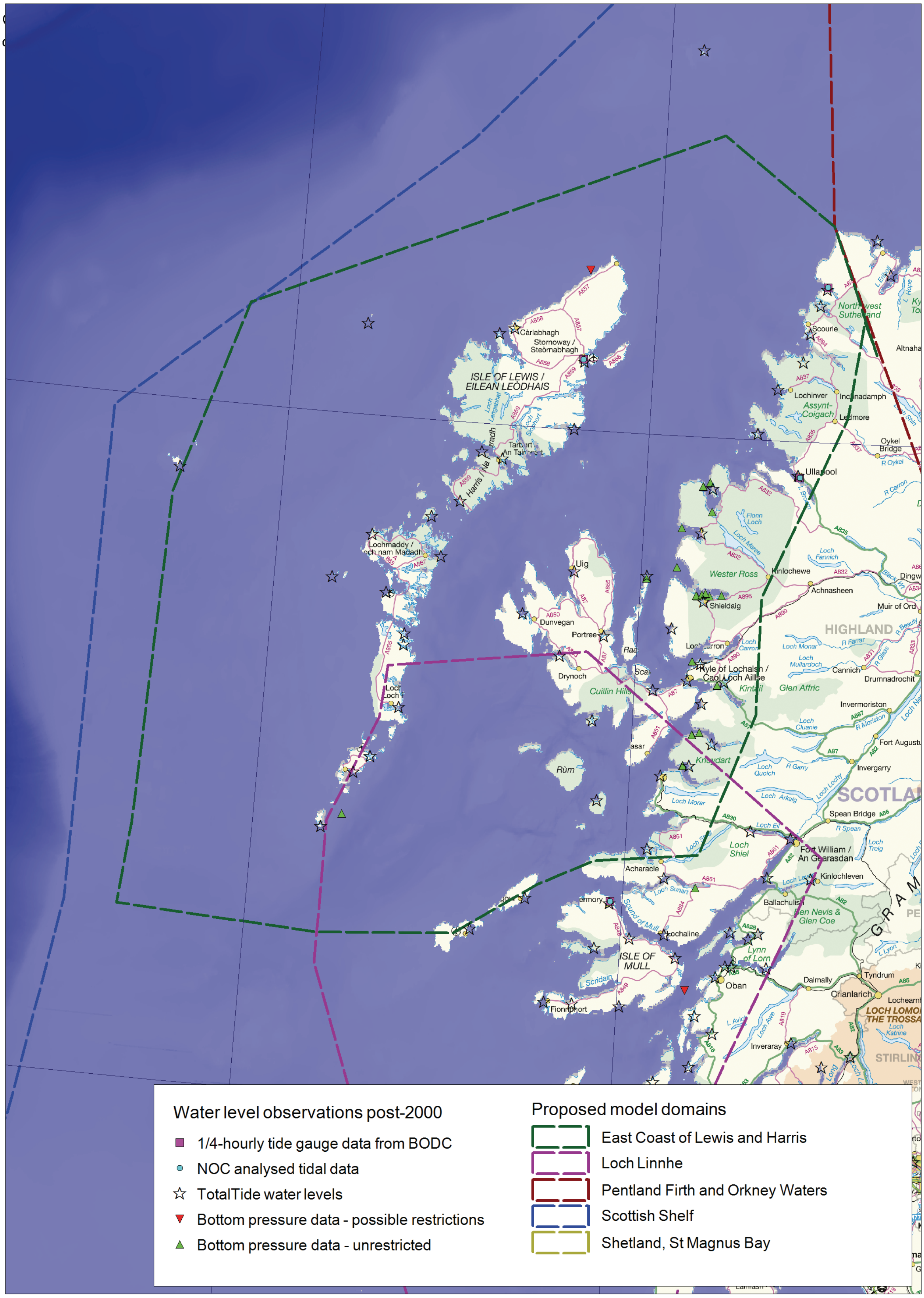
Water level observations

★ TotalTide water levels

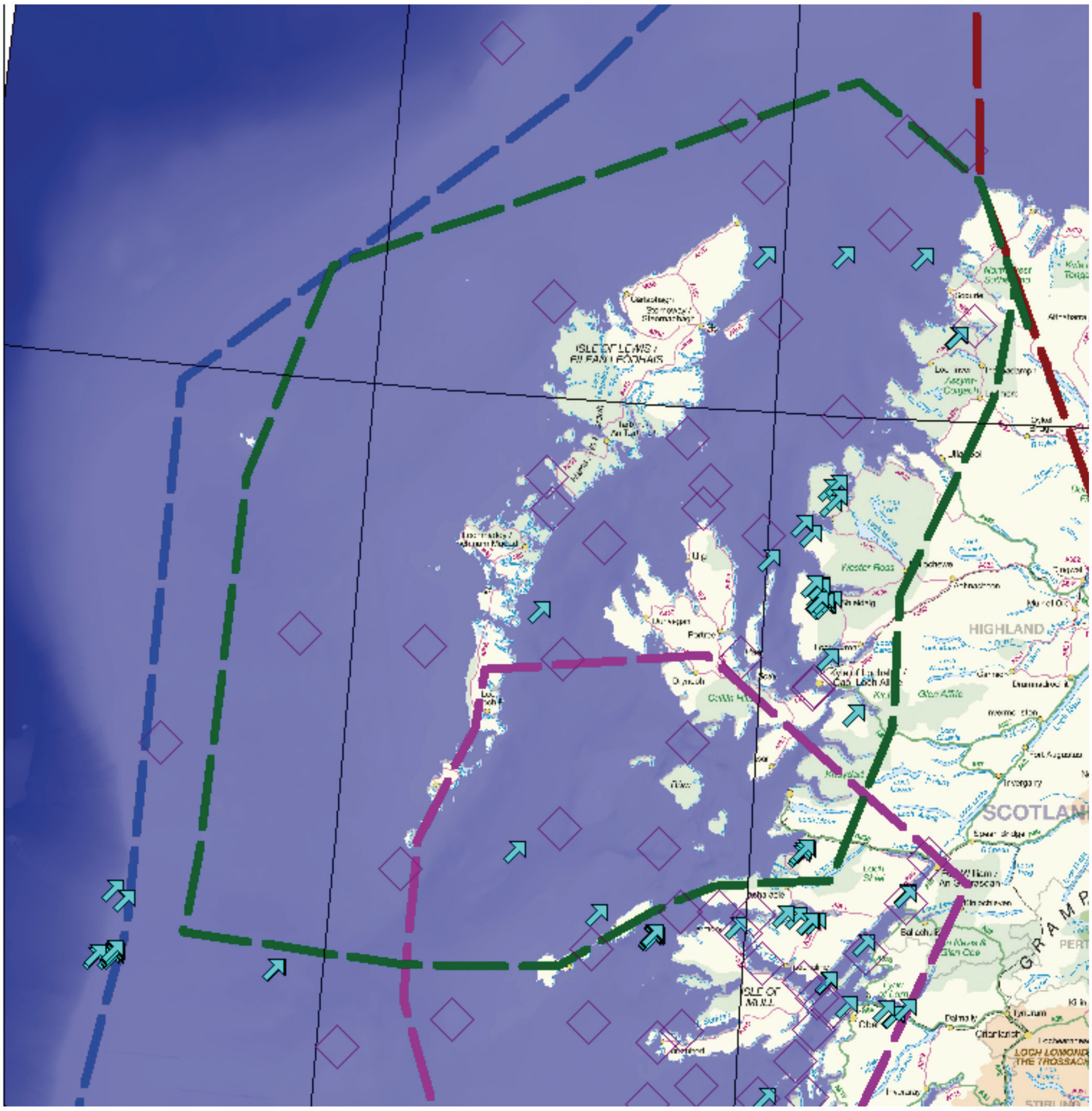
Proposed model domains

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

Client	Consulting Engineer	Project:	Figure 2-5
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Total-tide water level locations



Client	Consulting Engineer	Project:	Figure 2-6
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Post-2000 water level observations in the Lewis and Harris area



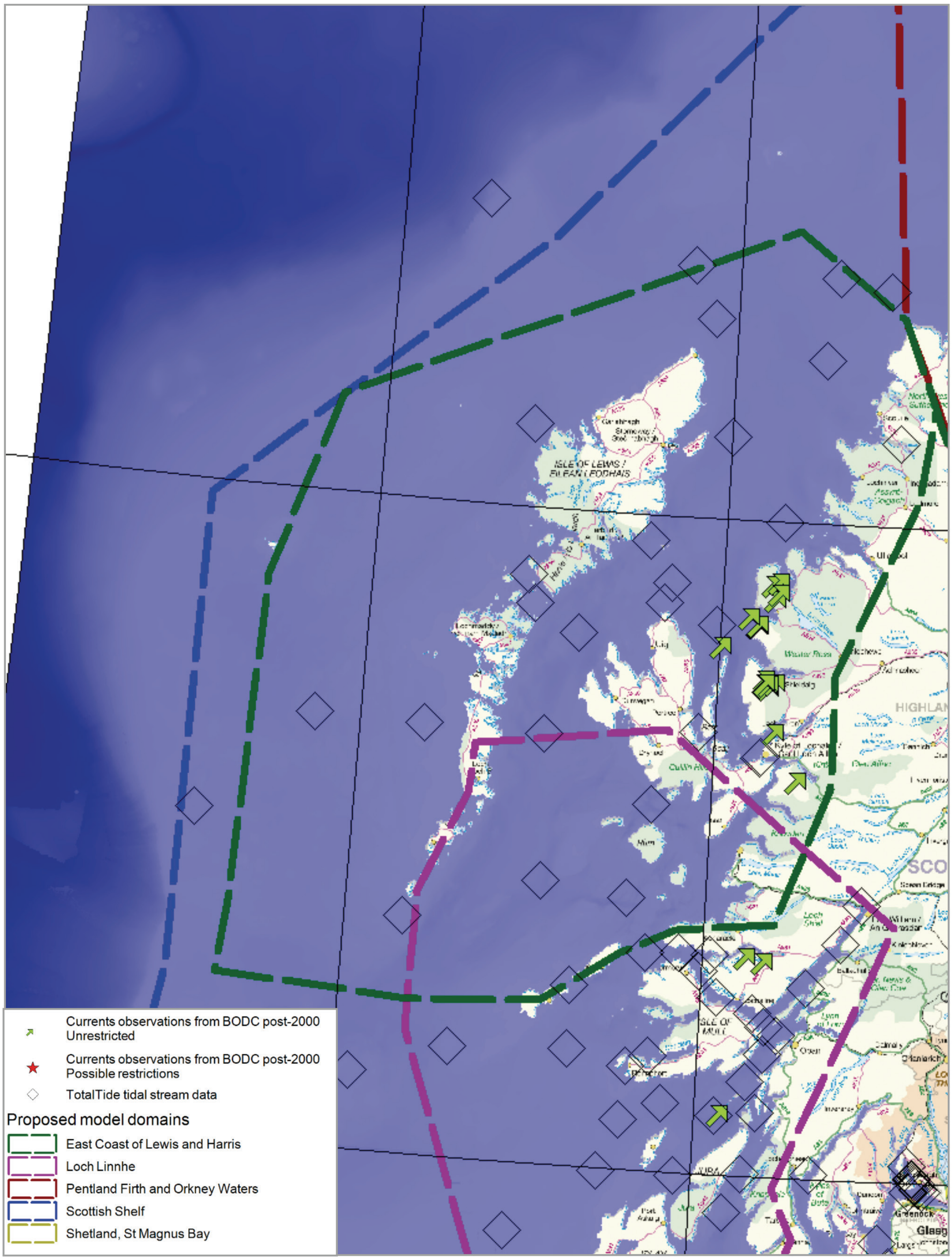
◇ All TotalTide locations

↗ All current observations

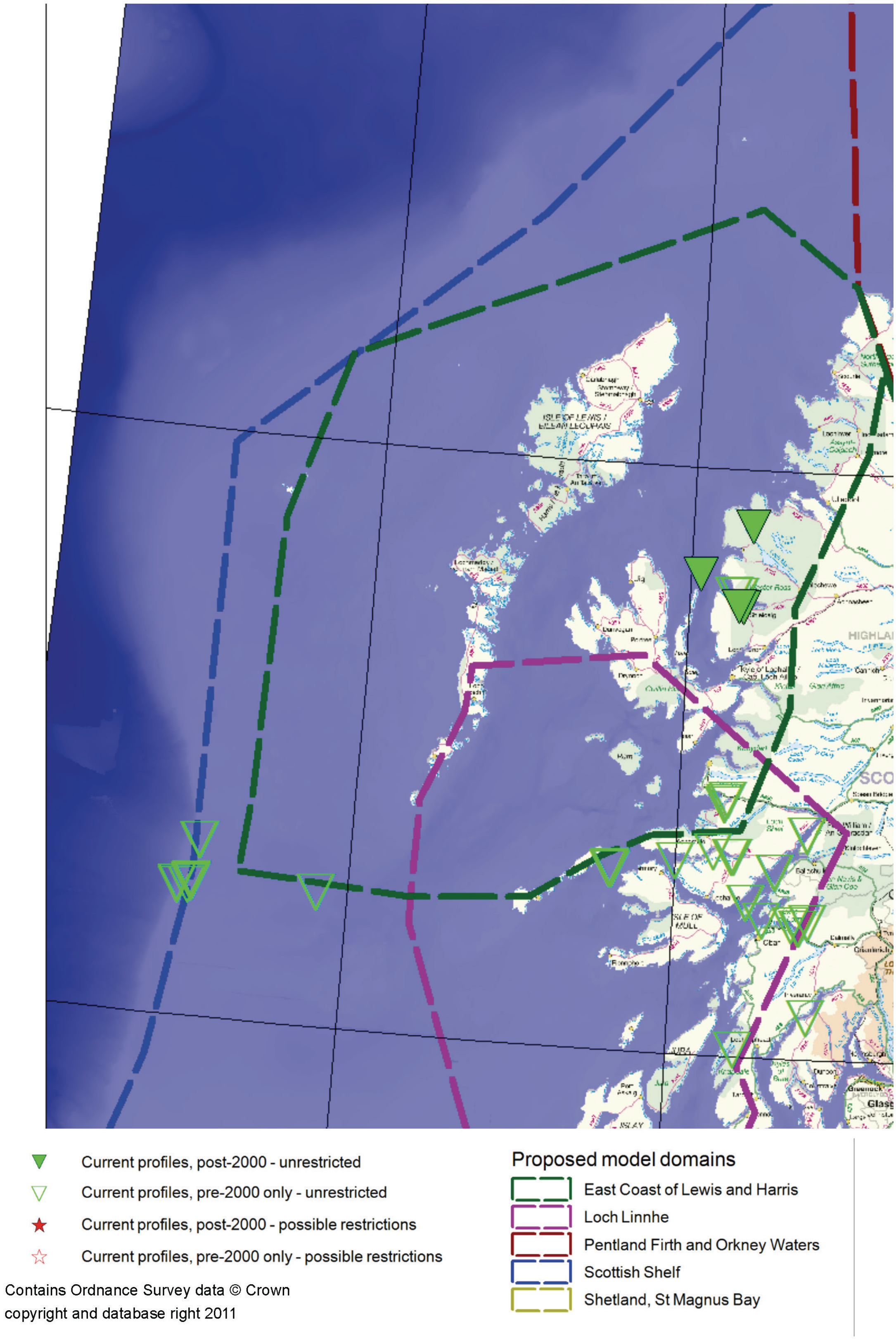
Proposed model domains

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

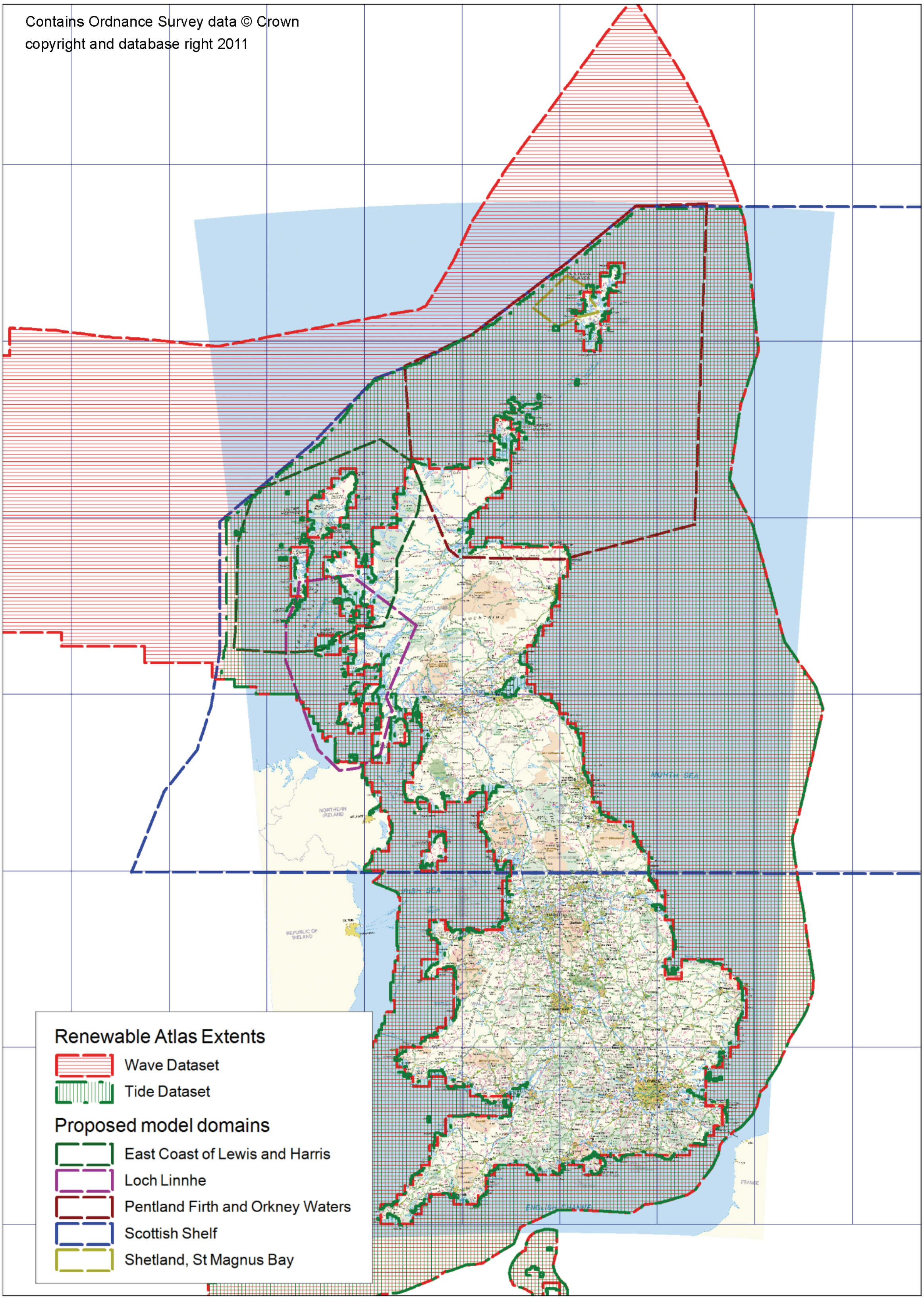
Client	Consulting Engineer	Project:	Figure 2-7
Marine Scotland	ch2m	East Coast Lewis and Harris Model	All current observations and TotalTide tidal stream locations



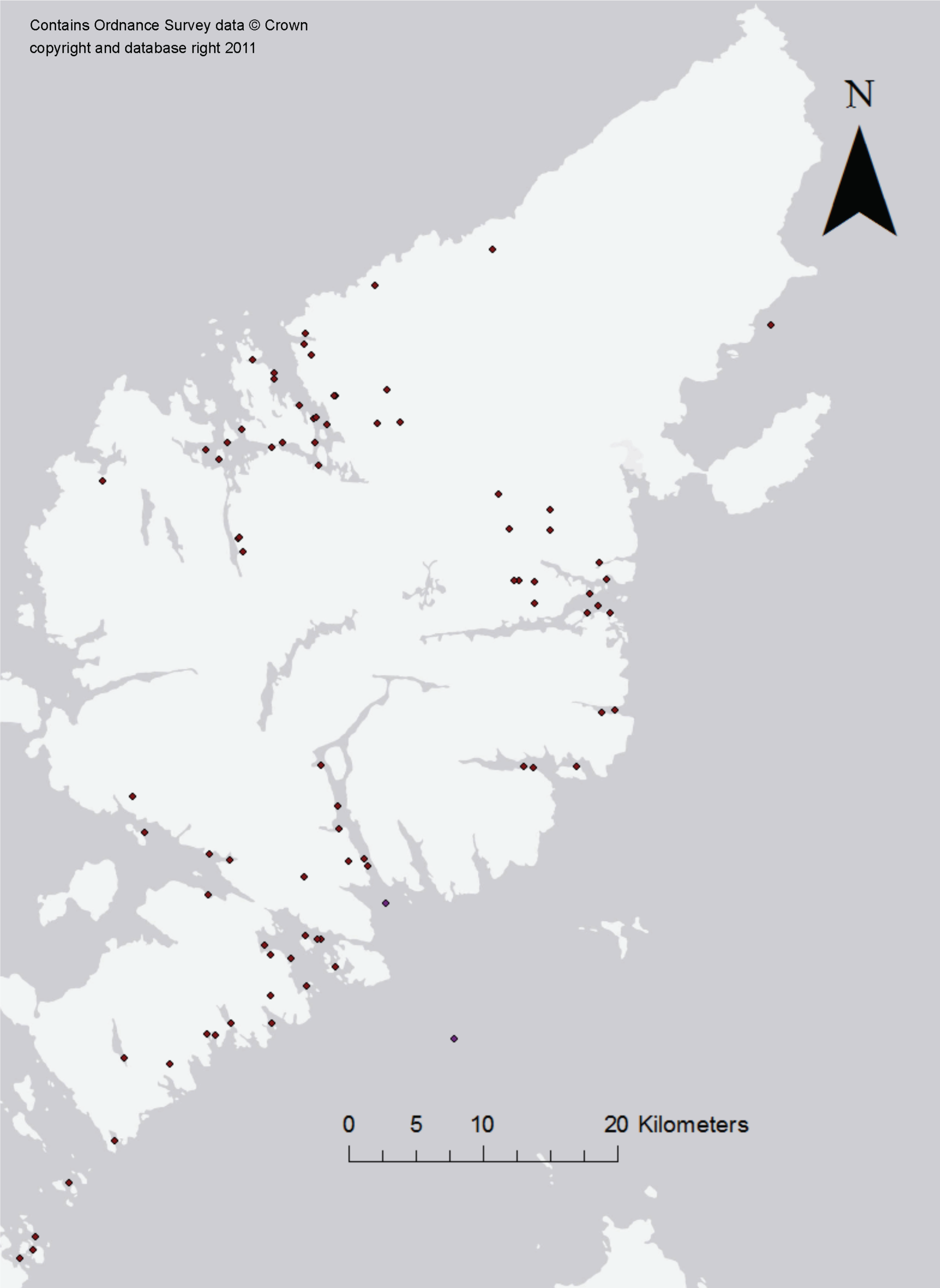
Client	Consulting Engineer	Project:	Figure 2-8
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Post-2000 current observations in the Pentland Firth and Orkney Waters



Client	Consulting Engineer	Project:	Figure 2-9
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Pre and Post-2000 current profiles



Client	Consulting Engineer	Project:	Figure 2-10
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Wave and tidal domains from the Renewables Atlas



Client	Consulting Engineer	Project:	Figure 2-11
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Location of all available current data at fish farms around Lewis and Harris

Selected Fish Farm Current Data + Additional Little Minch Data

Code	Location	Easting	Northing	Data available
CED1	Ceann Dibig	115500	897100	13/10/02 – 28/10/02
GRO1	Grosebay	115970	891250	23/04/10 – 08/05/10
NOS1	Noster	122840	903480	10/02/05 – 25/03/05 25/10/10 – 09/11/10
ODH1	Gravir Outer	141400	914500	05/06/04 – 19/06/04
PEC3	Sgeir Bhuidhe	140200	922230	01/02/06 – 16/02/06
PLOC1	Plocrapol	118600	894000	20/10/05 – 03/11/05.
ROS1	Rossay	120700	895500	03/08/07 – 18/08/07
SEA5	Seaforth	123080	902960	02/05/05 – 17/05/05 24/09/10 – 09/10/10
SOAY1	Soay Sound	106600	905400	04/11/04 – 19/11/04
TOL1	Toa Tolsta	153000	943000	07/07/09 – 22/07/09
TRM1	Trilleachan Mor	120870	907360	18/06/05 – 03/07/05
LMSL	Seaforth Loch Mouth	124444	890140	17/05/13 – 19/05/13
LMO	Offshore	129513	900136	17/05/13 – 19/05/13

Client	Consulting Engineer	Project:	Figure Title:	Figure 2-12		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Data selected for calibration purposes, map shows locations and table shows dates data is available	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 14/112012

ch2m

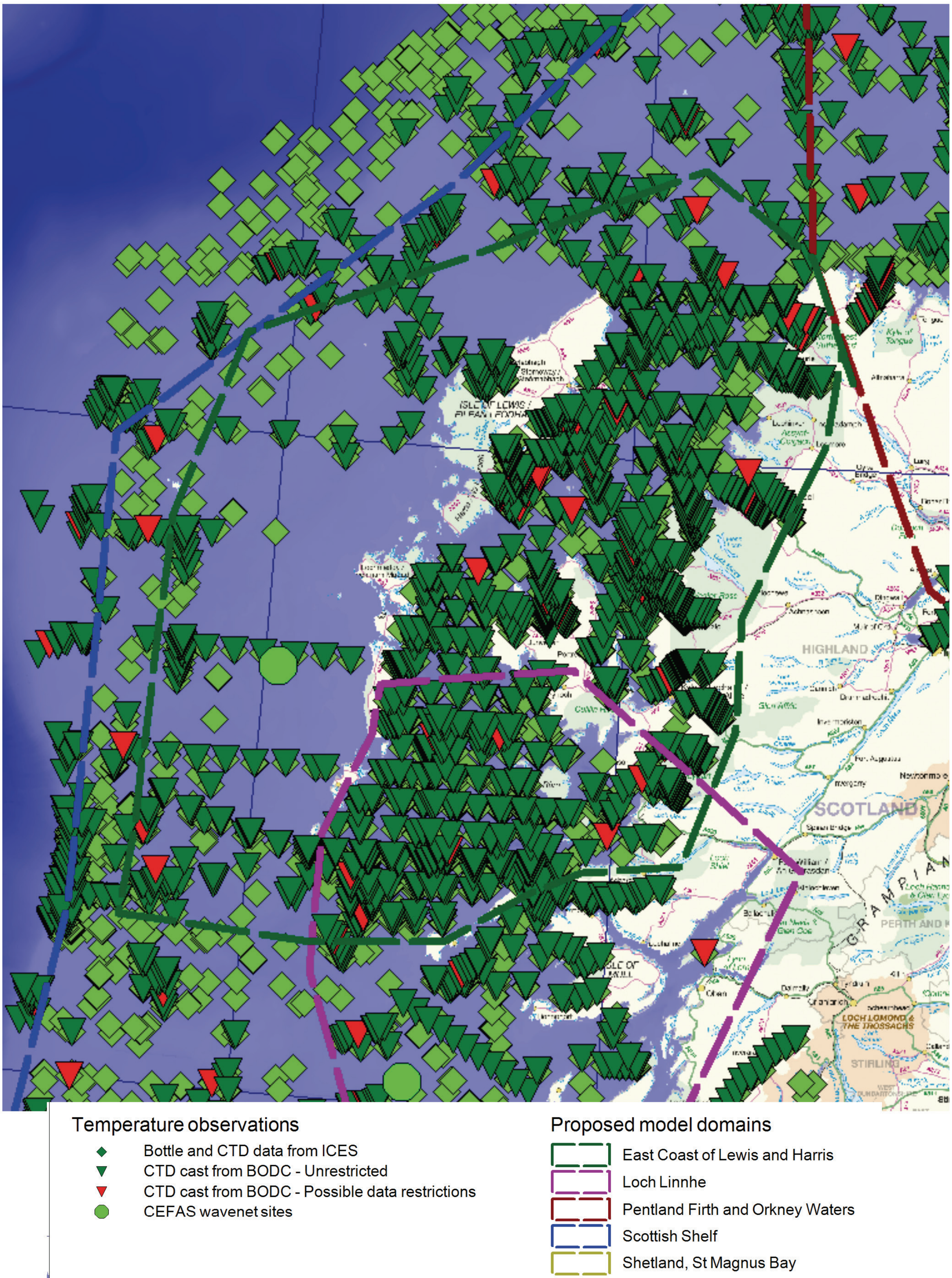
2.4.4 Temperature and Salinity

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

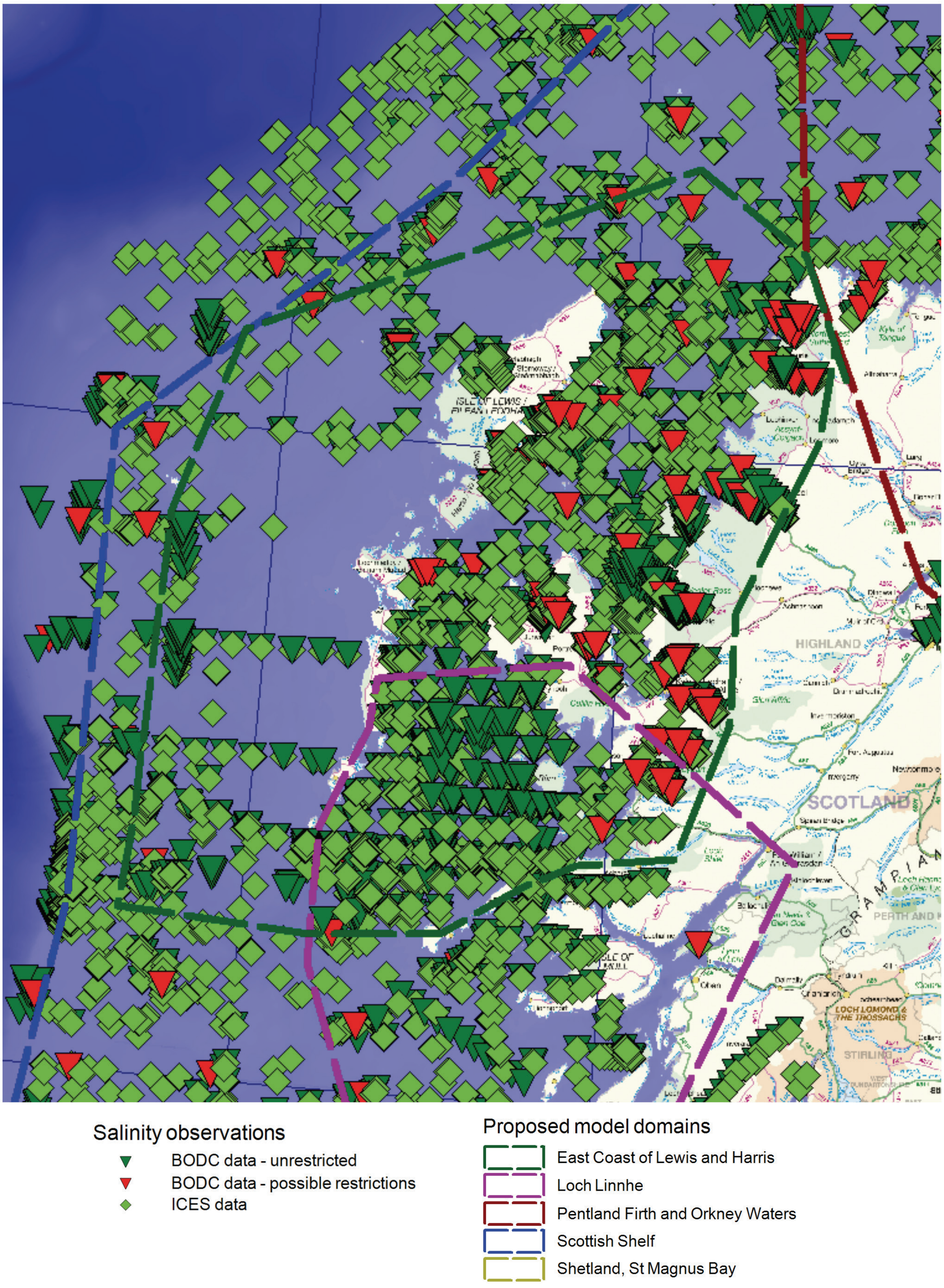
Figure 2-13 shows the locations of the temperature observations and Figure 2-14 shows the locations of the salinity observations. As Figure 2-15 shows, the temperature and salinity observations have occurred throughout the last two decades, with many observations throughout all model domains having occurred over the last two years. Figure 2-16 shows which of these observations include profiles over the entire water depth. Most temperature and salinity observations occurred at the same location and time. Figure 2-17 and Figure 2-18 show there are some temperature and salinity profiles within the model domain, both during the 1997 and 2001 periods when some current observations are also available.

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

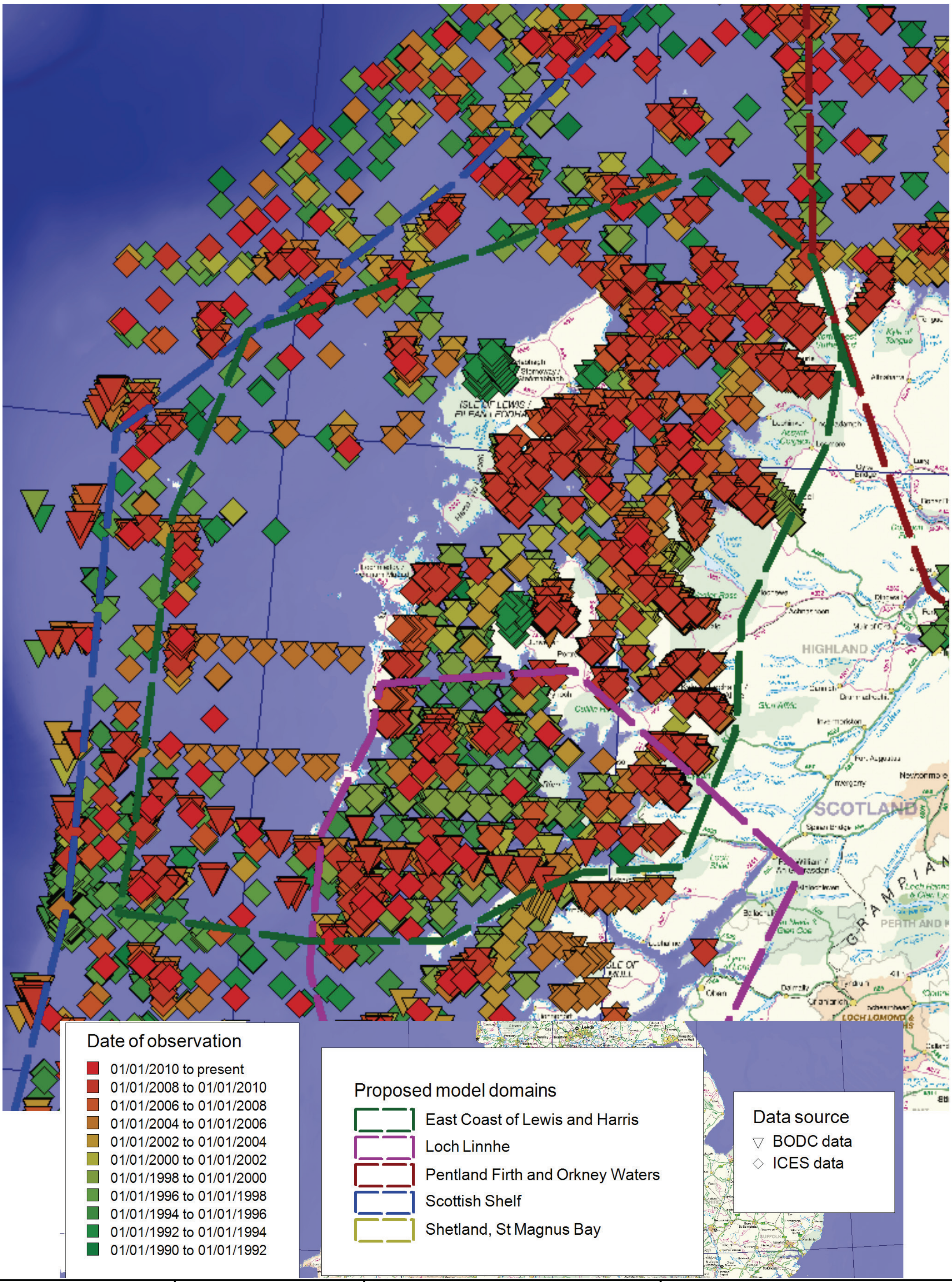
The results from the climatic run were compared with climatological atlas information for temperature and salinity, from the World Ocean Atlas (WOA) and International Council for Exploration of the Seas (ICES) climatological datasets.



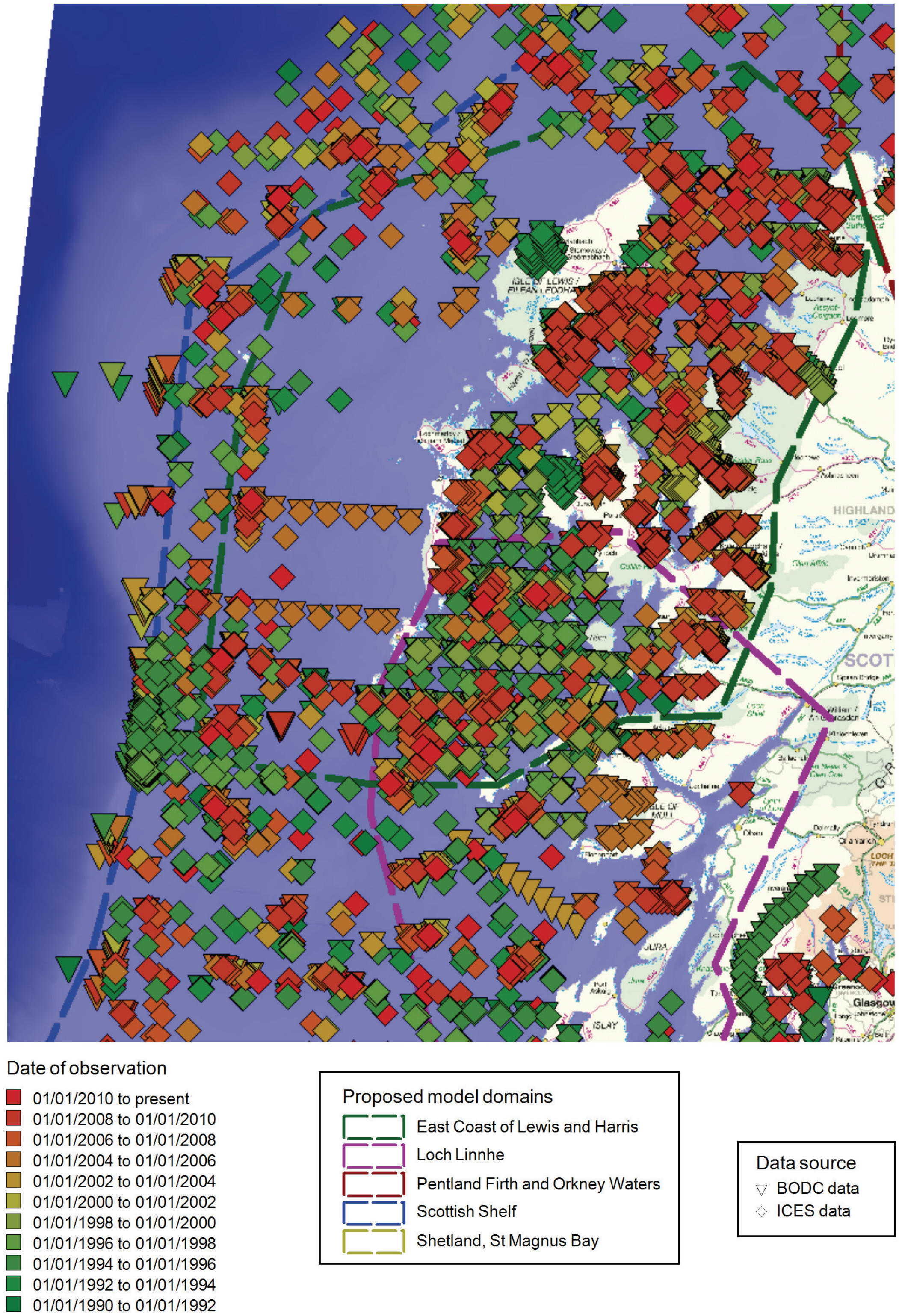
Client	Consulting Engineer	Project:	**Figure 2-13**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	All temperature observations



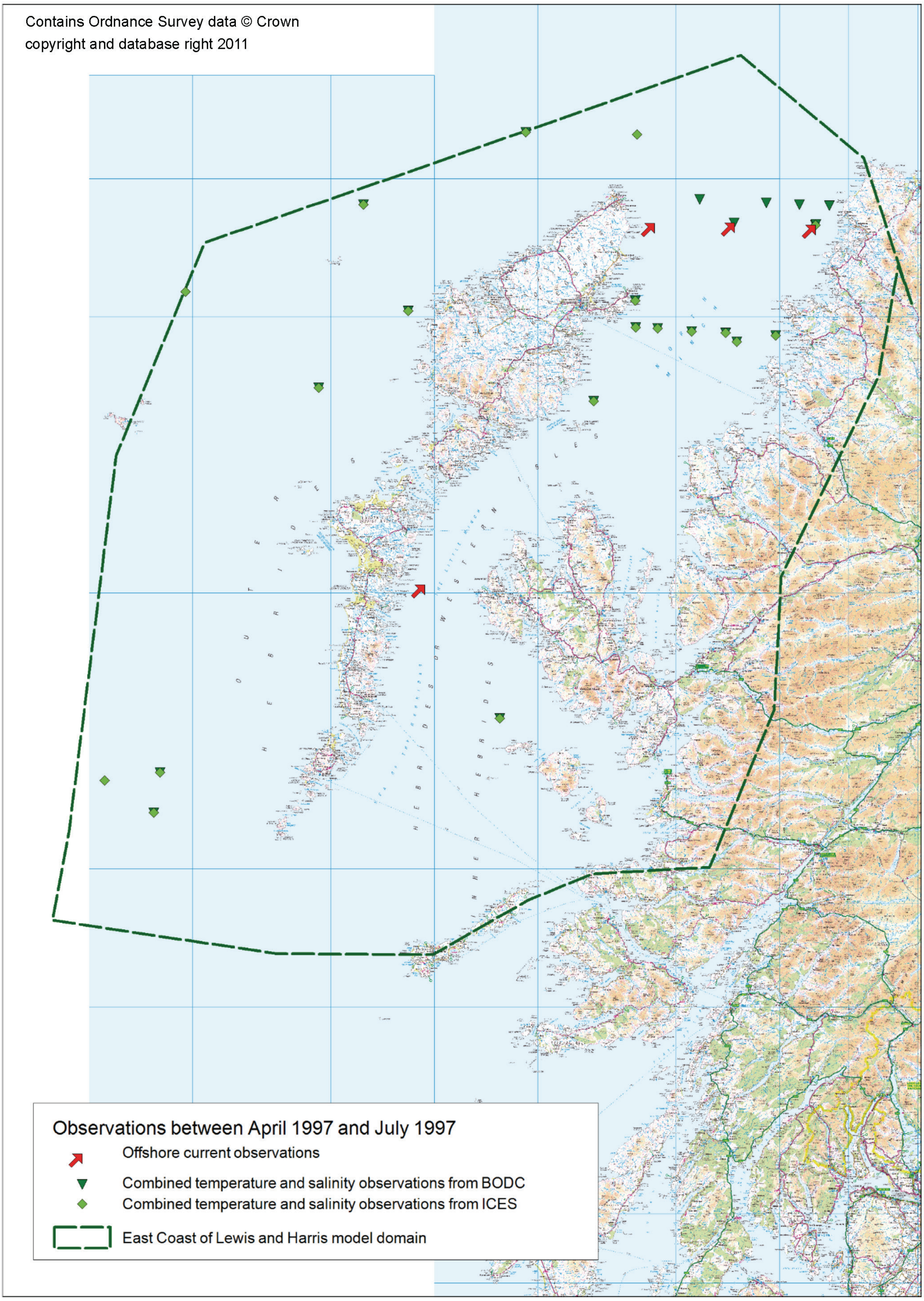
Client	Consulting Engineer	Project:	Figure 2-14
Marine Scotland	ch2m	East Coast Lewis and Harris Model	All salinity observations



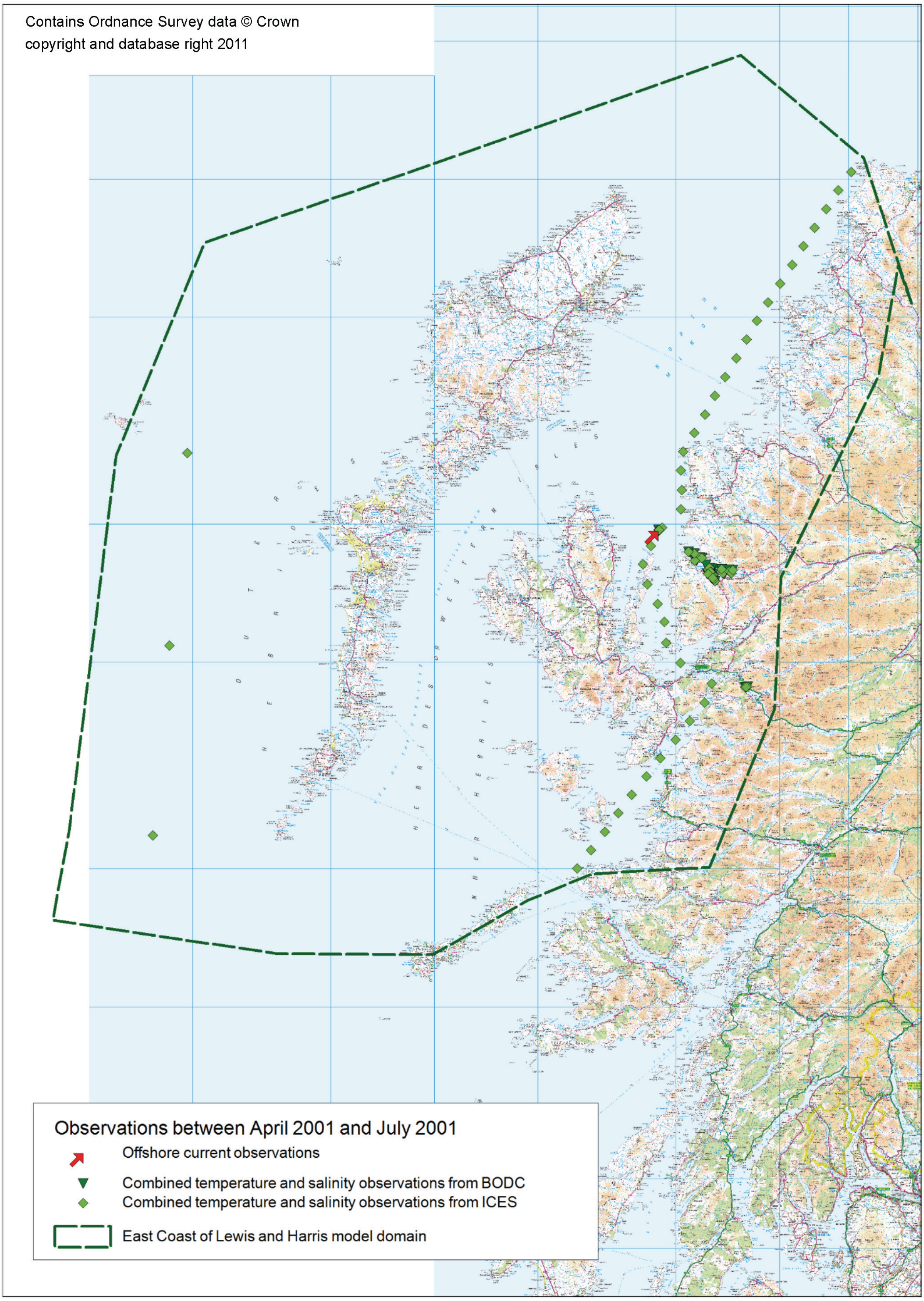
Client	Consulting Engineer	Project:	Figure 2-15
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Temperature and salinity observations by date, including surface observations and profiles



Client	Consulting Engineer	Project:	**Figure 2-16**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity profile observations by date



Client	Consulting Engineer	Project:	**Figure 2-17**
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Offshore current observations between April and July 1997 in the Lewis and Harris area, with temperature and salinity observations from the same period



Client	Consulting Engineer	Project:	Figure 2-18
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Offshore current observations between April and July 2001 in the Lewis and Harris area, with temperature and salinity observations from the same period

2.4.5 Summary of data availability for the ECLH model

This section summarises the availability of calibration and validation data for the ECLH 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 current, temperature/salinity and Meteorological/river flow data available for calibration of the ECLH model.

Table 2-1 Case Study models and available data

Sub model	Year	Water level	Currents	Temperature /salinity	Meteorological	Wind	River
East coast of Lewis and Harris	1997	✓	✓	✓	X	✓	X
	2001	✓	✓	✓	X	✓	X
	2009 + other years	✓	X	✓	✓	✓	✓

Tide gauge data have been obtained from Stornoway, Ullapool and Kinlochbervie. Figure 2-6 and Figure 2-8 show that many recent water level and current datasets exist near the west coast of the Scottish mainland. However most of the post-2000 current datasets are located close to the shore of the Scottish Mainland rather than the Outer Hebrides. No current measurements have been identified along the east coast of Lewis and Harris, or through the Sound of Harris. However there are three measurements across the northern entrance to the Minch, one between Skye and Benbecula, and another east of Skye. Tidal diamonds are effectively the only source of information for calibrating near shore currents in this region.

Figure 2-11 shows available fish farm current data and the Marine Scotland survey data locations. Figure 2-17 and Figure 2-18 show the available current observations, which occurred between April and July 1997, and between April and July 2001, with temperature and salinity observations occurring during the same time period. There is poor overlap between current and temperature and salinity observations; there are many CTD casts are available for 1992, 1998, 2002, 2004, 2005, 2006, 2007, 2008 and 2009 for the sea lochs on the east coast of Lewis and Harris, but CTD casts for 1997 and 2001 are some distance off shore.

The quantity of available datasets suggests they should be sufficient to calibrate for currents in the Minch, and for temperature and salinity inshore. However, multiple calibration periods may be required as current and inshore temperature and salinity data are not available for concurrent periods. Furthermore meteorological forcing data for temperature and salinity has only been archived at NOC-L post 2007 (going back to 2004 with some gaps).

2.5 Conclusions and Recommendations

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

2.5.1 Bathymetry

The EMODnet data is considered appropriate for use as the base bathymetry for model construction. This data forms our base coarser resolution data but is supplemented with higher resolution data.

Further UKHO data and other higher resolution datasets from ICES and Marine Scotland have been used to replace the coarser resolution data in areas that they overlap, with appropriate checks for consistency. However even with these data there are areas which have been identified in the data review report (Halcrow, 2012) as not having sufficient bathymetry data at a fine enough resolution. In this case data from digitised Admiralty Charts have been used.

2.5.2 Forcing data

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

Meteorological forcing for the ECLH model was derived from the Met Office model data that NOC-L holds. The Met Office data provides wind data from 1991 to present day, however other parameters such as sea level pressure, low, medium and high level cloud coverage, specific humidity at 1.5m, air temperature at 1.5m, total accumulated precipitation and sensible heat flux are only available from 2007 to 2011. This therefore limits the periods where calibration data are available coincident with full meteorological forcing. Due to the lack of full meteorological forcing during many of the potential calibration periods, all calibration and validation 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.

Fluvial inputs were derived from G2G river flow data obtained from CEH for the ECLH area.

2.5.3 Calibration and validation data

Section 2.4 presents information about which data were available for the ECLH model. In general there was sufficient data with which to undertake calibration for water level, currents, temperature and salinity. A summary of the dates where suitable calibration and validation 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 ECLH model mesh, bathymetry, boundary conditions and the calibration of the flow model. Model documentation and lessons learnt during this process have been captured in Volume 2 of this report.

3.2 ECLH flow model setup

3.2.1 Model mesh

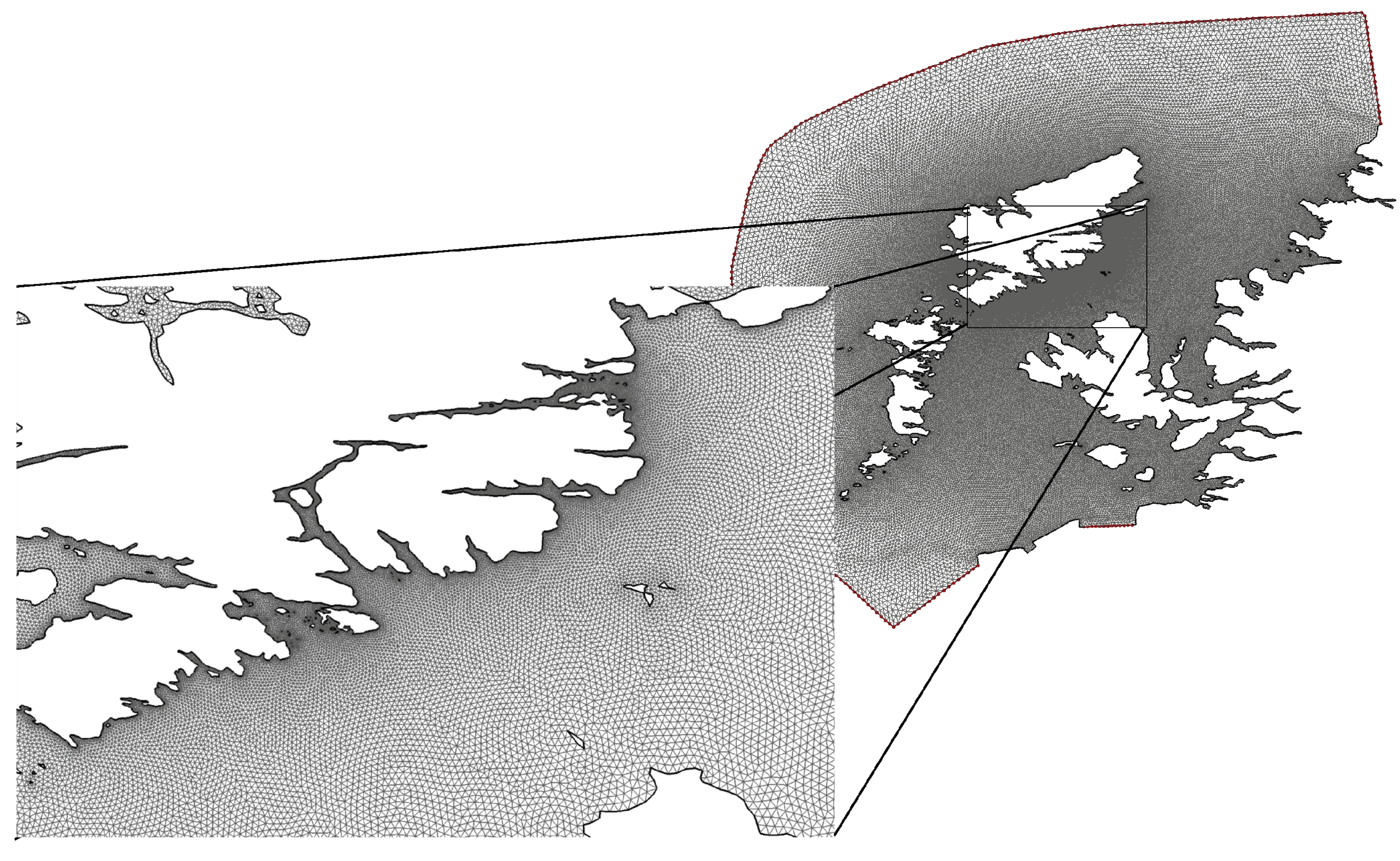
The model mesh developed for the ECLH model has been created using the SMS mesh generator. The horizontal coordinate system used has been latitude and longitude with a vertical datum of mean sea level (MSL). Ten vertical layers have been employed within the model simulations.

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 can be an iterative process in order to get a mesh that varies smoothly, with triangles that do not have angles that are too acute and resolution that does not require an overly small model timestep. SMS has a number of features to allow for a smooth resolution change throughout the model domain so that adjacent element volumes do not differ by more than a factor of 0.5. Additionally the Minimum interior angle was set as 30 degrees, maximum interior angle set as 130 degrees and the maximum number of connecting elements was set as 8. These values were obtained from the FVCOM manual (Chen et al., 2013).

It had been found previously that the volume factor and the number of connecting nodes did affect the model stability.

Figure 3-1 shows the mesh at different zoom levels. Resolution in the areas close to the offshore boundary of the model is in the order of 2000m, within the central part of the model it is approximately 500m, with most of the rest of the area close to shore on the east coast of Lewis and Harris having a resolution in the order of 150m.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-1		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Model mesh in the East Coast of Lewis and Harris (ECLH) model showing detail along the area of interest	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014

3.2.2 Model bathymetry

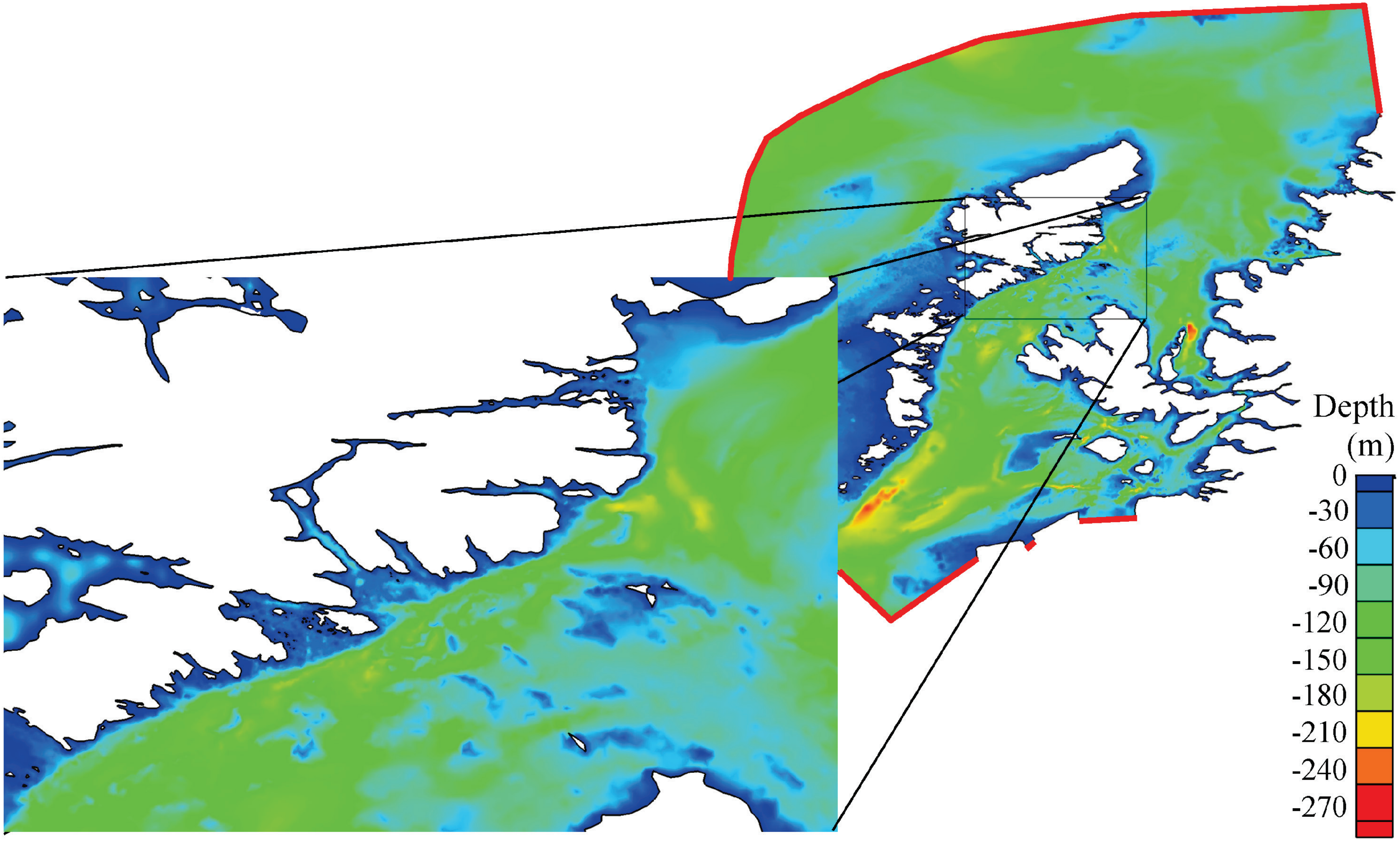
The ECLH model mesh was created using the SMS mesh generator. The bathymetry used for the ECLH model was derived from the same sources as the other case study models, namely:

- EMODNET (coarser and generally offshore),
- higher resolution survey bathymetry (data and other higher resolution datasets from ICES and Marine Scotland) and
- digitised Admiralty Chart data where no other data was available.

The coastline was derived from Ordnance survey coastline data.

These bathymetry datasets were combined to a common datum of MSL and interpolated onto the model mesh within the SMS mesh generator.

Figure 3-2 shows the extent of the model domain along with a zoomed in view showing detail along the east coast of Lewis and Harris which is the focus of this study. The open boundary is highlighted in red; note that there is a break in the boundary at the southern part of the model where it straddles a number of islands (Tiree and Coll). The contour levels on this and subsequent images of the model bathymetry is relative to MSL.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-2		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Model bathymetry in the East Coast of Lewis and Harris (ECLH) model showing detail along the area of interest	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014

3.2.3 Boundary data

The hydrodynamic boundary data applied to the ECLH model are water levels relative to MSL, depth-averaged velocities, temperature and salinity. These were obtained from the AMM model. Initial runs to drive the hydrodynamic model made use of only a water level boundary, however it proved difficult to get the model to be stable. Therefore a nesting boundary approach has been used.

The nesting boundary consists of all of the elements on the open boundary as well as all of the attached nodes. All nodes attached to the elements on the open boundary are hereafter called “nesting nodes”. Scripts have been created to automatically determine the element numbers and nesting node numbers along the open boundary. These element and node numbers are then used by another script to read in the results from the AMM model and create a netcdf nesting boundary file. For the climatological simulations described in Section 3.4, the code was amended to read in FVCOM shelf model results for the same purpose.

The data we had from the AMM model consisted of hourly water level and depth-averaged currents. As the ECLH model had 10 vertical layers, the depth-averaged velocity was applied equally at each layer, thus letting the model adjust the depth variation. The temperature and salinity were supplied as daily values for each of the AMM’s 40 layers and incorporated into the nesting boundary with a time interval of 10 minutes, the same time frame as the water level and current speeds had been interpolated to. The temperature and salinity were interpolated onto the model boundary nodes for each of the models layers.

The ECLH model is run initially with constant temperature and salinity for a short warm-up period, this outputs a hotstart file which contains information about water levels, current speed and temperature/salinity. To reduce the warm-up period for the temperature and salinity, a Matlab script has been used which writes AMM temperature and salinity results to the hotstart file (over-writing the constant values in the hotstart file). This allows the follow-on ECLH model hot start conditions to match those applied at the boundary and to have suitable temperature/salinity within the model domain. The external timestep used in the simulations was 3 seconds, with Isplit set as a factor of 3 (ratio of internal to external timestep).

3.2.4 Meteorological forcing data

There are two options when including heat input into the FVCOM model; either the net heat flux inputs are provided by way of netcdf files, or FVCOM calculates it internally. NOC-L found that the shelf model was heating up too much with the former approach over a 4-month simulation. Furthermore, they found that this overheating problem was solved by allowing FVCOM to calculate the heat inputs internally. The reason for the overheating problem is due to the difference in sea surface temperature used in the Met Office model and the AMM model used for deriving initial conditions.

It is therefore advantageous to follow the NOC-L approach and have the heating calculated within the model so this is the method employed for this case study.

The meteorological forcing data was retrieved by NOC-L for 2009. This was processed and a Matlab tool produced which provided the necessary meteorological file for FVCOM. A more detailed description of the Meteorological forcing used in both the Shelf Model and the case study models can be found in Halcrow (2012), Section 3.2.5.

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

3.2.5 River input

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

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

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

3.3 Flow model calibration

3.3.1 Introduction

A range of datasets were available with which to calibrate the ECLH hydrodynamic model. Water level data were available for long periods at Ullapool, Kinlochbervie and Stornaway (on Lewis). Current measurements were available at a number of locations from the British Oceanographic Data Centre (BODC) at the northern end of the model domain in the Minch as well as towards the southern end of the model and to the south of Harris. Additionally SEPA provided fish farm current data at a number of locations within our model area along the east coast of Lewis and Harris, these were all recorded at different times for a minimum of 15 days. Additionally Marine Scotland deployed two ADCP instruments along the study area (Loch Seaforth entrance and offshore in the Little Minch) for a three tide period.

The different timeframes at which the various current measurements were available, combined with the periods when we had suitable boundary and meteorological forcing data meant that it was difficult to run the model with all of the met forcing and coincident boundary conditions to the available data.

Boundary conditions were available for 2009, as was the met data. However there was only one data set (from a fish farm measurement) when current data was coincident with the met and boundary data, a direct comparison between the baroclinic model and this data is presented in section 3.3.4.

Initially, the model was run for the month of May 2009, with river input and full met forcing. The results of this simulation were compared with measured water levels at Ullapool, Kinlochbervie and Stornaway. No current data was available for direct comparison with the May 2009 run, comparisons against the current data were made by undertaking a harmonic analysis of both the model speed components as well as the observed speed components and reconstructing both the model and observed speeds. This approach removes the meteorological forcing from the data and allows the reconstruction of the two sets of speeds to a common time-frame.

3.3.2 Guidance used for model calibration

The guidance that we have used to assess the level of calibration for calibration of water levels and currents speeds is provided in Bartlett (1998) and reproduced below:-

- *Water levels to within +/- 0.1m*
- *Speeds to within +/- 0.1m/s*
- *Direction to within +/- 10 degrees*

- *Timing of high water to within +/- 15 minutes*

Alternatively some of these could be expressed in percentage terms:-

- *Speeds to within +/-10-20% of observed speed*
- *Levels to within 10% of Spring tidal range or 15% of Neap tidal range*

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

The results from the model were gauged against this criteria.

3.3.3 Sensitivity to bed roughness

One of the main parameters that affects current speeds within a hydrodynamic model is bed roughness; this section describes the results of this sensitivity analysis.

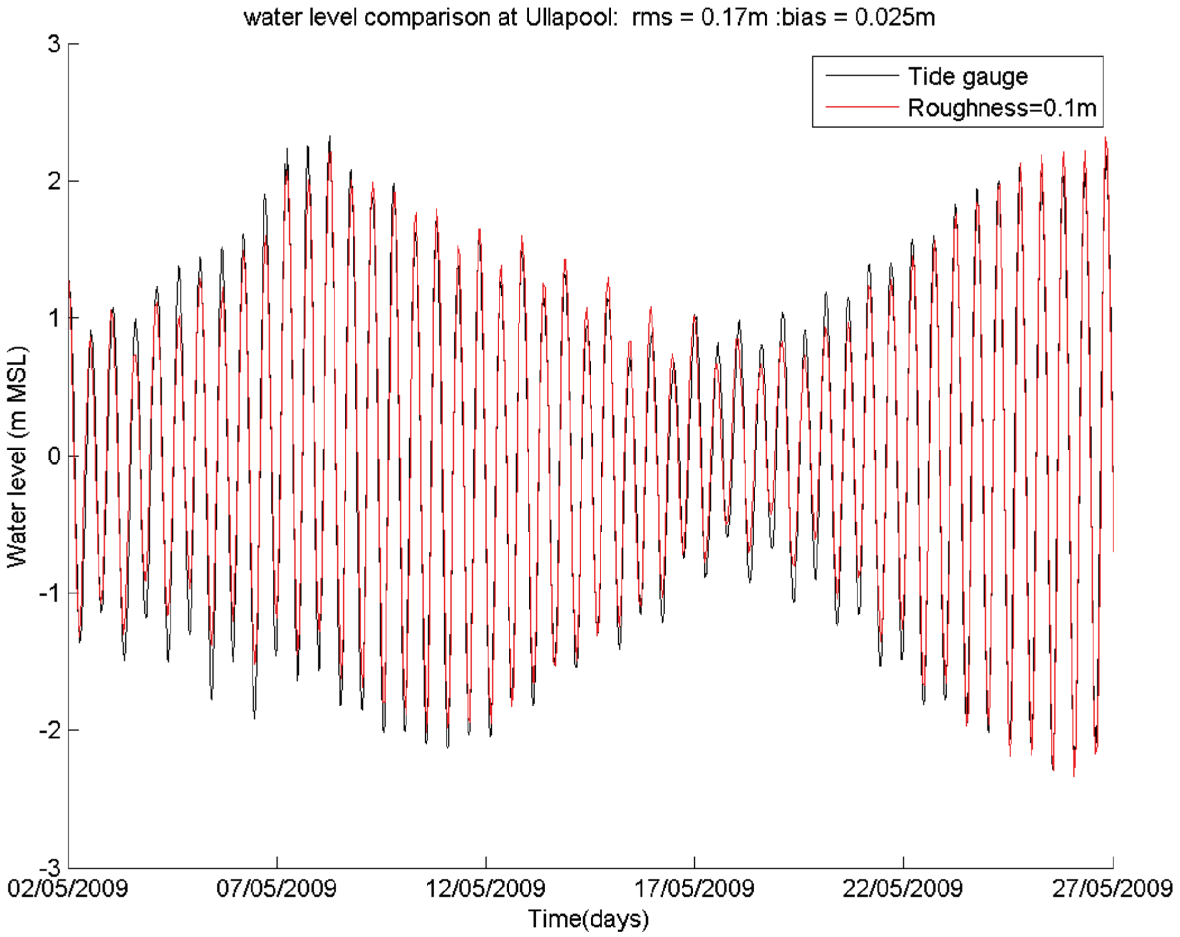
3.3.3.1 Water level comparisons

The ECLH model had initially been run using water level boundaries only, this lead to some instability issues. Therefore a nesting boundary approach was undertaken using type 2 nesting. This meant that a file for water levels was applied along with a nesting file that contained velocities, temperature and salinity. This approach made the model much more stable.

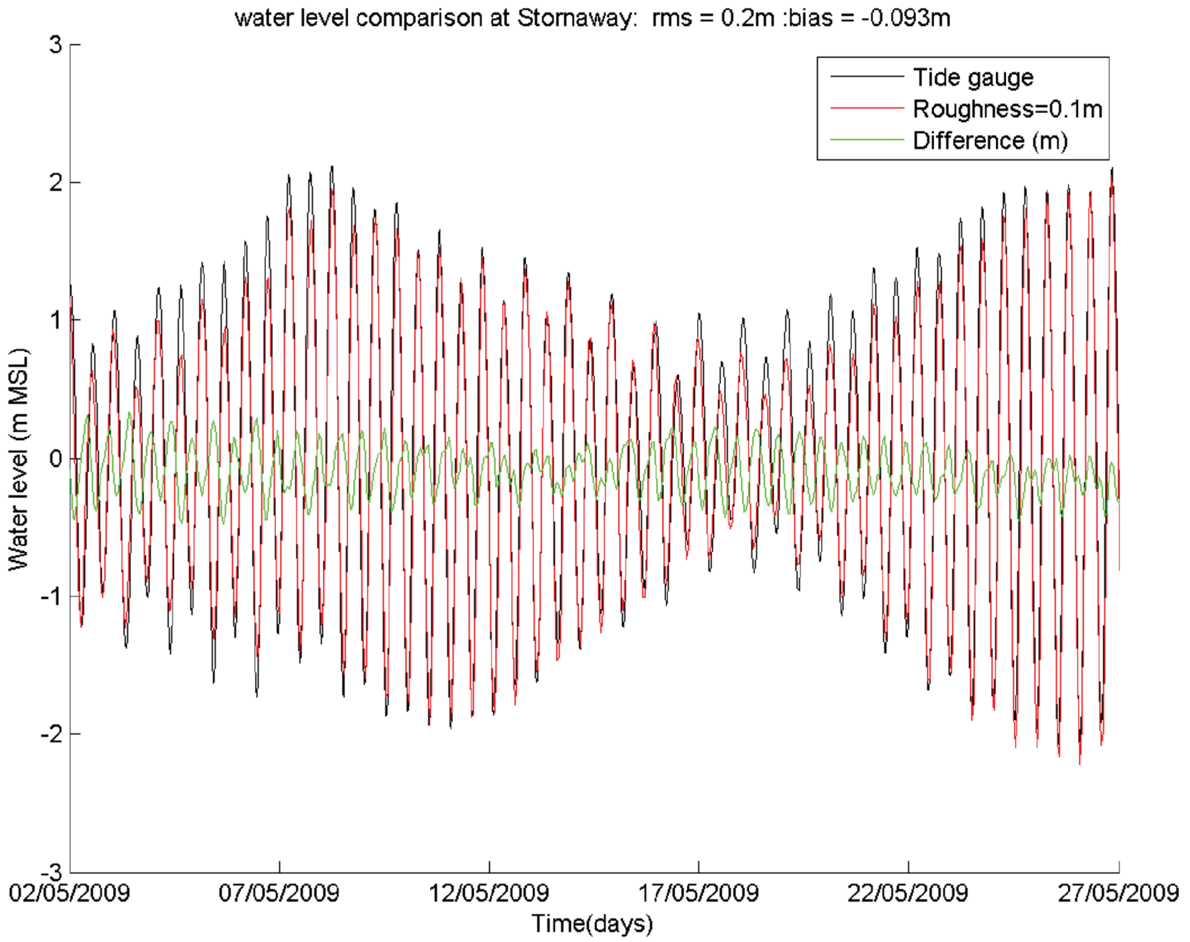
Three simulations were undertaken for the month of May 2009 with a range of roughness lengths; 0.01, 0.04 and 0.1m to test the sensitivity of the model to this parameter.

Figures 3-3a-c show comparisons between the water levels predicted by the model for the roughness of 0.1m compared with the tide gauge measurements. The differences between the three model simulations for water levels is very small and not easily visible and therefore has not been plotted. The main effect from the changes to roughness is to the current speeds presented later.

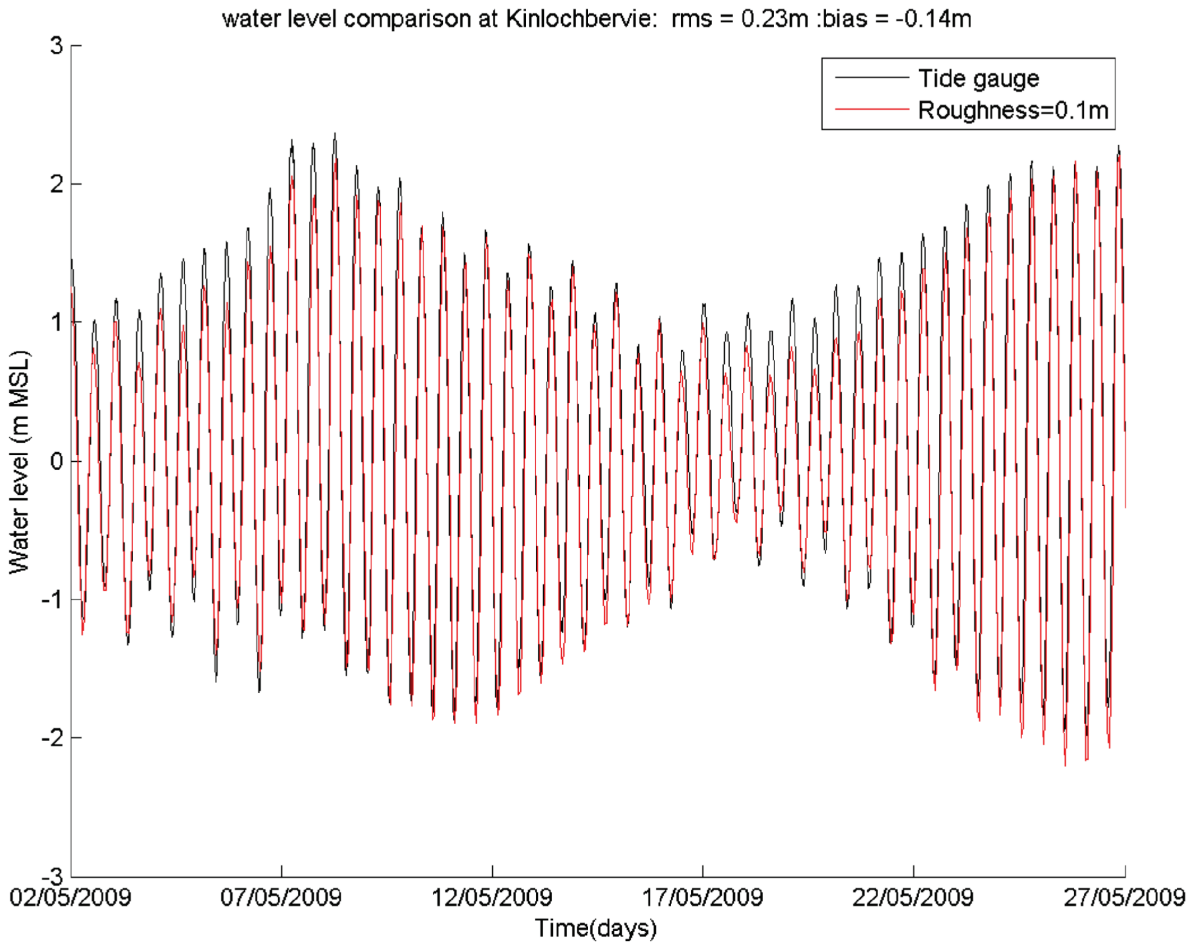
The locations of Kinlochbervie and Ullapool are on the northwest coast of Scotland located within lochs. Unfortunately the model does not resolve these locations as well as would have been liked, although for good reason to keep the overall number of elements down (these locations are far away from the area of interest). Stornaway however is located on Lewis provides a comparison closer to the area of interest.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison between tide gauge measurements (black) and model results (red) - Ullapool	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison between tide gauge measurements (black) and model results (red) - Stornaway	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-3c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison between tide gauge measurements (black) and model results (red) - Kinlochbervie	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

What can be seen in these plots is that the model is able to reproduce the change in the tidal signature over a spring-neap cycle reasonably well. There appears to be a small under-prediction of the tidal range during the phase where neap tidal ranges are increasing to intermediate tides but a good reproduction is made during springs. The drop from intermediate tides to neaps is reproduced well. This feature is evident at all the locations. For the Stornaway plot the difference between the model and the data is plotted in green. A tidal signature can be seen which may suggest that some constituents are not included in the model boundary conditions.

The Root Mean Square error (RMS) and bias (mean of the difference between model and data) are also included in the title of these three figures and summarised below in Table 3.1

Table 3-1 error statistics for comparisons of the model against measured water level data

	Ullapool	Stornaway	Kinlochbervie
RMS error	**0.17m**	**0.2m**	**0.23m**
Bias error	**0.025m**	**-0.093m**	**-0.14m**
RMS error % (compared with neap tidal range)	**11%**	**15%**	**17%**
RMS error % (compared with spring tidal range)	**4%**	**5%**	**5%**

It can be seen in the Figures 3-3a-c and in Table 3-1 that the percentage errors for the spring tide are within the 10% criteria, whereas for the neap tides they are all higher up to and including 15% for Ullapool and Stornaway, but slightly higher for Kinlochbervie. Therefore in general the model meets the criteria for percentage error for most of the time and locations with the exception of neap tides at Kinlochbervie. Although the 15% is exceeded at Kinlochbervie, it is only just over, far from the area of interest and not resolved fully in the model mesh. Therefore given that the differences occur for only part of the time during a subset of tides, it is recommended that the calibration for water level be accepted. Sensitivity to bed roughness did not have a significant effect on the water levels.

3.3.4 Current speed calibration

3.3.4.1 Sensitivity test to bed roughness

The sensitivity to bed roughness was undertaken to assess how this impacted both water levels and current speeds. The water levels were not very sensitive to this parameter, however differences were observed for the current speeds in the model.

In order to assess the sensitivity, comparisons between the three model simulations with roughness lengths of 0.01, 0.04 and 0.1m and observed current meter data have been made. The data was obtained from the BODC archive at locations shown on the following Figures.

On each of the Figures 3-4a-d, current speeds from the three sensitivity simulations are shown. The remaining comparisons are displayed in Appendix A. However because the model was run for different periods than the data, harmonic analysis and then reconstruction of both the model results and the data for the time frame of the model simulation was undertaken. This had the advantage of then allowing comparison of the two sets of data (just using astronomical components) although differences in the period analysed could introduce differences.

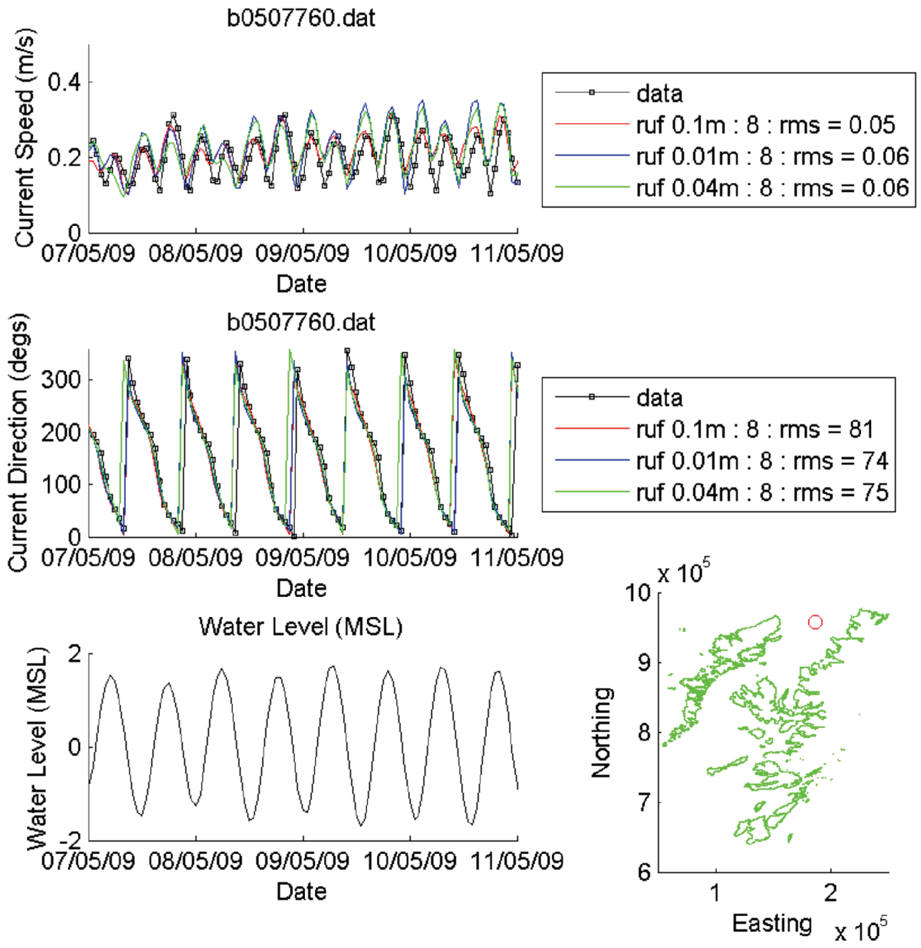
On each of these Figures the RMS value for current speed and direction are included. All of the current speed comparisons have an RMS error of less than 0.1m/s which is within the guidance we are using. Using percentages it is more difficult to achieve the guidance range for speeds of 10-20% as the speeds are generally low.

Based upon the Figures it was decided from the statistics and visual comparison that a bed roughness of 0.1m gave marginally better results. Figures 3-5a-i show the comparisons with only the results from this simulation compared against the data.

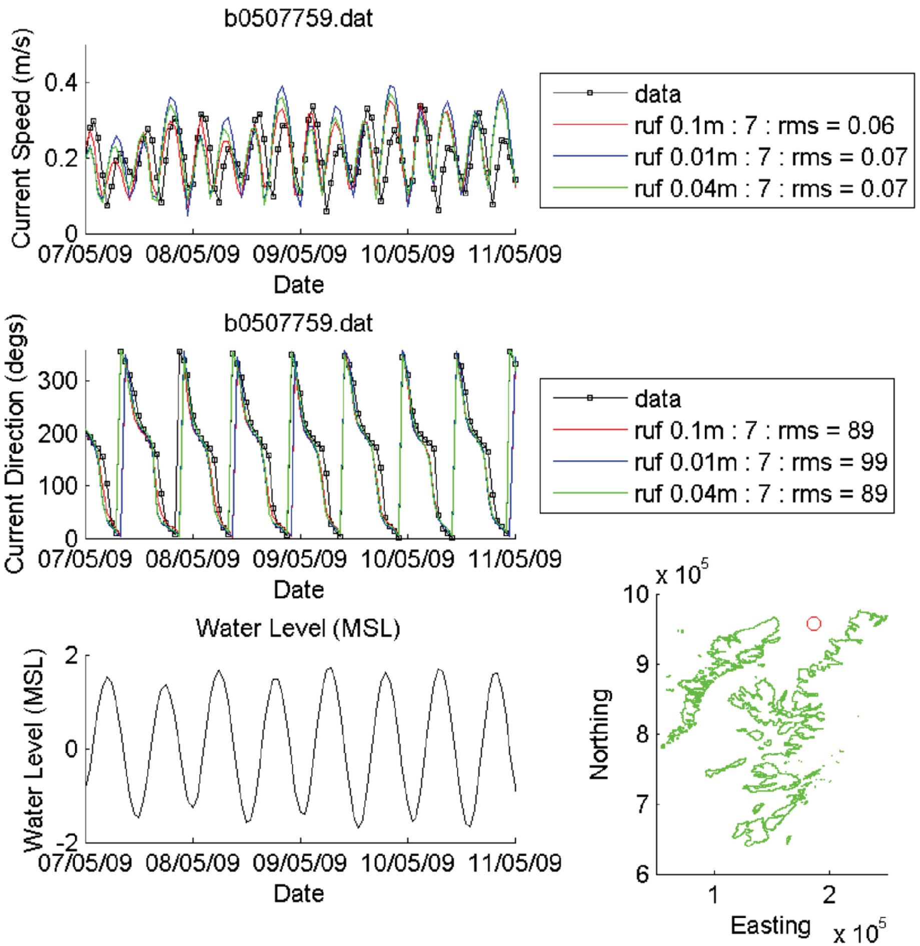
Table 3-2 presents the RMS errors between the model and observed data (both have been reconstructed to give astronomical currents only). Subsequent simulations therefore have a bed roughness of 0.1m.

Table 3-2 RMS errors for current speed comparisons (BODC data)

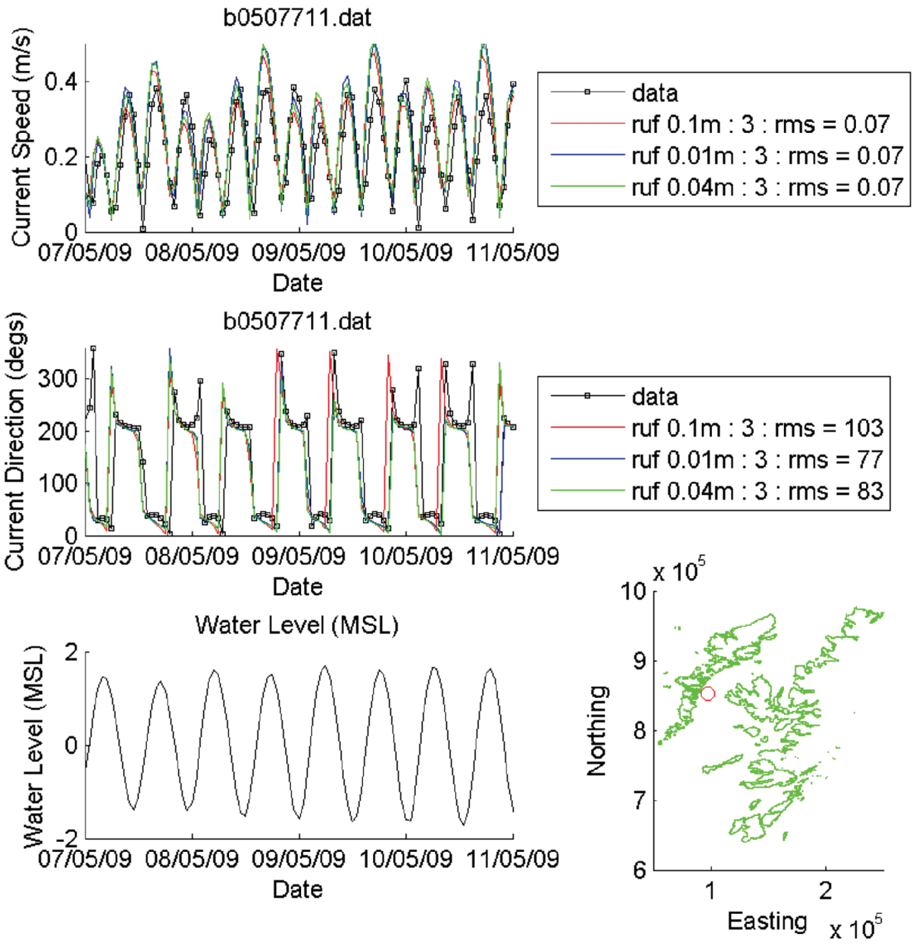
Location	**Current speed RMS error (m/s)**
B0507784	**0.05**
B0507772	**0.07**
B0507760	**0.05**
B0507759	**0.06**
B0507747	**0.07**
B0507723	**0.08**
B0507711	**0.07**
B0507692	**0.07**
B0507680	**0.06**



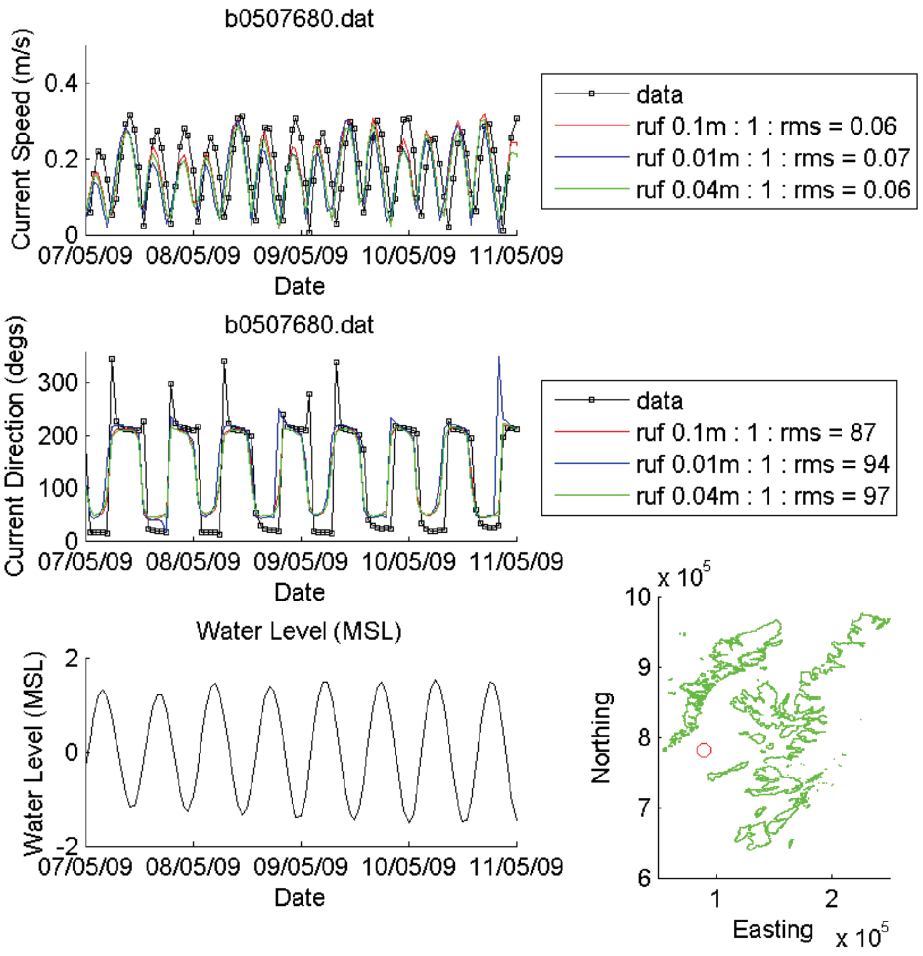
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



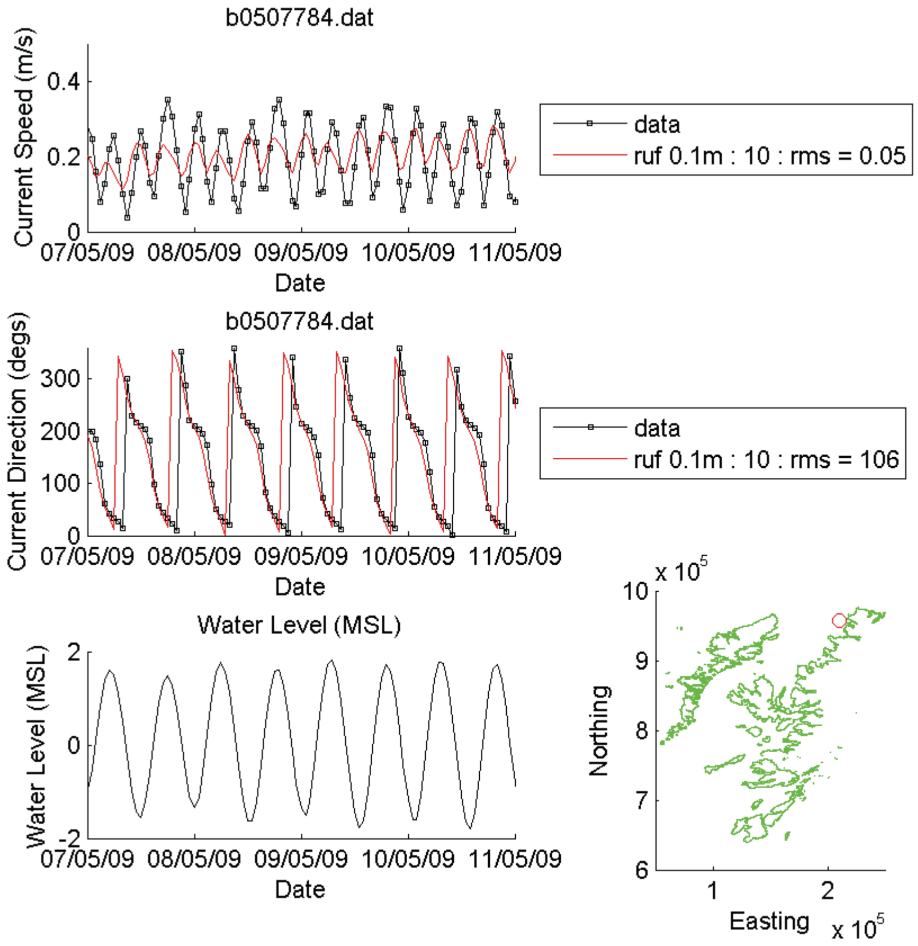
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



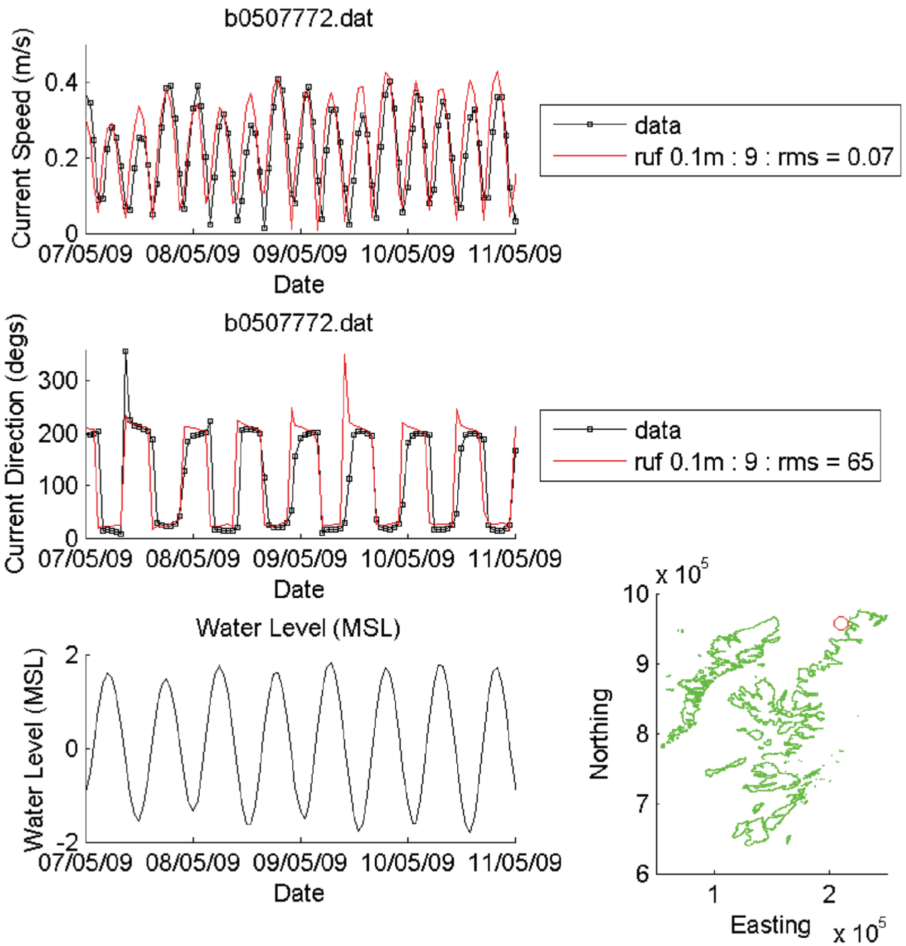
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



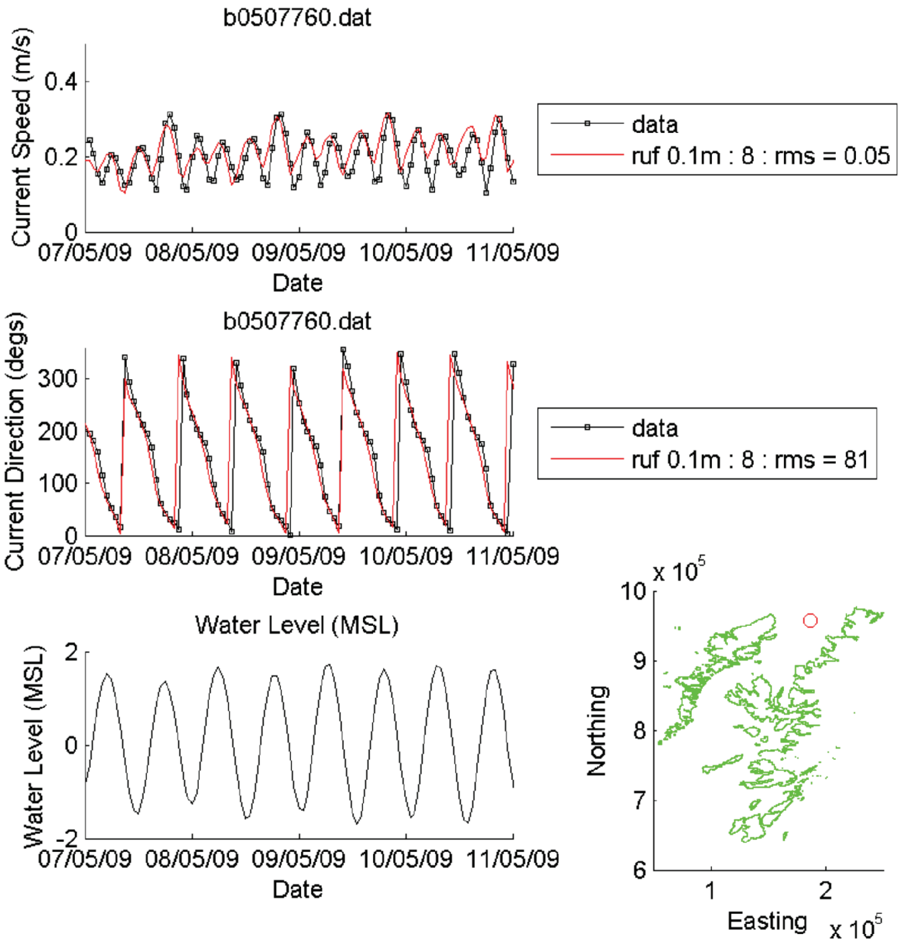
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-4d		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



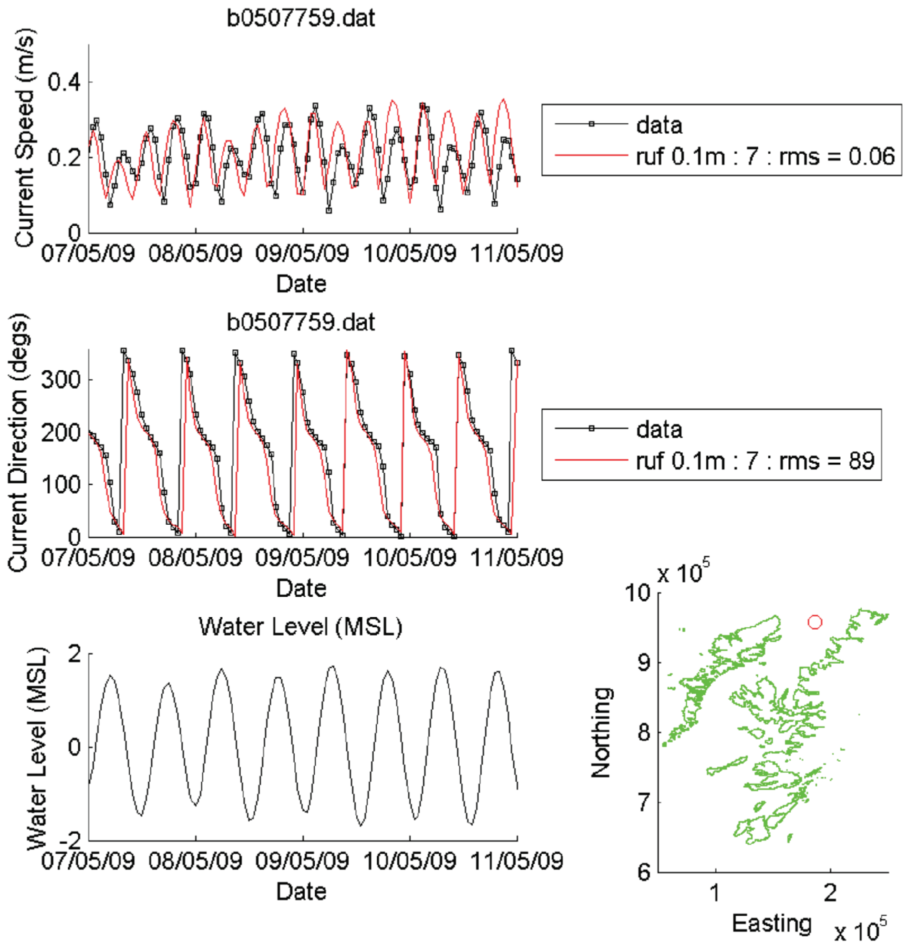
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



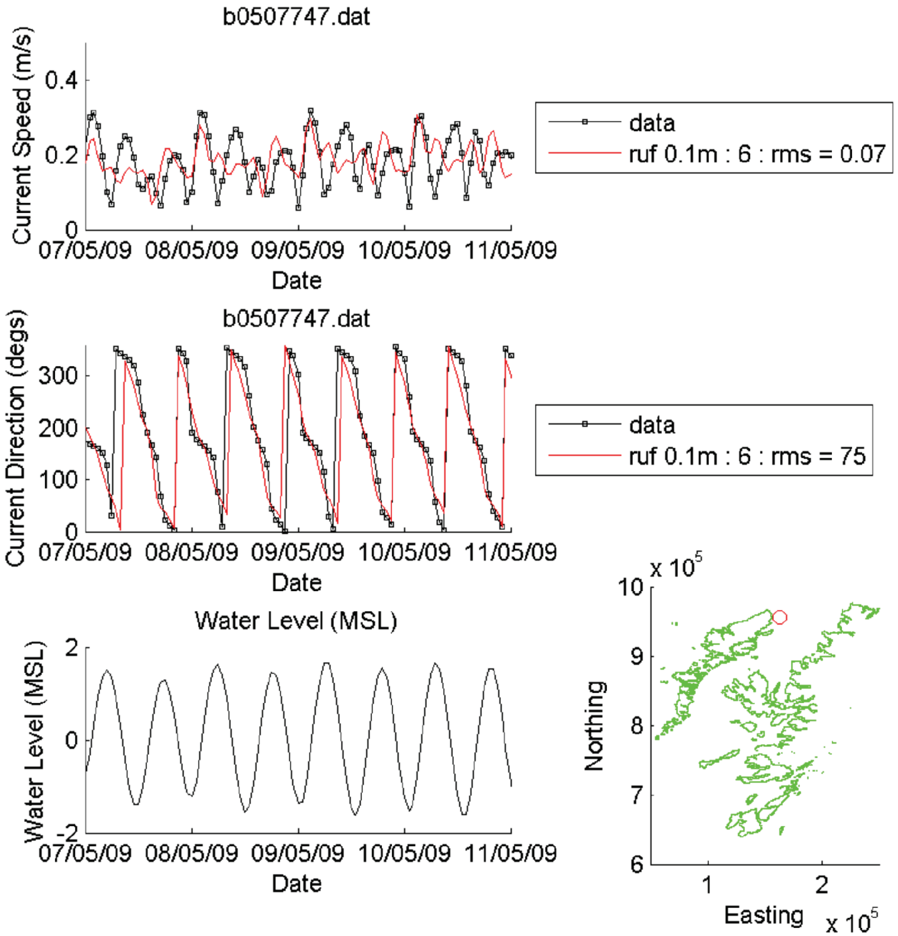
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



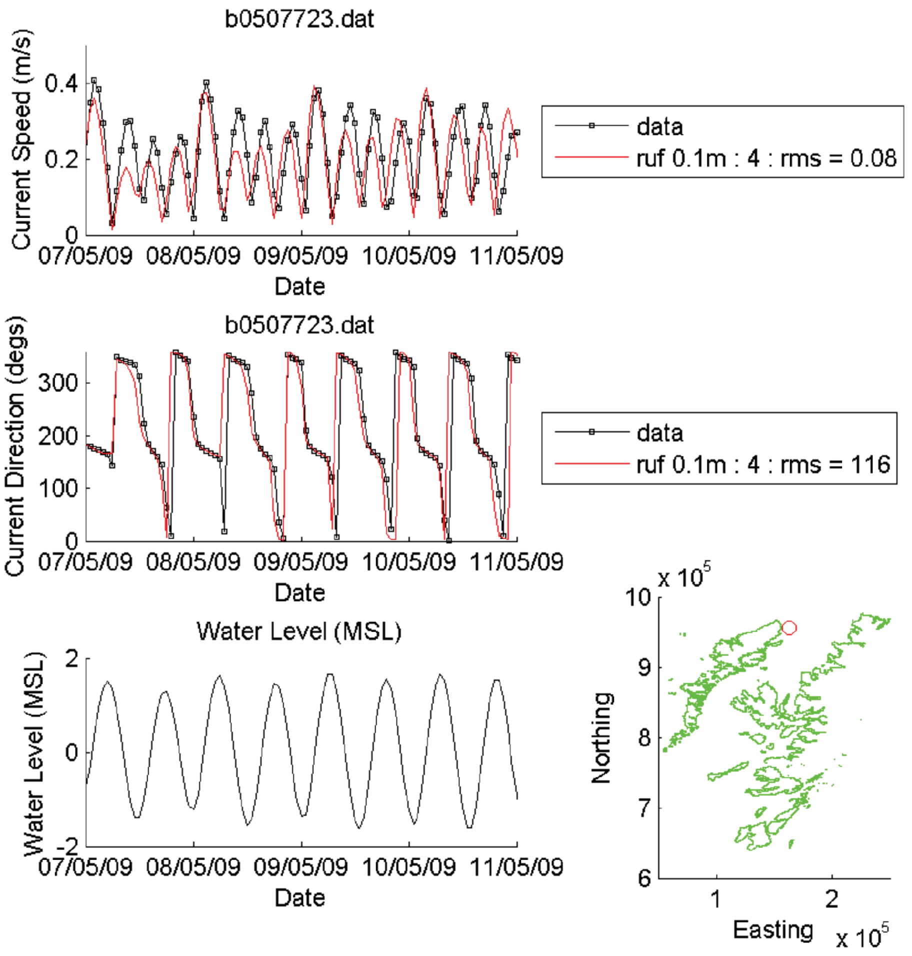
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



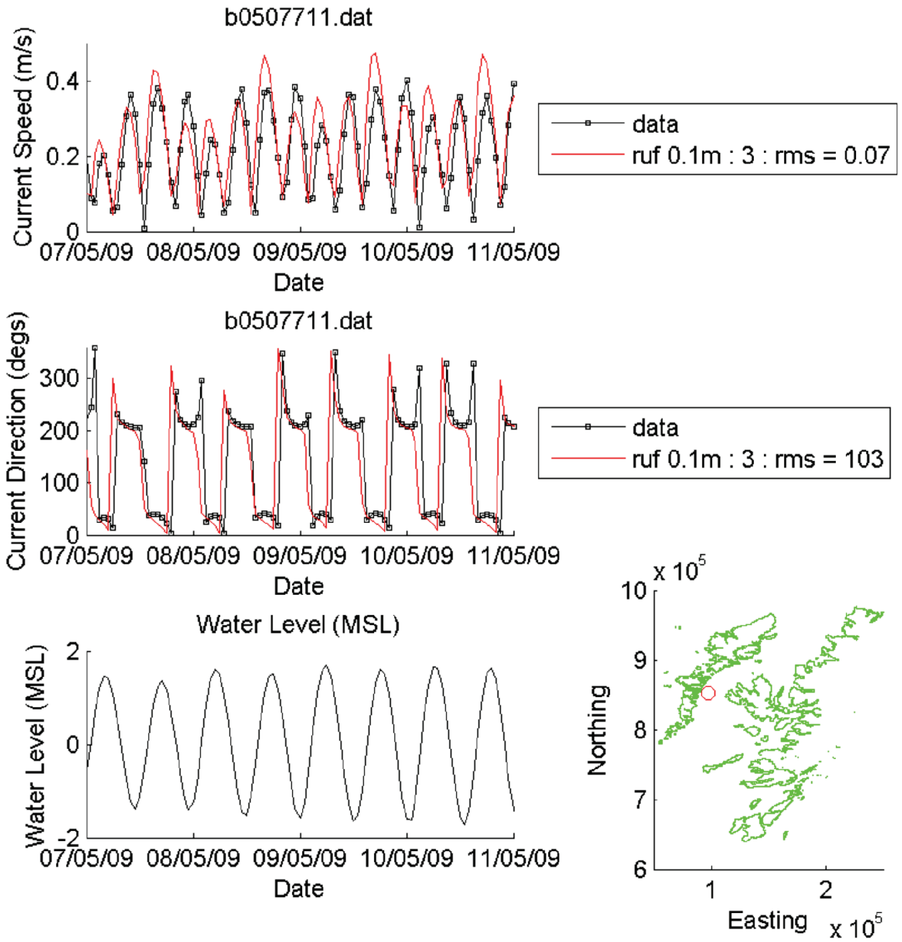
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5d		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



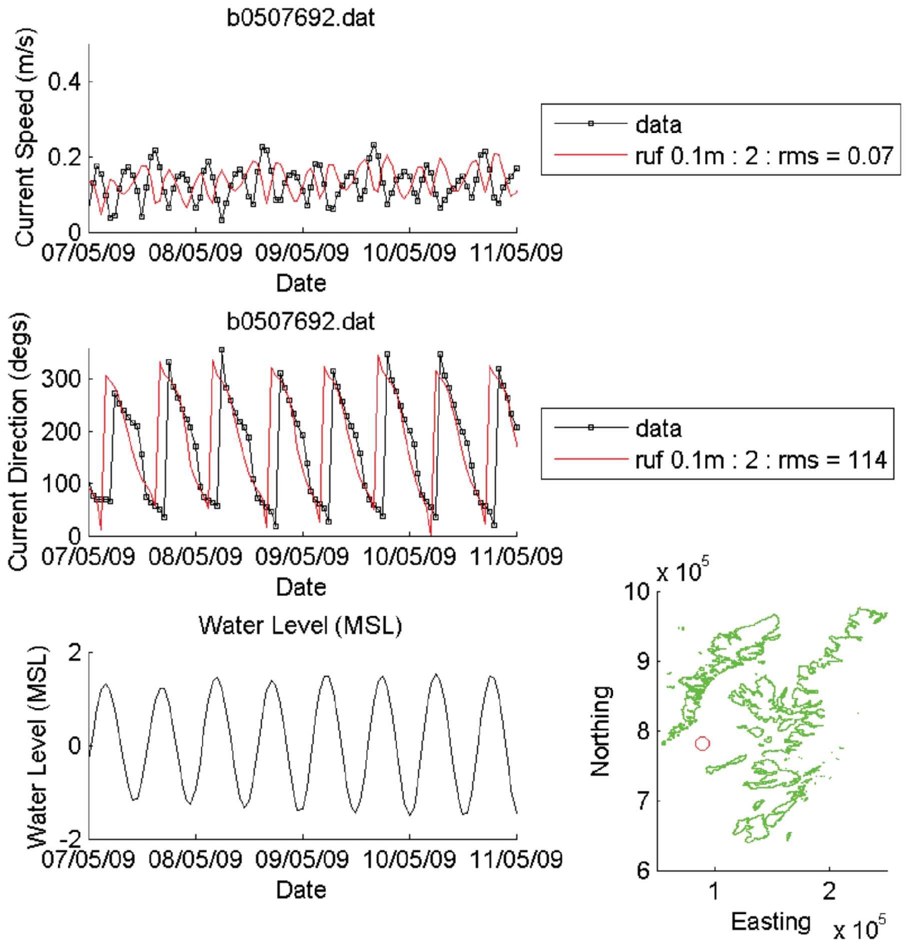
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5e		
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



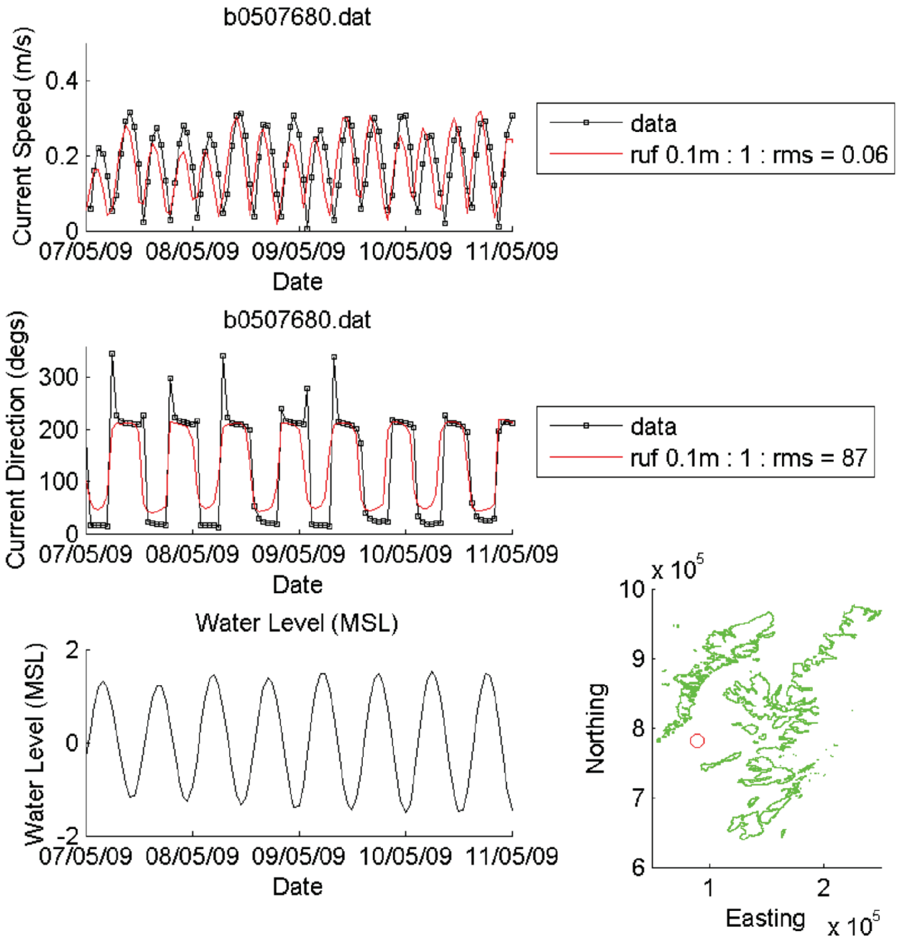
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5f		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5g		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5h		
Marine Scotland		East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



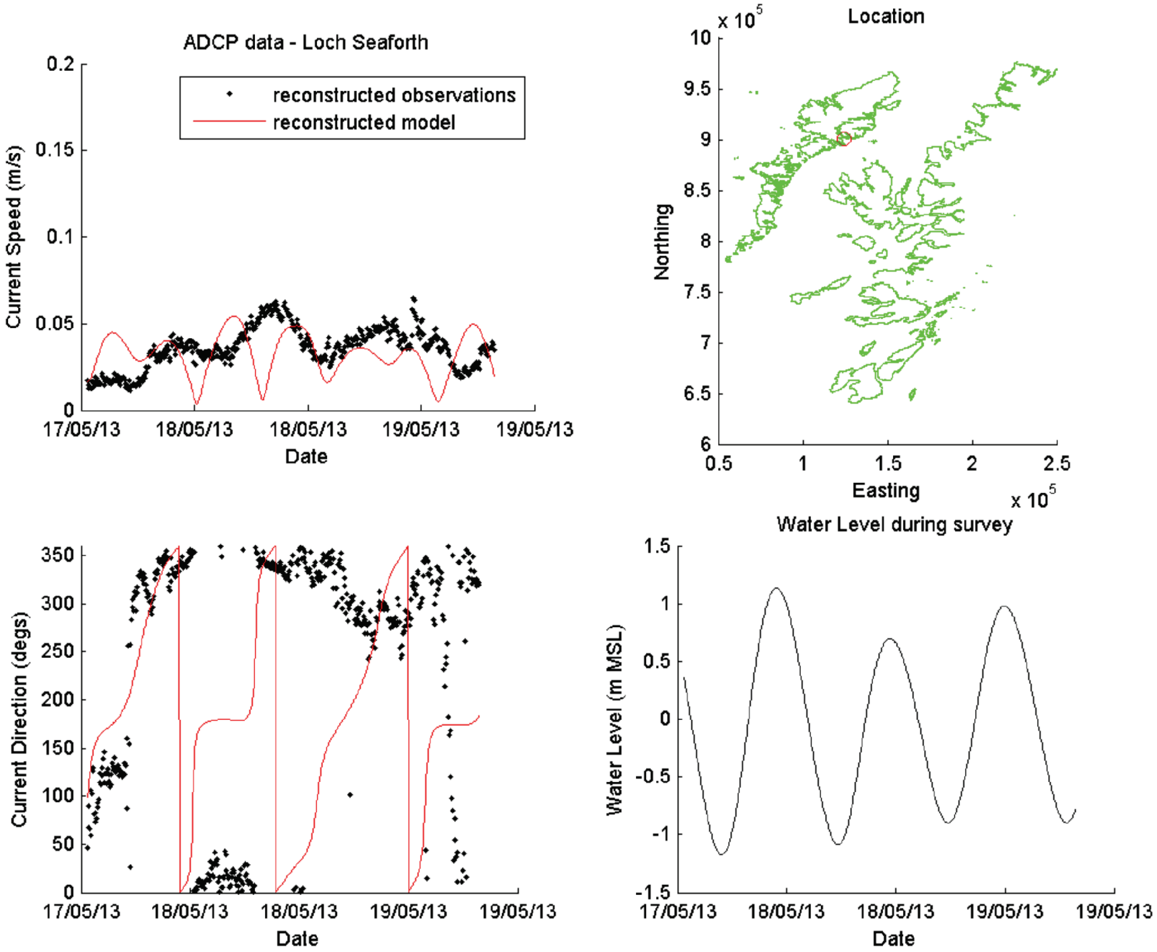
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-5i		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and model run with preferred roughness lengths of 0.1m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.3.4.2 Comparison against Marine Scotland data

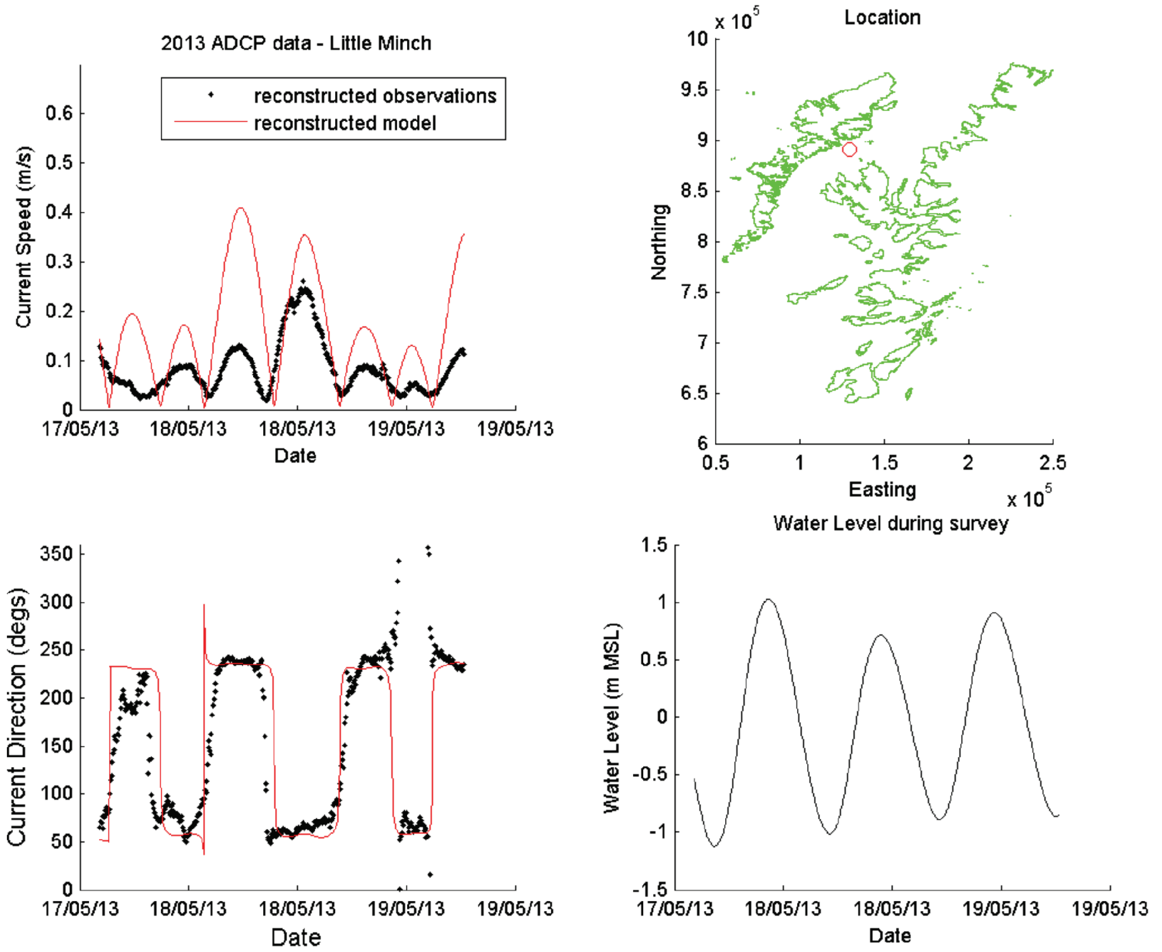
On 17-19th May 2013, the MRV Scotia undertook a short survey recording current measurements at two location, one in the mouth of Loch Seaforth and the other further offshore in the Little Minch. The measurements were recorded using an ADCP the results of which were depth-averaged for comparison with the results from the 10 layer ECLH model. As boundary and met forcing were not available during this period of time, the results from a simulation for one month in May 2009 were harmonically analysed and reconstructed for the period that the data was collected for.

Figures 3-6a and b show the results of this comparison. Within Loch Seaforth entrance (Figure 3-6a) the magnitudes of the current speeds are reproduced well, being around 0.06m/s or lower. The speeds in the model however do drop lower than those observed, this could happen if the data is being influenced by wind and with such low current speeds the wind could create flows of a similar magnitude to the tidal flow. Apart from the beginning of the observed data, the flow is continuously flowing between west and northwards whereas the model does vary depending upon the phases of the tide with periods when the flow is southwards. This difference also suggests that wind may have been involved and coming from the south – southeast.

Figure 3-6b shows the comparison between the observed depth-averaged current speeds against the reconstructed model results in the Little Minch offshore from Loch Seaforth. The comparison here is not as good as would be hoped. On the late ebb tide when the currents are going in a southwest direction the model over predicts speeds.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between Marine Scotland data (black) in the mouth of Loch Seaforth and model run (red). Model results reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-6b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between Marine Scotland data (black) in the Little Minch and model run (red). Model results reconstructed to be on the same timeframe	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

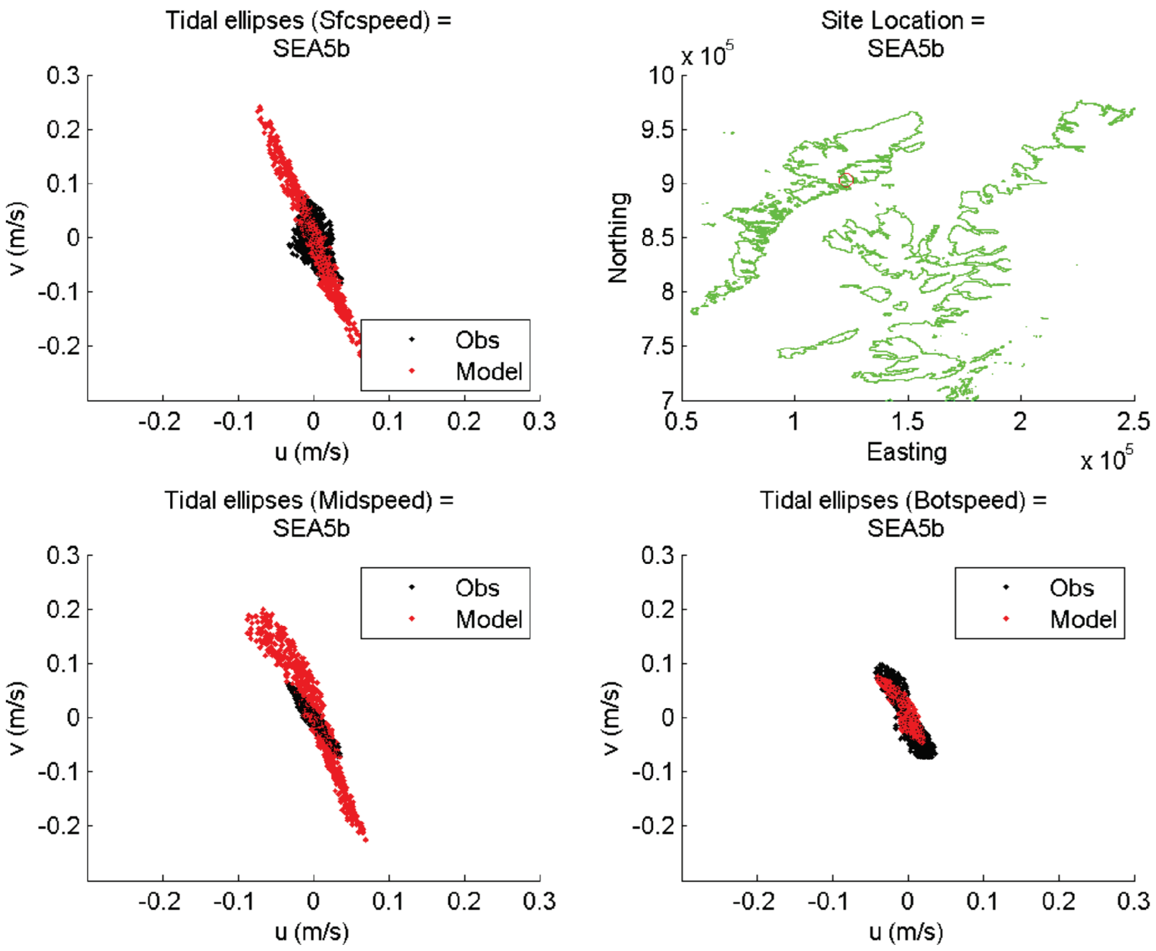
3.3.4.3 Comparisons against fish farm data

As mentioned previously, SEPA provided data from a large number of fish farms; a subset of these on the east coast of Lewis and Harris have been used for comparisons with the model results. Each dataset was recorded at different times for a minimum, of 15 days and therefore apart from the location presented in Section 3.3.4.2 there were no times coincident with boundary conditions or met forcing. Therefore a month long simulation of the baroclinic simulation from May 2009 was used to undertake a harmonic analysis of the model results as well as harmonic analysis of the fish farm data. Both sets of data were then reconstructed from the constituents to provide current speeds for a common time frame.

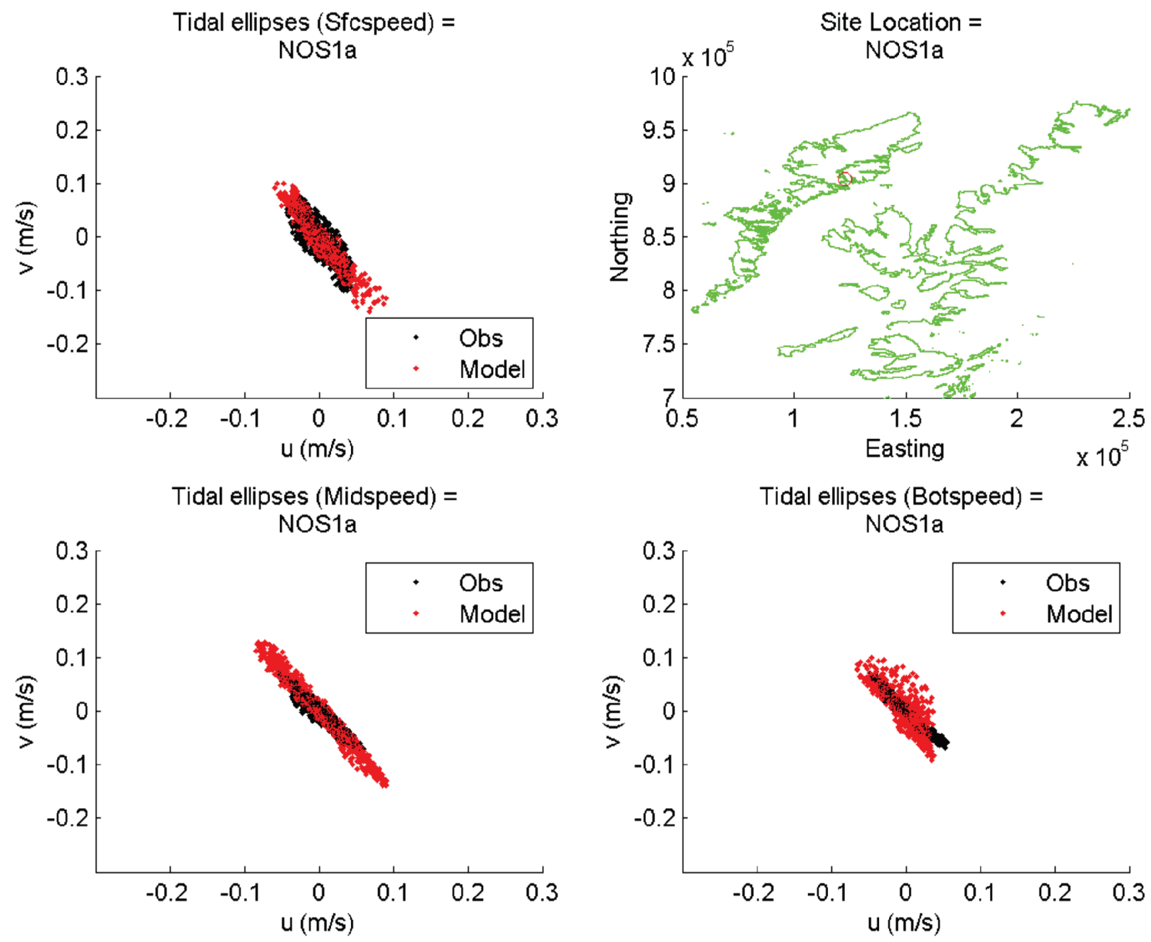
The results have been plotted as a scatter diagram of both the u and v components of the current speeds at the surface, mid –level and near bed representing the tidal ellipses at each location. It is these ellipses from the model and the data that have been compared against each other to check both the main direction and magnitude of the astronomical components of the local current regime.

The results are presented in Figures 3-7 a-h. In general the current speeds are very low in both the observations and model results with a good representation of these speeds and directions by the model. Figure 3-7a does not appear to provide as good a comparison as the other locations presented here. Other locations not included in this main body of the report can be seen in Appendix A.

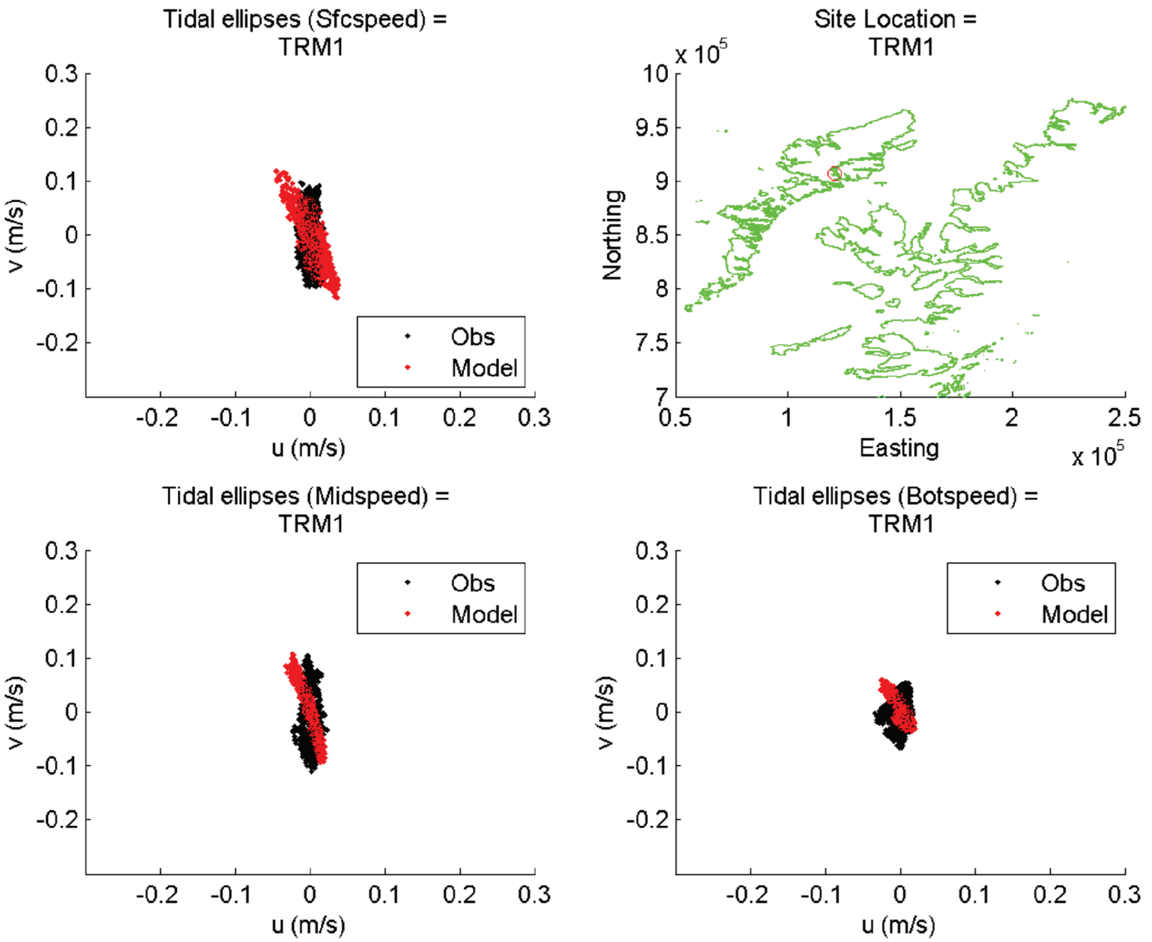
At speeds of 0.1-0.2m/s, it is likely that wind could dominate surface currents, the raw data from the fish farm measurements showed much more scatter due to the effects of meteorological forcings.



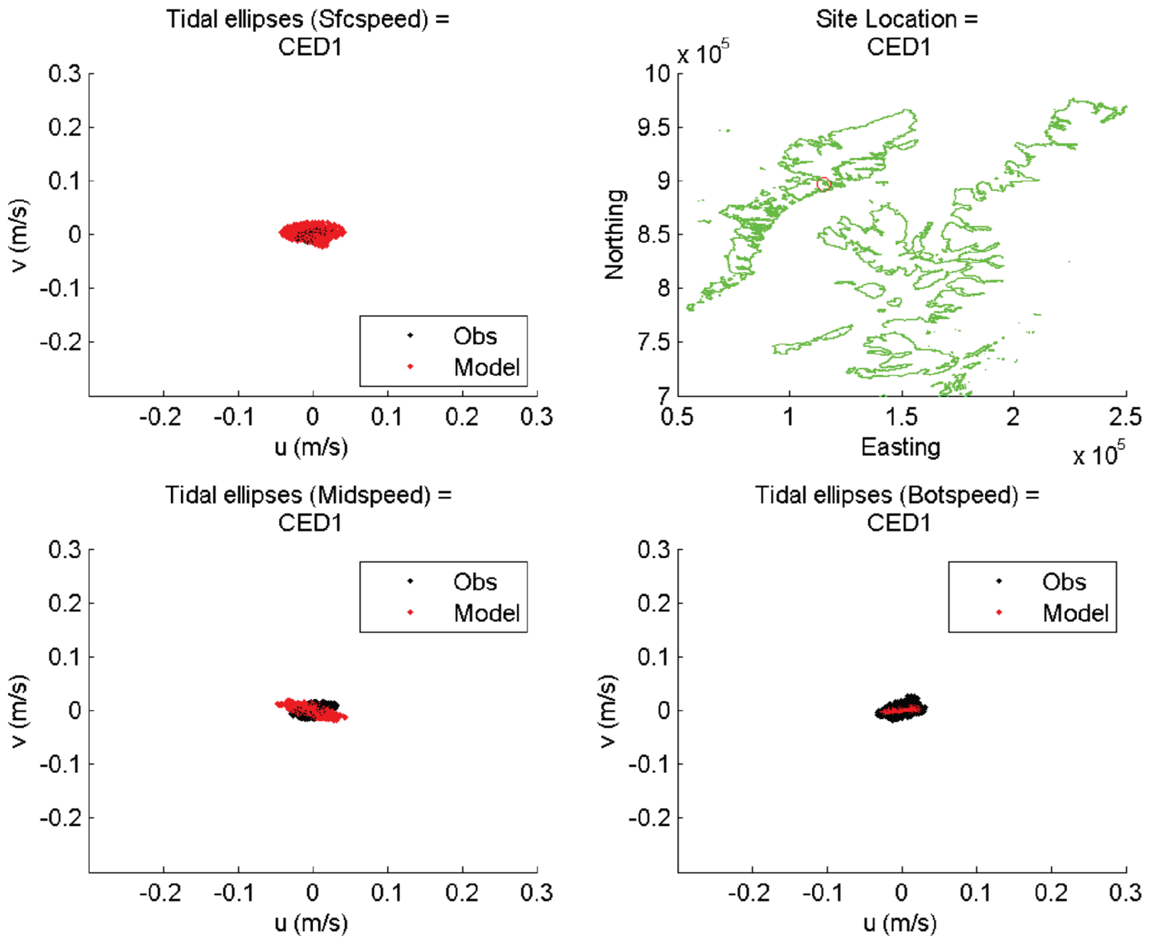
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



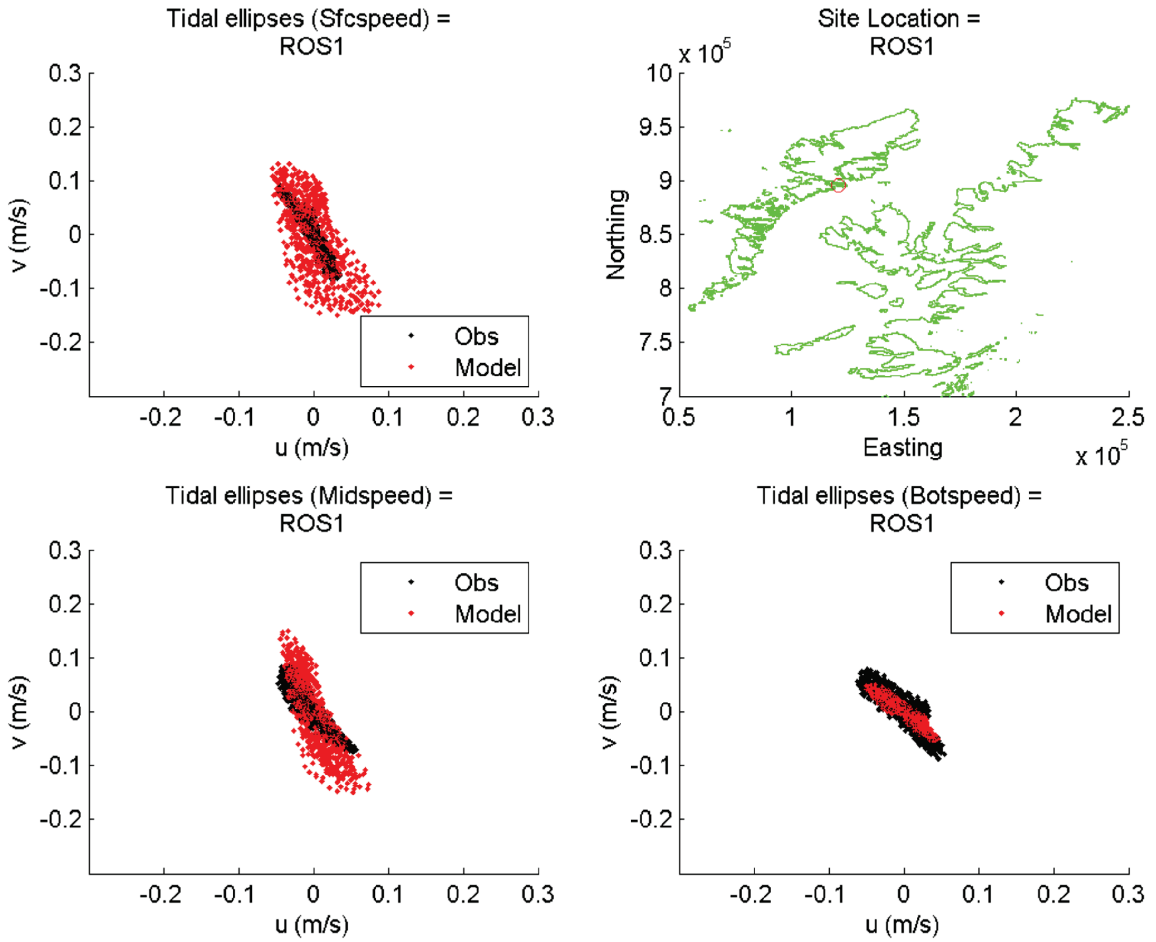
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



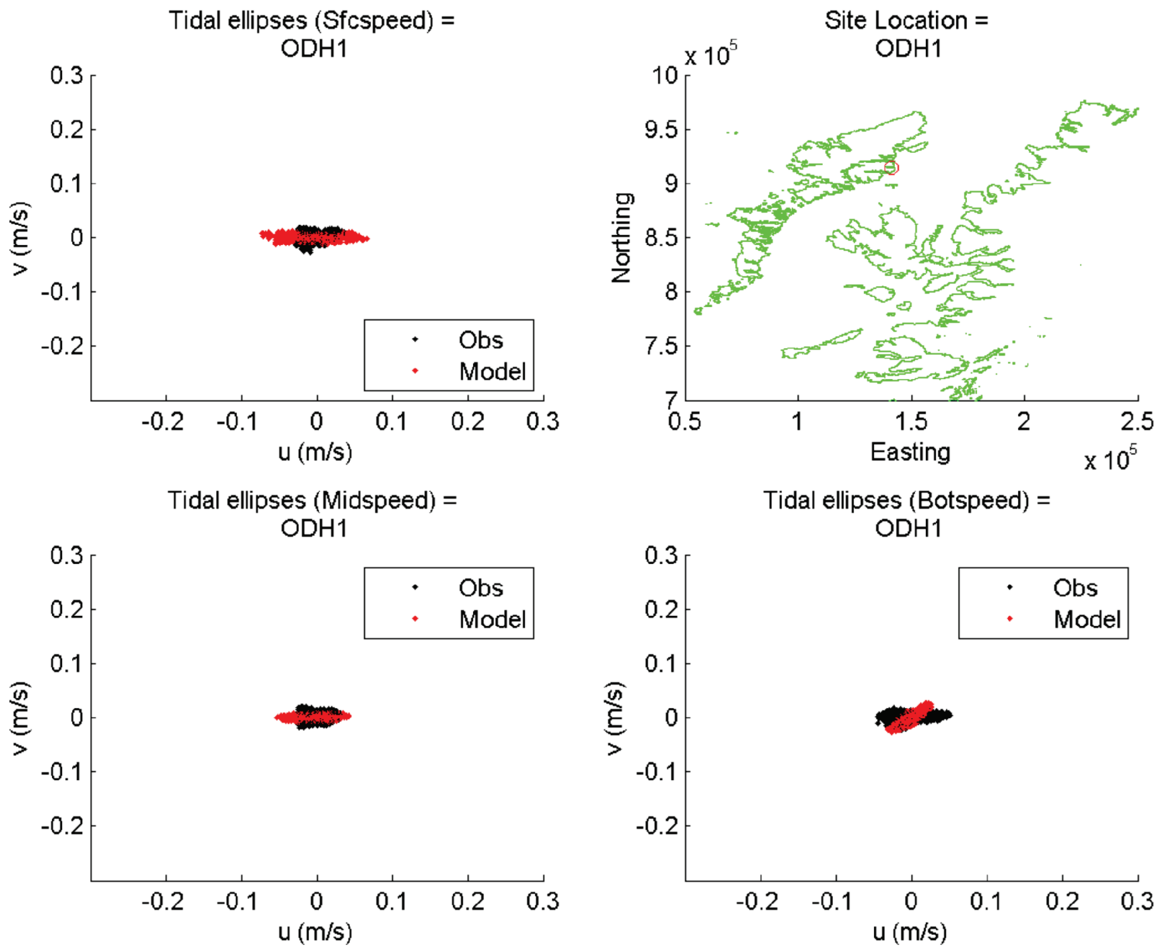
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



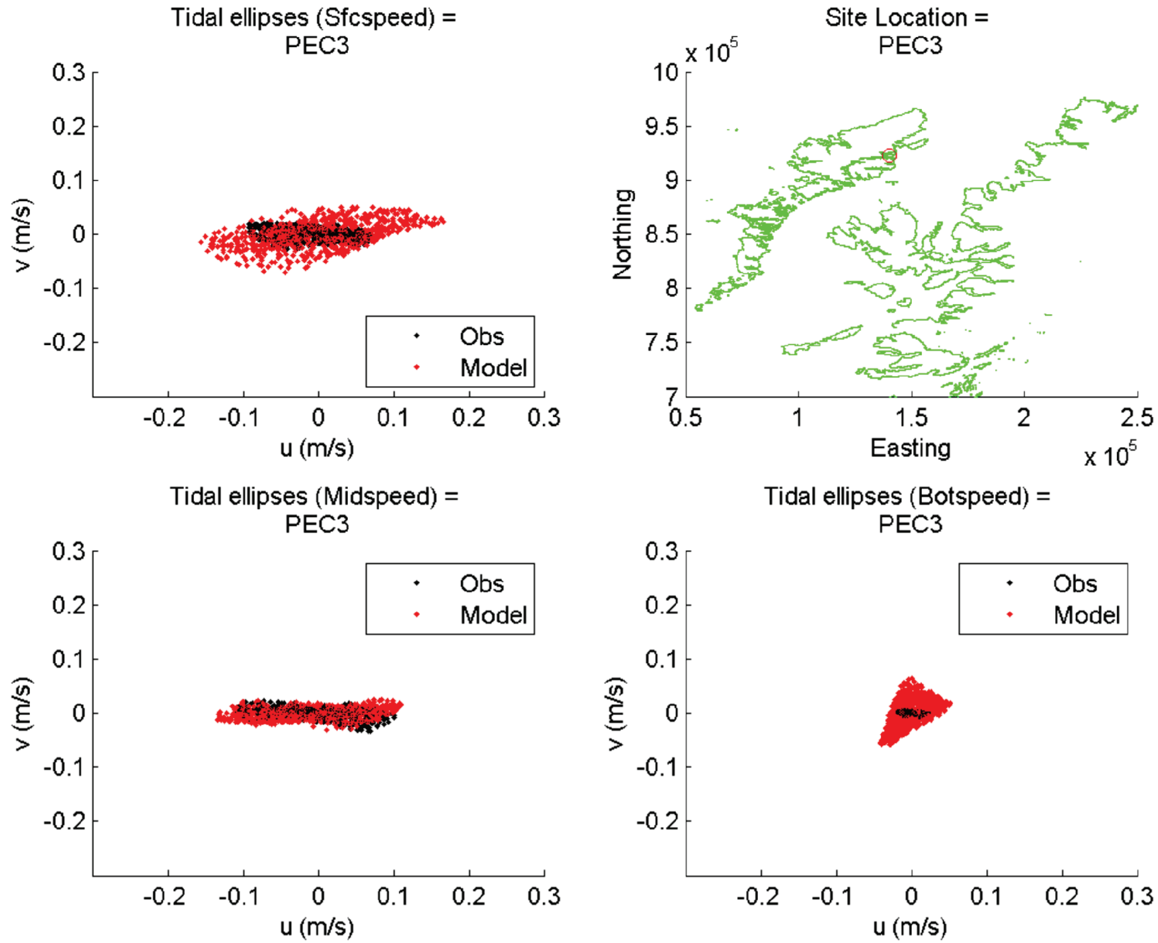
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7d		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



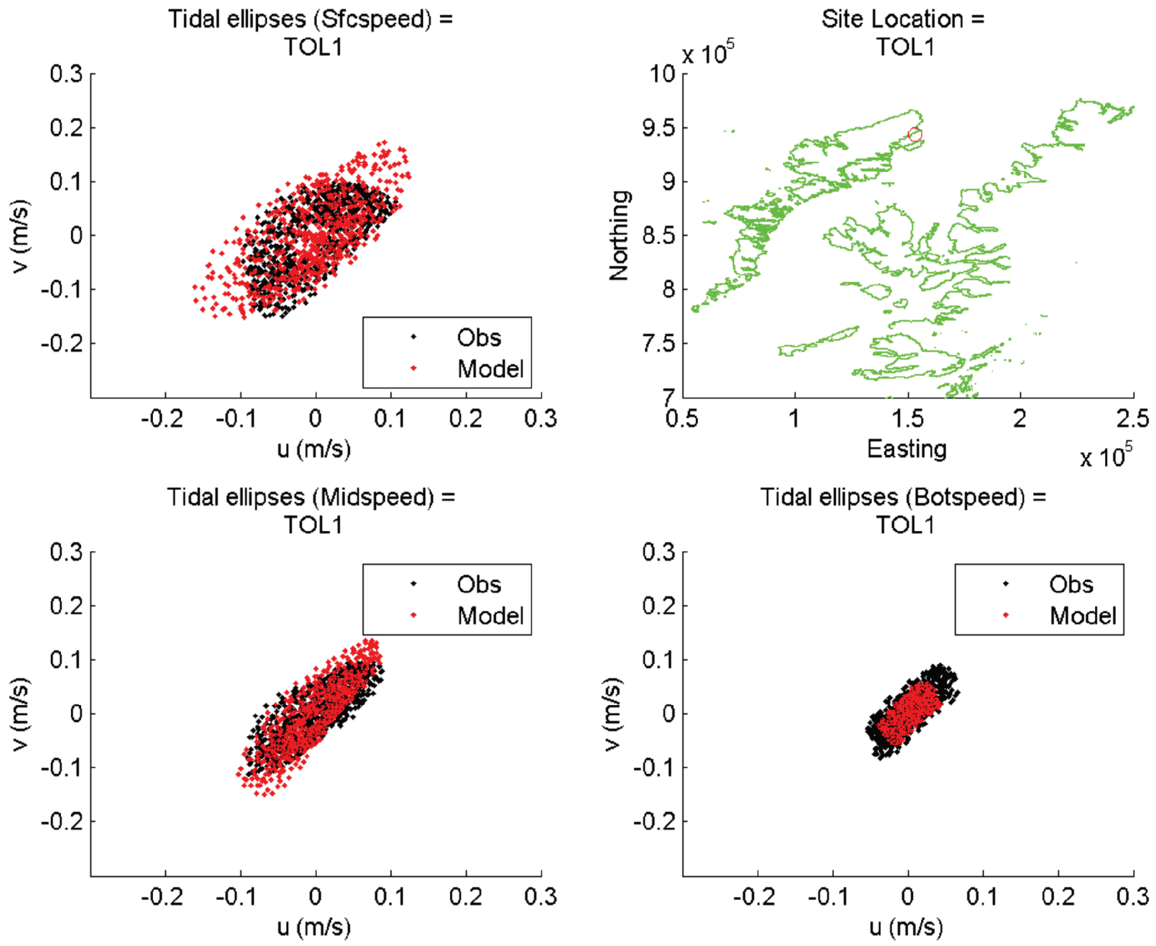
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7e		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7f		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7g		
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed:	Drawn:	Date: 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-7h		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.4 Flow model validation

3.4.1 Introduction

Validation of modelled currents was carried out for July 2009 against measured fish farm current data. The temperature and salinity validation took place by running the baroclinic model (all met forcing and river inputs) for March 2009 when various vertical profiles were available for direct comparison.

3.4.2 Current speed validation

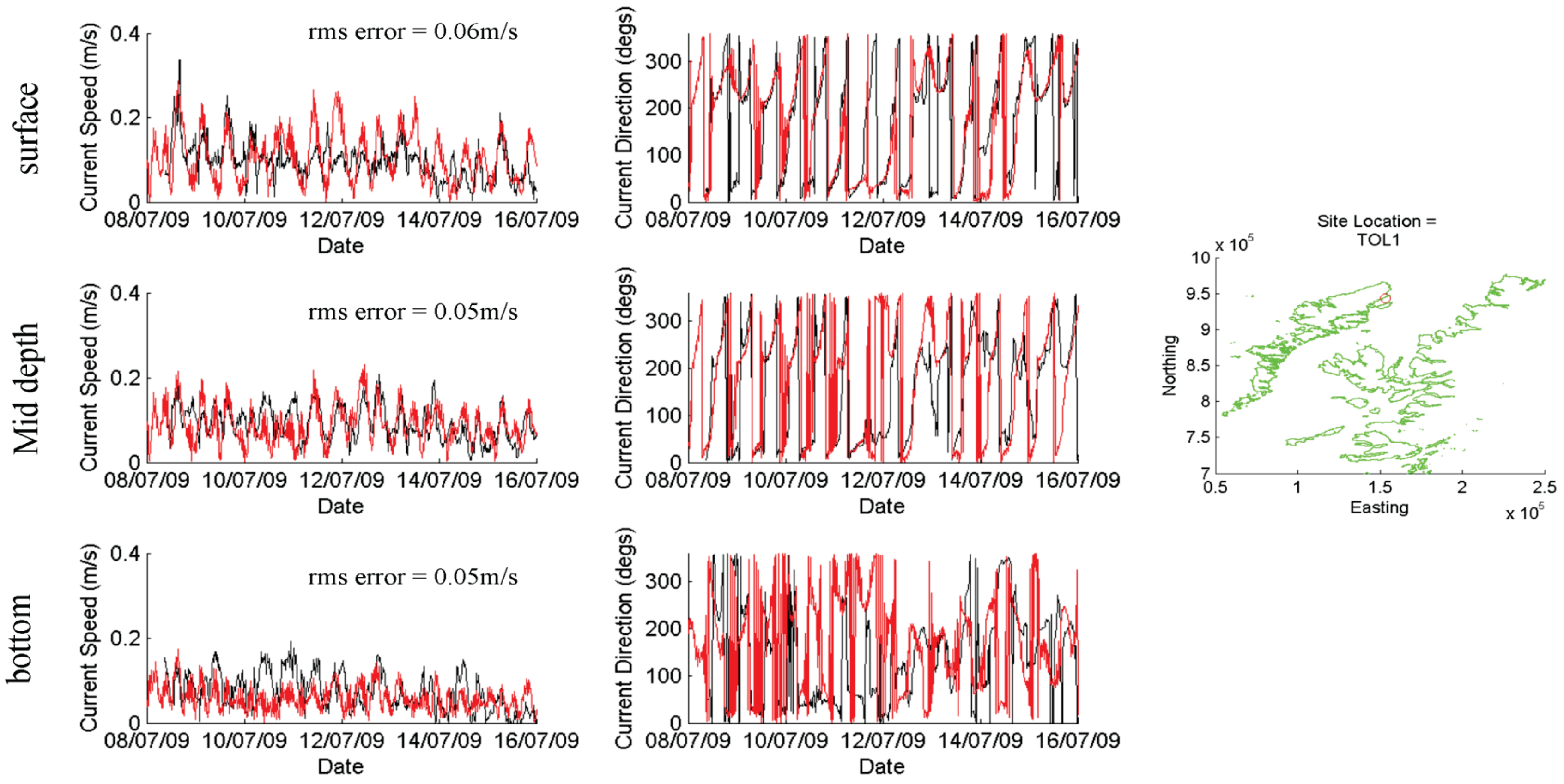
SEPA provided fish farm current speed data which had been recorded at a large number of locations around Scotland as part of the fish farm application process. Each data set consisted of near surface, mid depth and near bottom measurements of current speed and direction.

For many of these data sets, boundary conditions and met forcing were not available and therefore harmonic analysis and reconstruction was undertaken, as in the previous section. However for one location located off the east coast of Lewis (although it is towards the northern end) the period coincided with available boundary conditions, river data and meteorological forcing. Therefore the baroclinic model of the ECLH model was run to coincide with the period of the available data.

Figure 3-8 shows the comparison between the model and observed speeds and directions at the 3 depths. The near surface comparisons are on the top row and the near bottom are on the bottom row. The measurements are denoted with a black line and the model results with a red line.

It can be seen that in general the current speed comparisons are good with model and observed speeds generally less than 0.3m/s near to the surface and less than 0.2m/s at lower levels. RMS errors are 0.06m/s close to the surface and 0.05m/s at the lower levels. A visual comparison suggests that the model results are closer at the mid depth that at the others. The comparison is reasonable given the low current speeds. Another factor that may be affecting the results is the relatively coarse wind data used compared with the location of the data close to land and a loch. Local wind conditions may play a part in some of the differences observed.

Comparison of model and observed current speed & direction at Tol 1



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-8		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison fish farm data (black) at location TOL1 and model results (red).	Checked: DMP	Scale: Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.4.3 Comparison of baroclinic model results against vertical temperature and salinity profiles

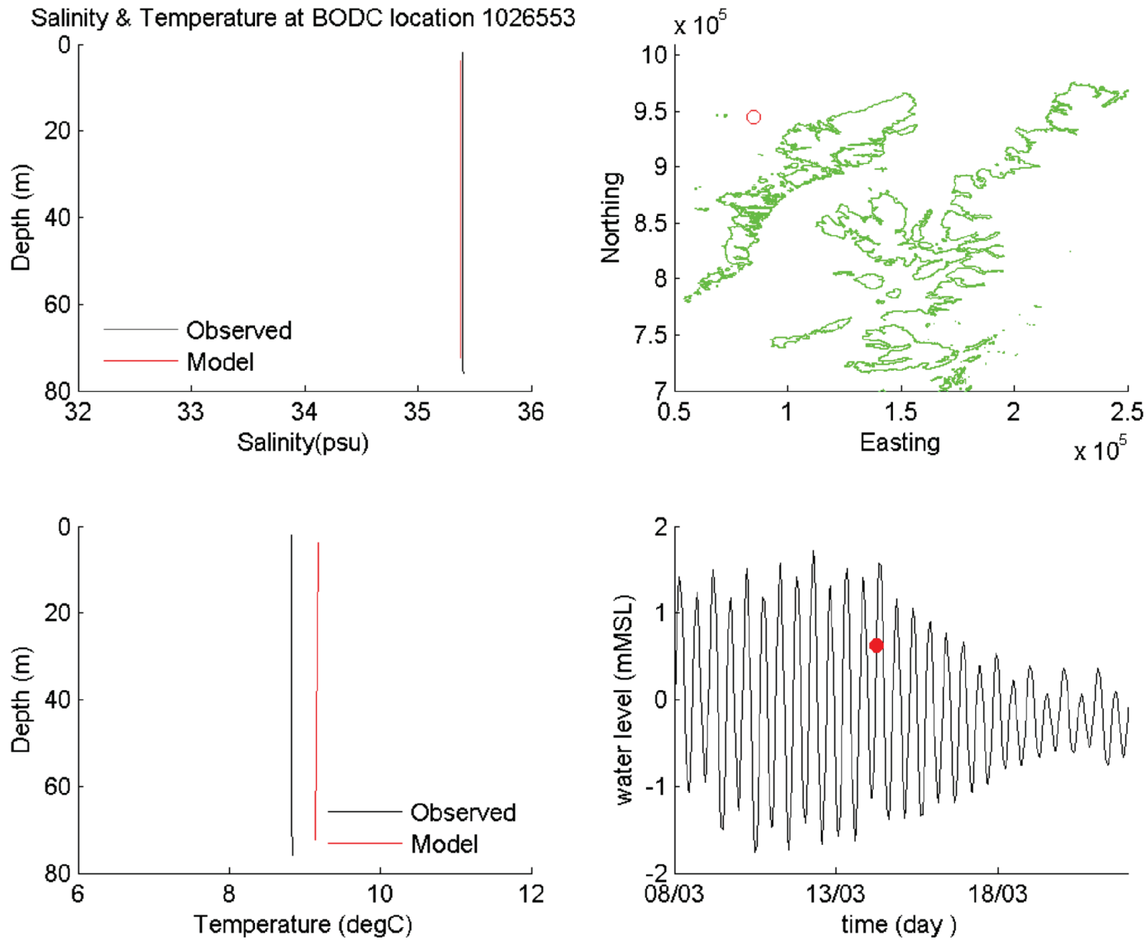
The ECLH baroclinic model has included freshwater river flow input using data provided by CEH. Temperature and salinity daily data from the AMM model was applied at the nested boundaries as well as being used as initial conditions with which to start the simulation to reduce warm-up periods. Additionally it includes the internal calculation of heating (HEATING_CALCULATED is turned on in the model) within the model as well as wind, evaporation, precipitation and air pressure.

Vertical profile data was available in March 2009 throughout the model area and was obtained from the BODC archive. Therefore the Baroclinic model was run for a period during this month using the corresponding forcing information from the AMM model, river inflows and meteorological forcing.

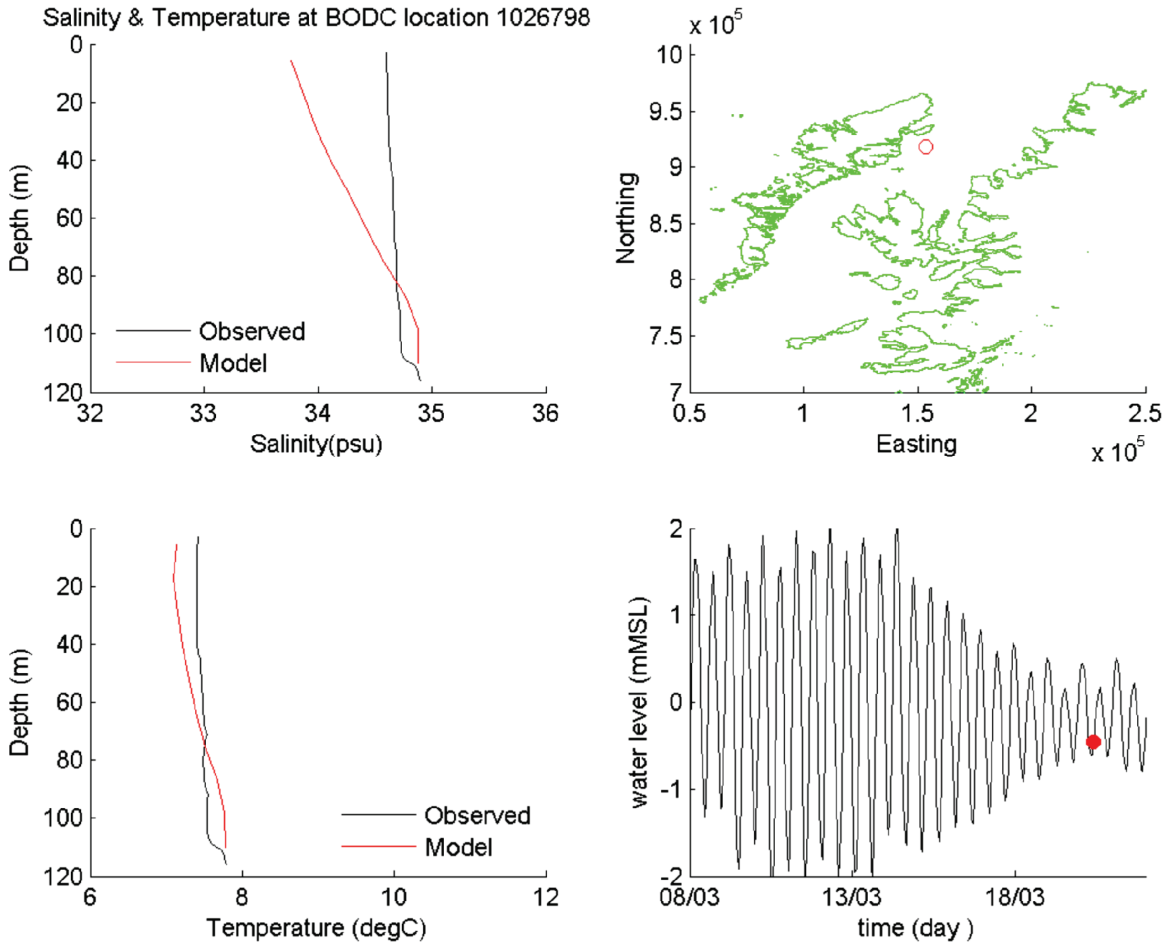
The results from the model are presented in Figures 3-9a-h in the form of vertical profiles of salinity (top left frame), temperature (bottom left frame), location (top right) and tide curve with the time of the measurement highlighted (bottom right). Other locations not included in this main body of the report can be seen in Appendix A.

The observed data is shown with black lines, and the model results in red. It can be seen that the model simulates the temperature through the depth well, with differences being less than one degree and generally in the order of half a degree.

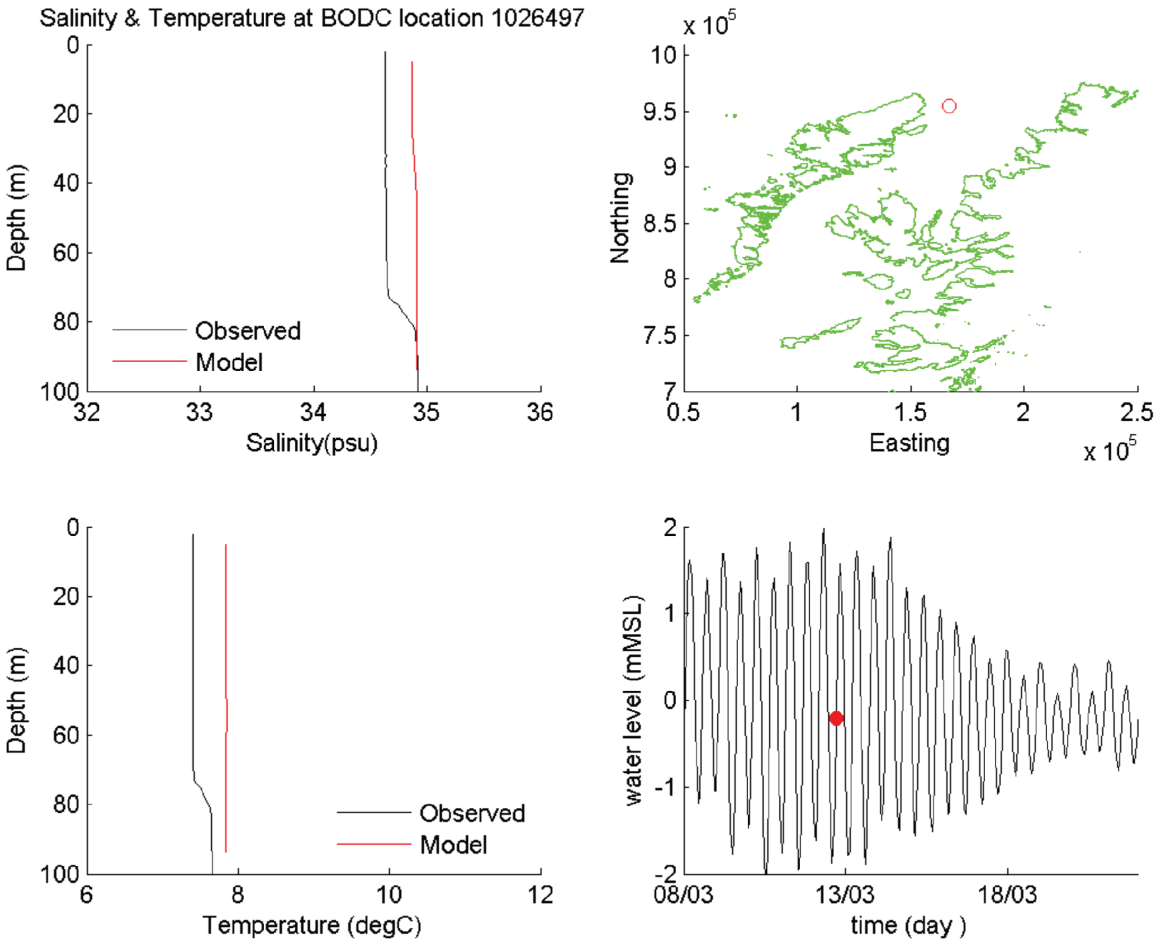
Salinity results from the model are at times a very close match, but at other times/locations there is up to a 1psu difference with the model predicting slightly lower salinities although closer to the bed the difference is reduced.



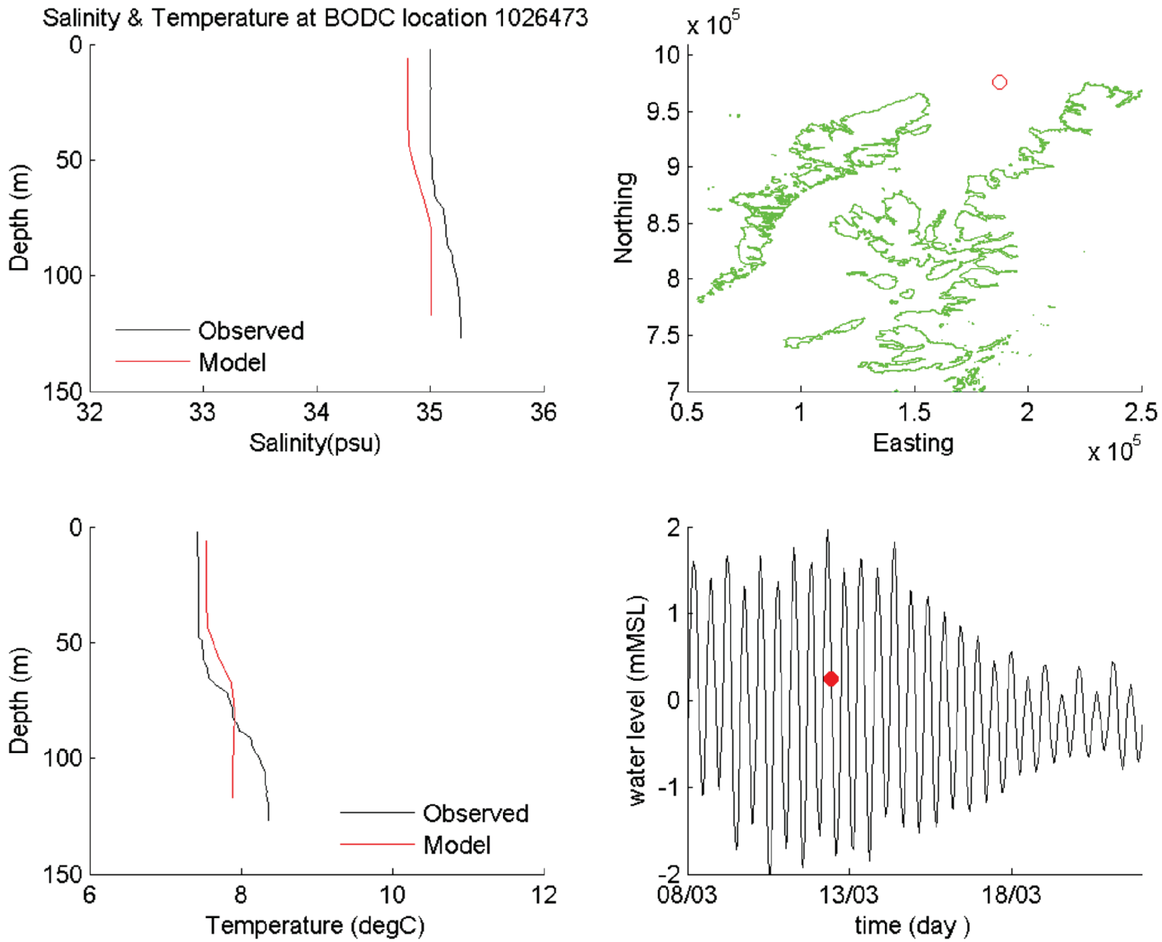
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014



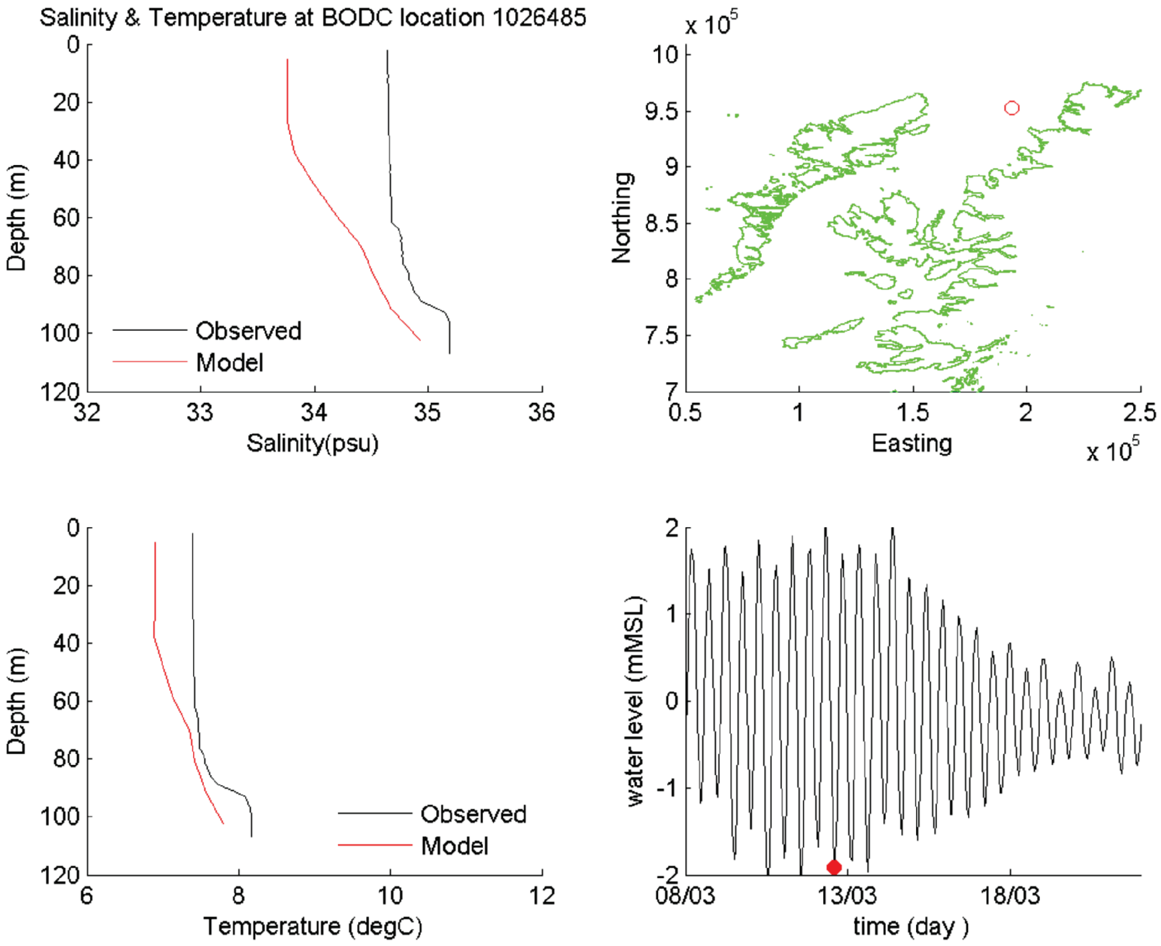
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



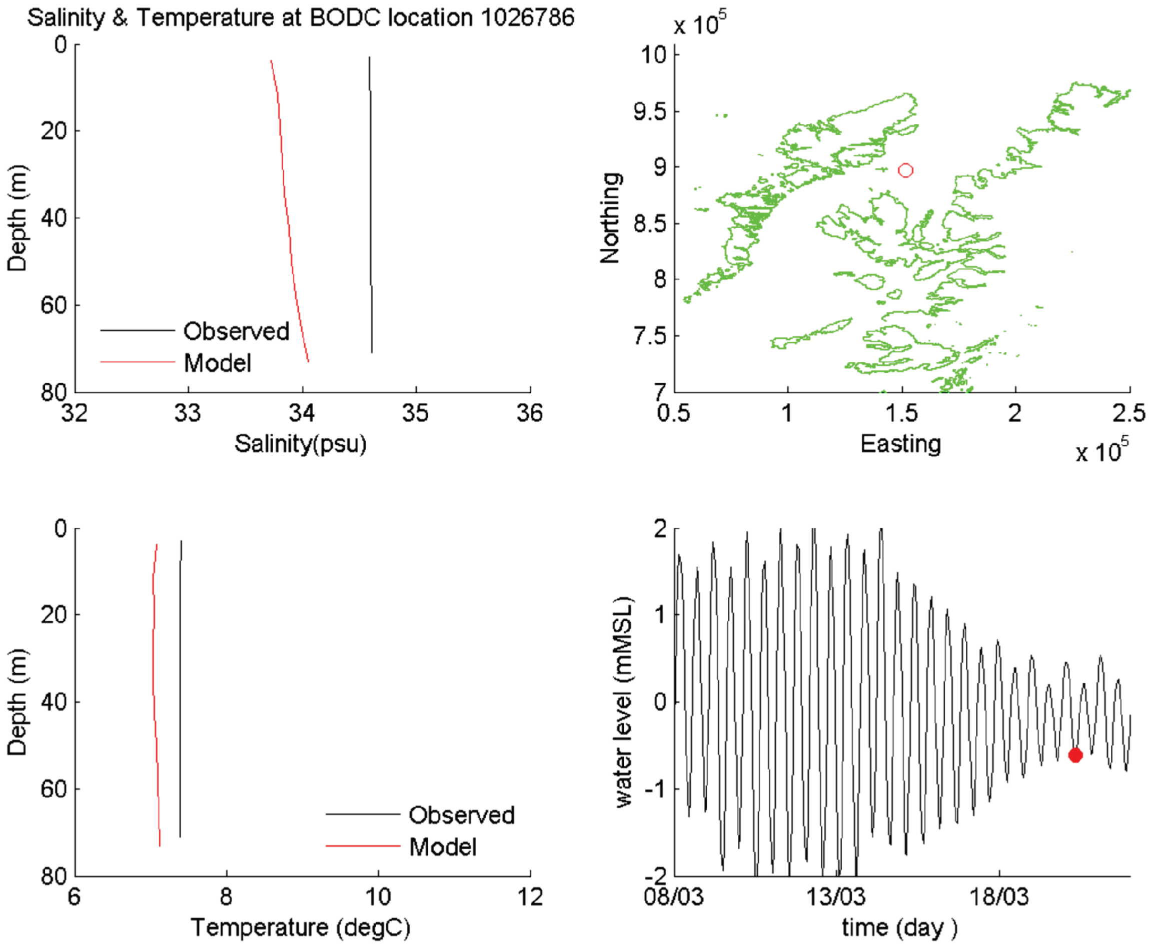
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



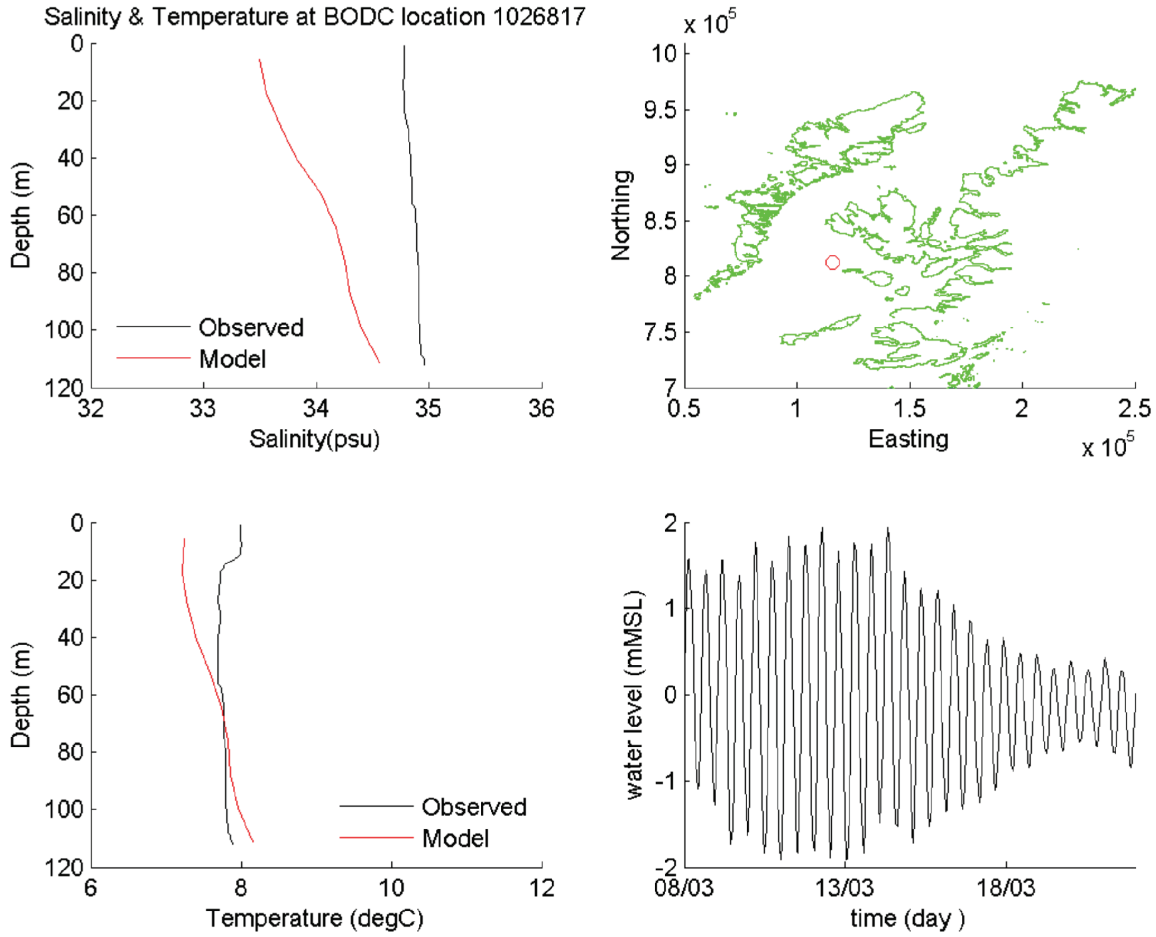
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9d		
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



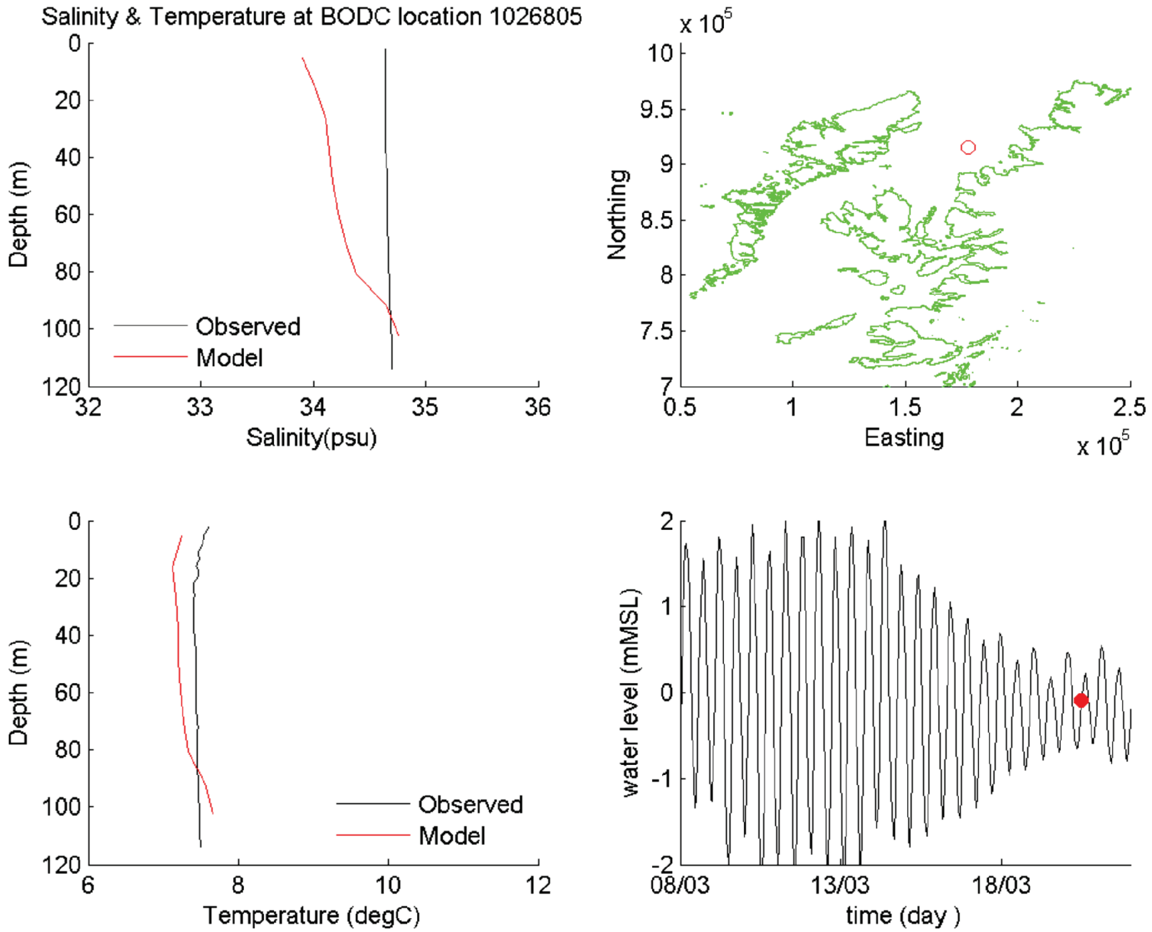
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9e		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9f		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9g		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-9h		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.5 Summary of ECLH model calibration and validation

The ECLH model was initially setup to run with water level boundaries only. However as with other case study models within this project, there were numerous problems with instabilities which led to the use of nested boundaries. The type 2 nested boundary was used for this purpose, with water levels prescribed in a separate file to the velocities and temperature/salinity. This improved the stability of the model and allowed an external timestep of 3 seconds and an Isplit of 3 (therefore internal timestep = 9 seconds).

The boundary data used for the model calibration/validation stage came from the AMM model. However, for the climatological runs boundary data from the Scottish Waters Shelf Model developed under Stage 1 of this study are used.

The results in this section present comparisons between results from the ECLH model and observed data. In general, the model is able to reproduce current speeds and water levels within the guidance targets as well as the temperature being reproduced within 0.5 degrees and the salinity within 1psu. Therefore the model has been deemed to have been calibrated to a sufficient level to be taken forward for use with the climatological forcing. This is presented in the next Chapter.

3.6 Flow model simulations

3.6.1 Introduction

This section of the report describes the climatology runs of the flow model. The model set up used has been described in the calibration section. The requirement was to produce a six month run, from May to October, based on climatological forcing. This run was carried out using the Scottish Shelf model climatology results as initial conditions as well as for boundary conditions. The climatological input data sets for meteorological forcing and river fluxes used in the Shelf model were also used for the ECLH model. For a full description of the input data, the sources and how it was processed for climatological runs see the Scottish Shelf Modelling report, (Wolf et al. 2015)

The results from the climatic run have been compared with climatological atlas information for temperature, salinity and currents. The neap and spring tidal ranges and peak flows are also compared with the ABPmer tidal atlas.

The model results provide a distribution of the typical tidal and residual currents over ECLH which is used for particle tracking and to develop connectivity indices.

3.6.2 Climatology input data

3.6.2.1 Boundary conditions

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

3.6.2.2 River input

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

Only 155 of these rivers fall within the ECLH model domain. The rivers were processed in the same way as those for the baroclinic calibration model runs. Figure 3-10 shows the location of the rivers and the location of the nodes the rivers were applied at.

3.6.2.3 Meteorological forcing

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

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

3.6.3 Validation

3.6.3.1 Temperature and Salinity Comparisons

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

1) The ICES dataset (http://www.ices.dk/marine-data/data-portals/Pages/ocean.aspx) gridded and averaged for 1960-2004 (45 years) by Jason Holt. Data are also available from the NOAA/NDBC World Ocean Atlas (2013);

3.6.2 Climatology input data

3.6.2.1 Boundary conditions

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

3.6.2.2 River input

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

Only 155 of these rivers fall within the ECLH model domain. The rivers were processed in the same way as those for the baroclinic calibration model runs. Figure 3-10 shows the location of the rivers and the location of the nodes the rivers were applied at.

3.6.2.3 Meteorological forcing

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

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

3.6.3 Validation

3.6.3.1 Temperature and Salinity Comparisons

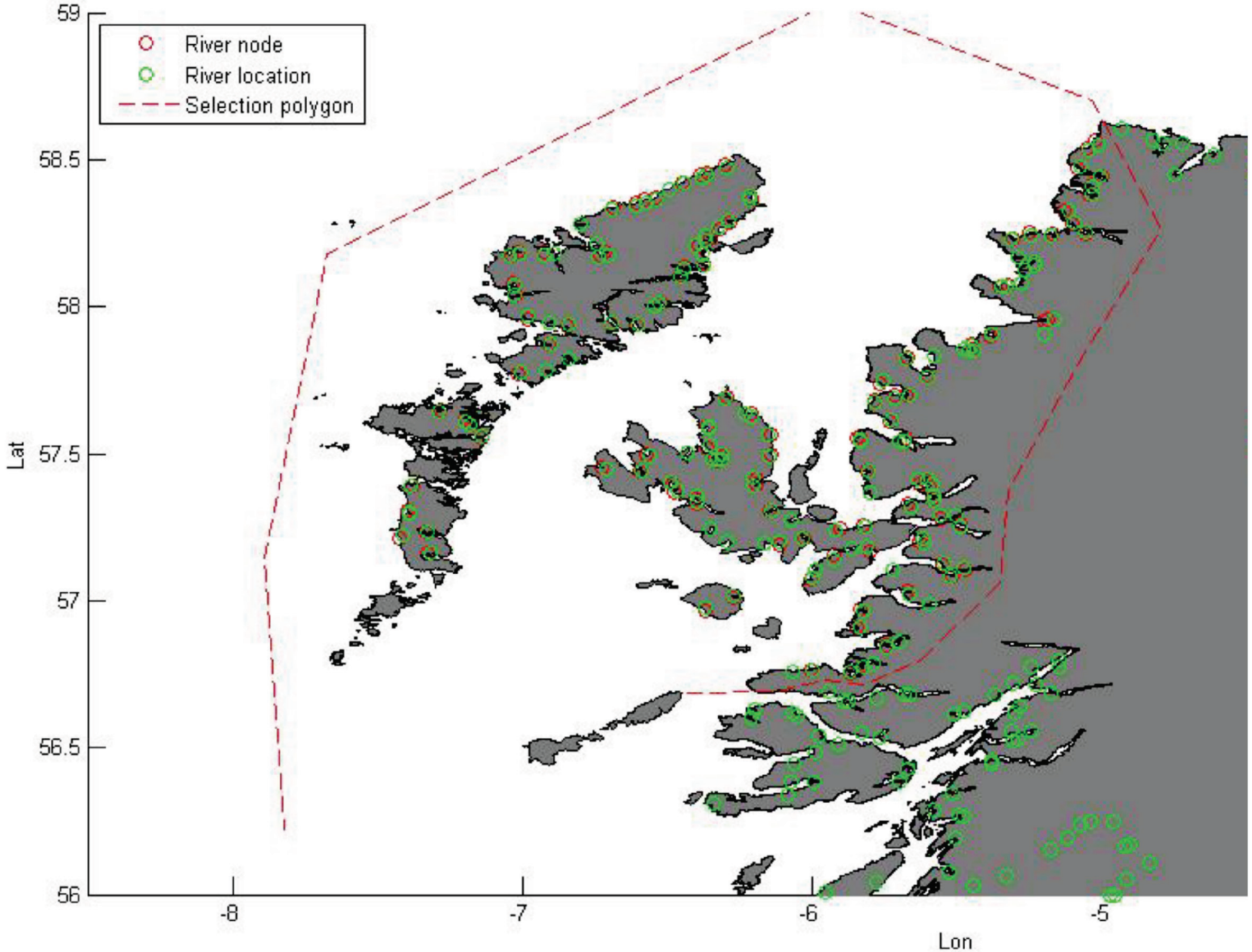
Average monthly sea surface temperature (SST) and sea surface salinity (SSS) observations are available from two sources:

1) The ICES dataset (http://ocean.ices.dk/HydChem/HydChem/aspx?plot=yes) gridded and averaged for 1960-2004 (45 years) by Jason Holt. Data are also available from the NOAA/NDBC World Ocean Atlas (2013);

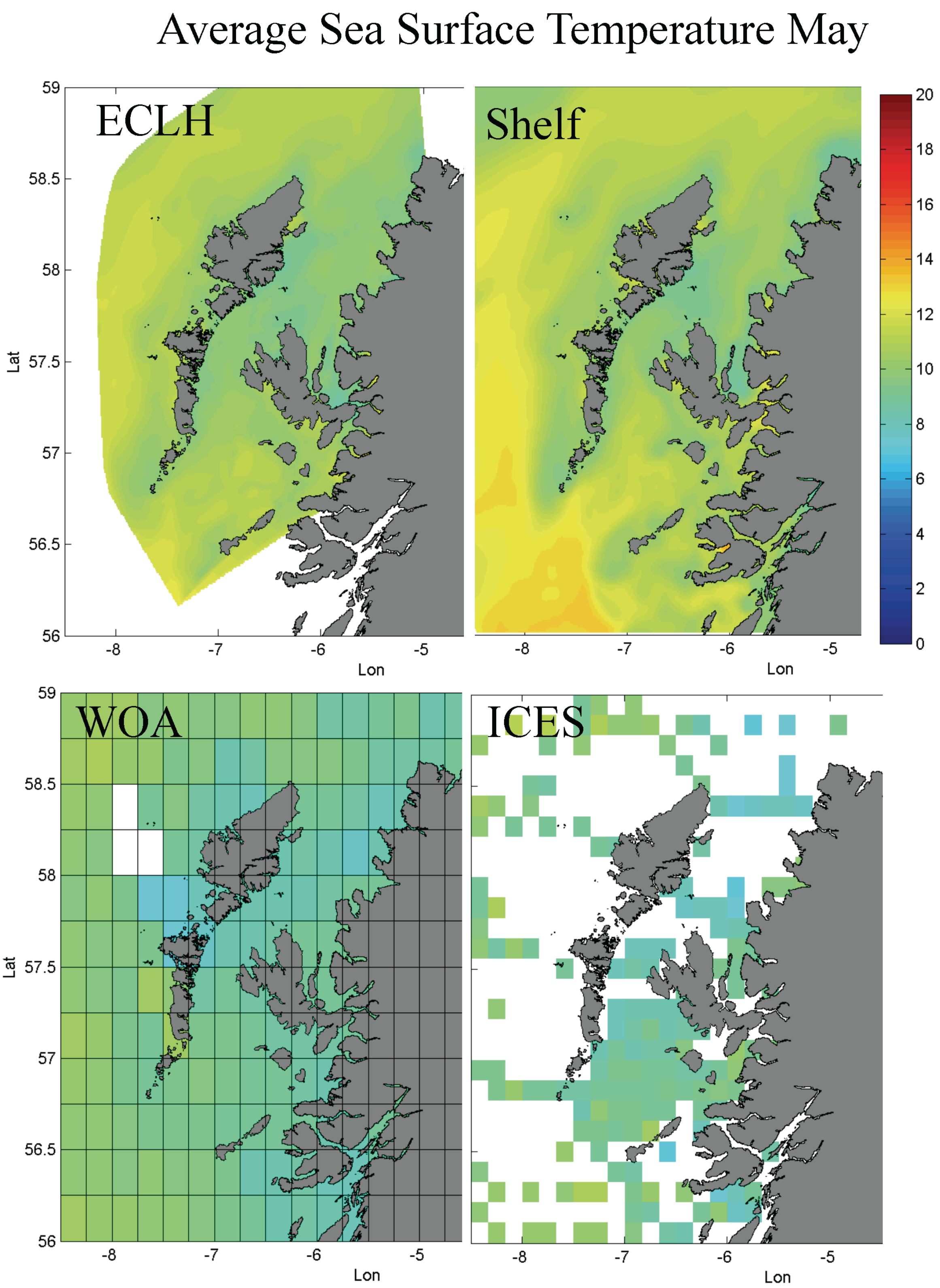
2) The WOA (World Ocean Atlas) http://www.nodc.noaa.gov/OC5/woa13/) based on over 100 years of observations interpolated on to a 0.25° resolution grid.

These datasets are used for qualitative comparison with the ECLH FVCOM results for May, August and October. The results from the shelf model are also presented. Figures 3-11a-c shows the comparison of the data sets for SST. The comparison between the data sets is good for all months.

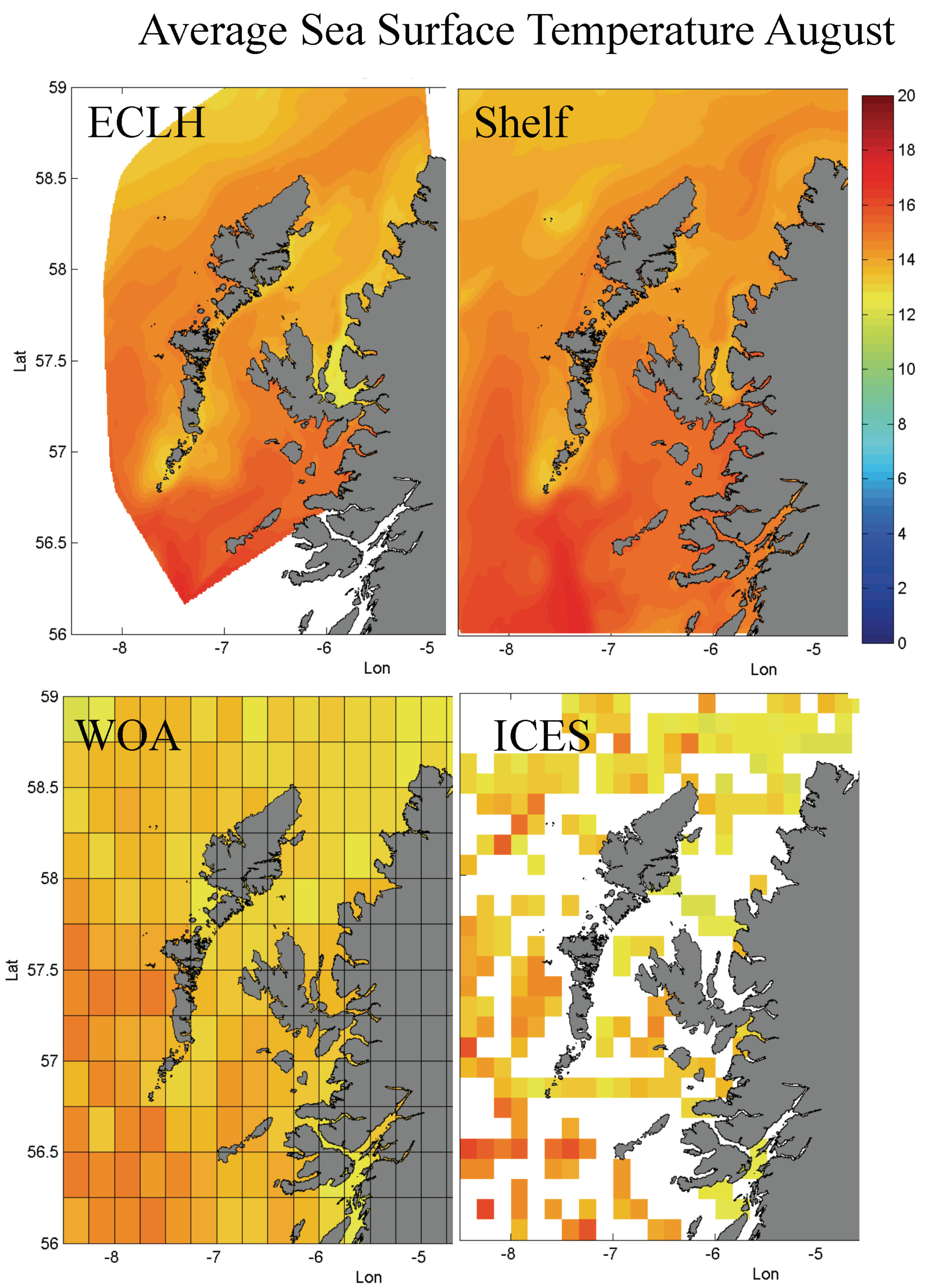
Figure 3-12a-c shows the SSS comparisons. The salinity close to land where rivers are discharging are lower in May than August and October due to the relative levels of rainfall and river discharge. The comparison between the data sets shows good agreement for all months.



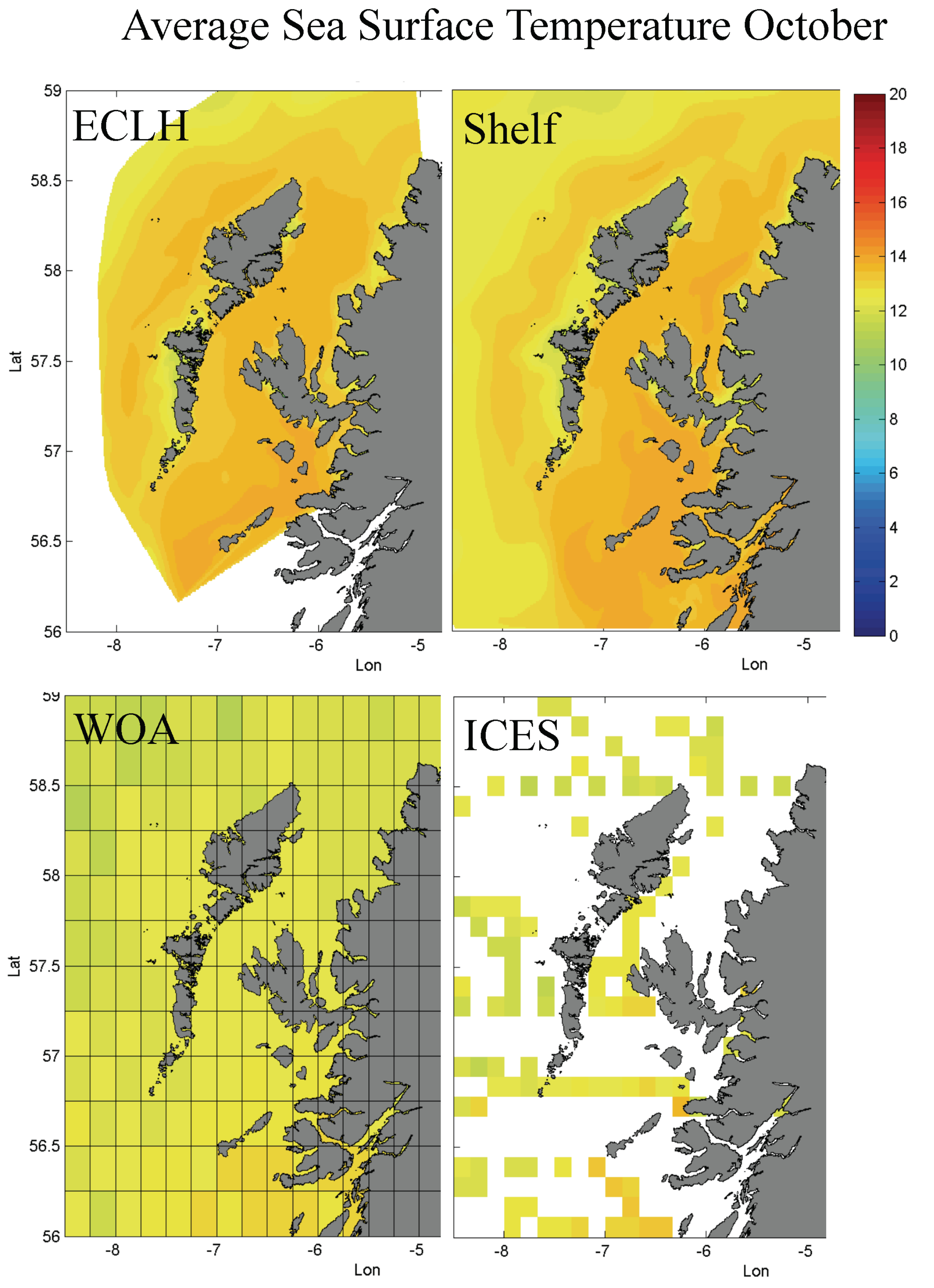
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-10		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Locations of rivers (Green) and the node locations at which the river flows were applied at (red)	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



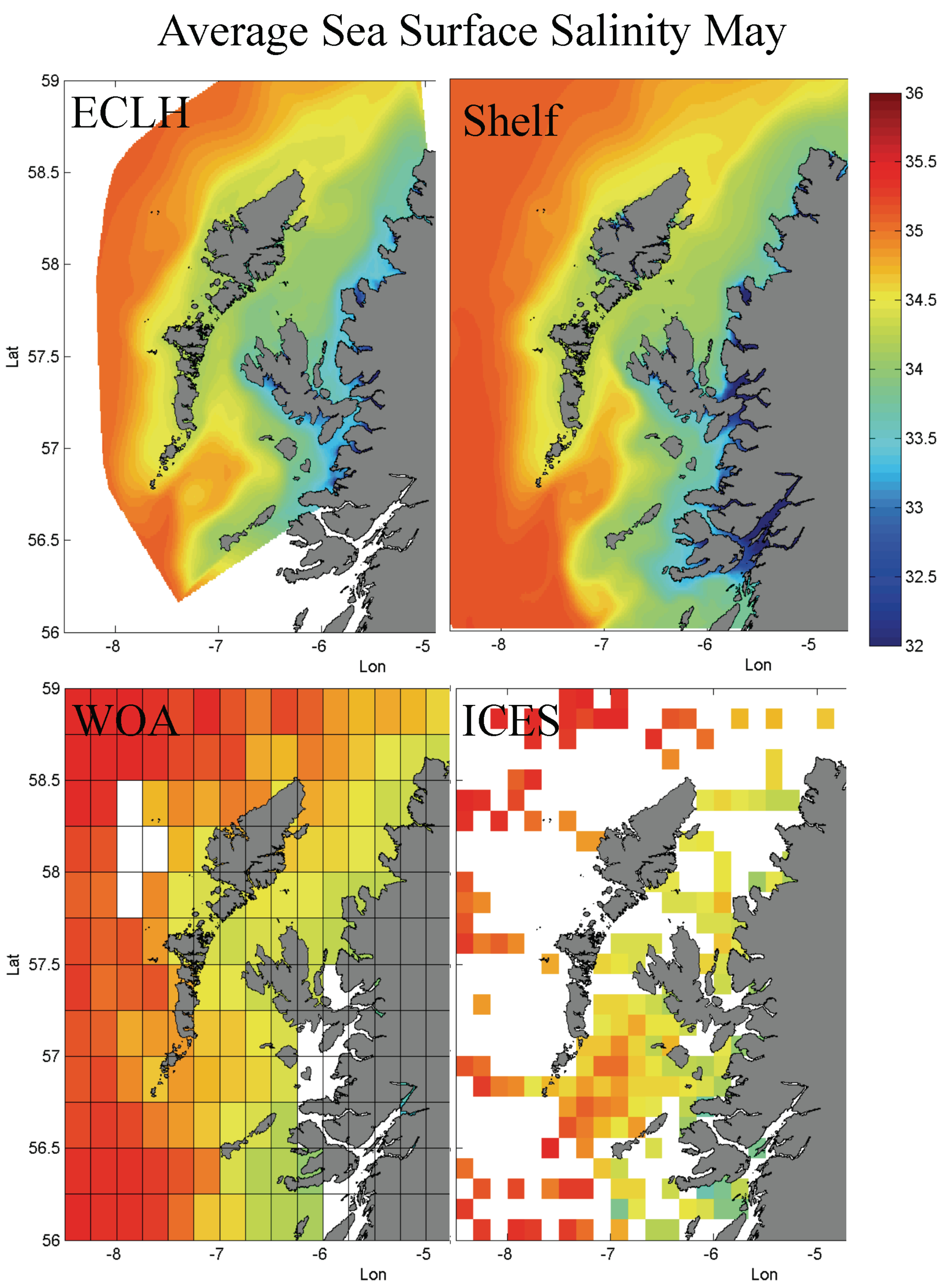
Client	Consulting Engineer	Project:	Figure 3-11a
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of sea surface temperatures averaged for May from the ECLH climatology run, the shelf model, WOA and ICES data



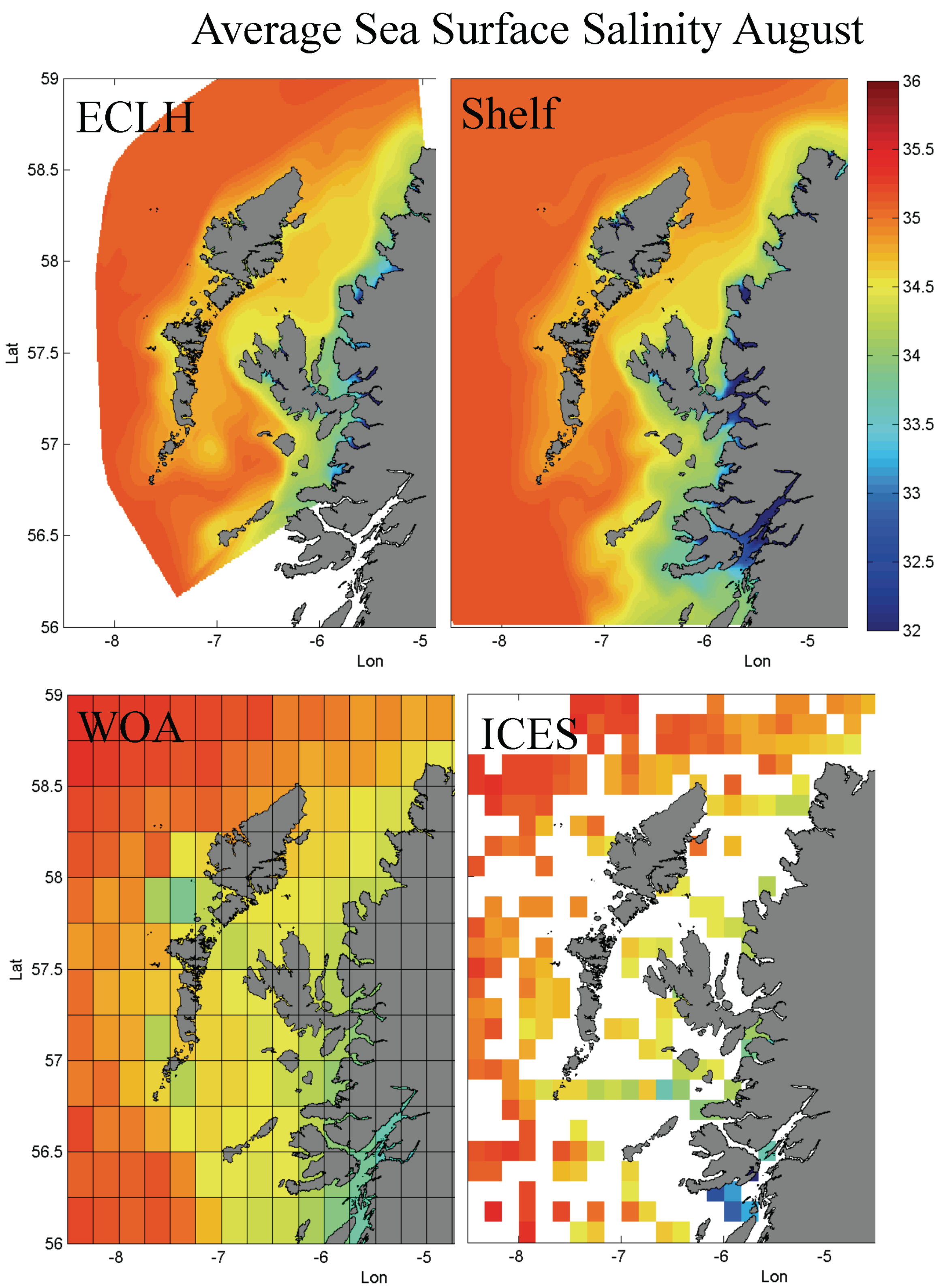
Client	Consulting Engineer	Project:	**Figure 3-11b**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of sea surface temperatures averaged for August from the ECLH climatology run, the shelf model, WOA and ICES data



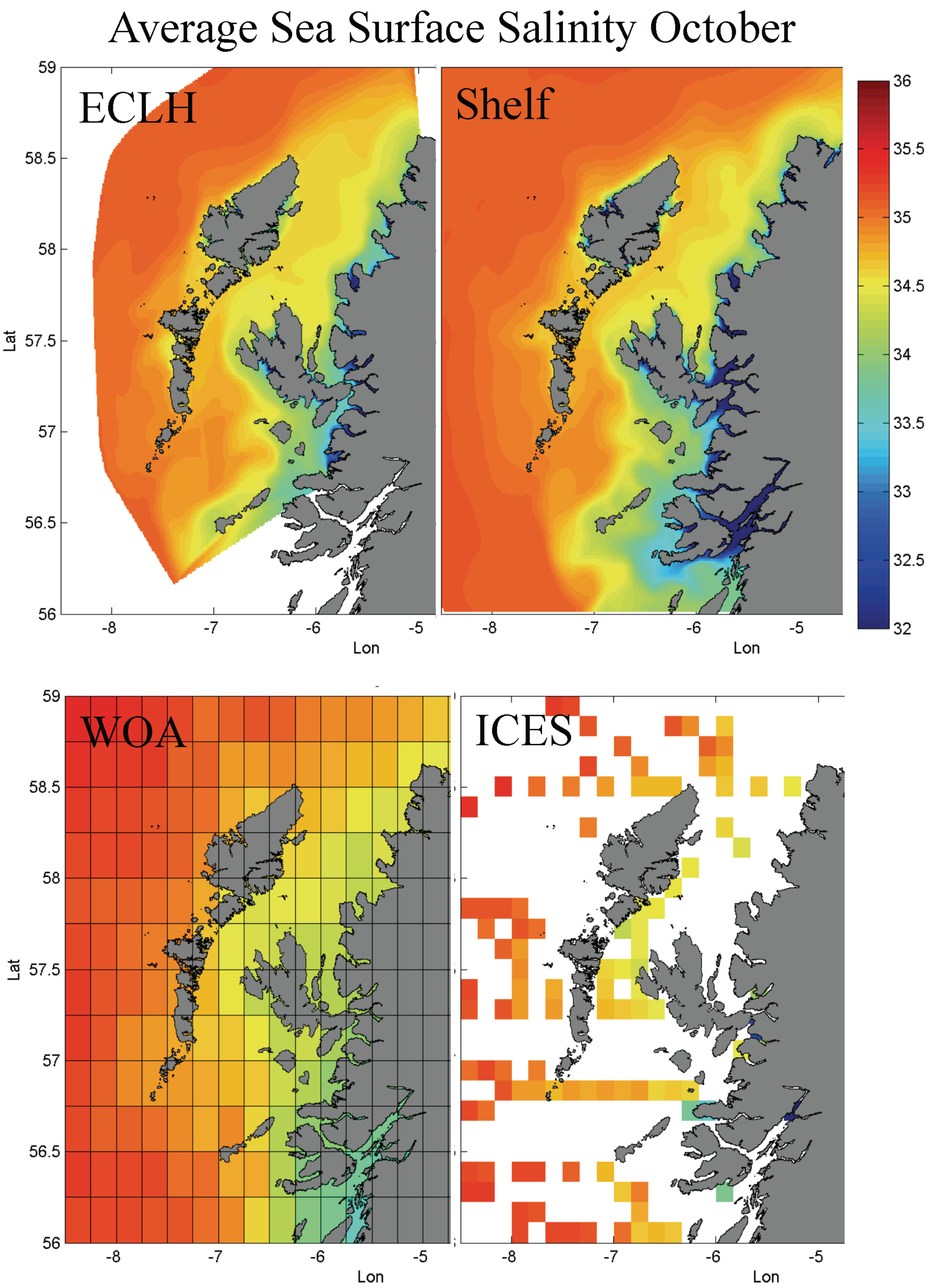
Client	Consulting Engineer	Project:	Figure 3-11c
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Comparison of sea surface temperatures averaged for October from the ECLH climatology run, the shelf model, WOA and ICES data



Client	Consulting Engineer	Project:	**Figure 3-12a**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of sea surface salinity averaged for May from the ECLH climatology run, the shelf model, WOA and ICES data



Client	Consulting Engineer	Project:	**Figure 3-12b**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of sea surface salinity averaged for August from the ECLH climatology run, the shelf model, WOA and ICES data



Client	Consulting Engineer	Project:	**Figure 3-12c**
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of sea surface salinity averaged for October from the ECLH climatology run, the shelf model, WOA and ICES data

3.6.3.2 Mean Spring/Neap Tidal Range

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

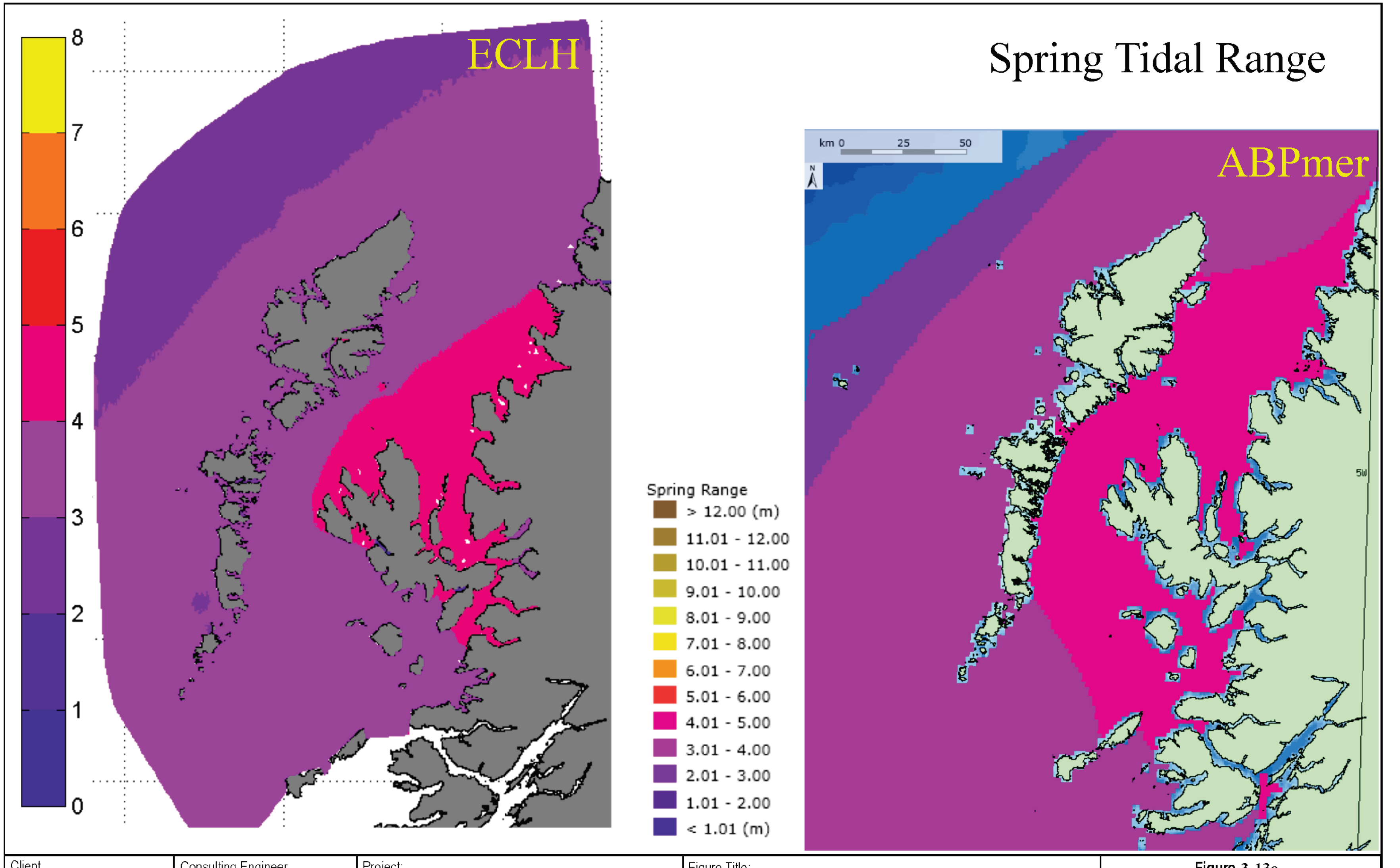
mean high-water springs = $Z_0 + (H_{M2} + H_{S2})$
mean low-water springs = $Z_0 - (H_{M2} + H_{S2})$
spring tidal range = mean high-water springs – mean low-water springs

Values for these constituents were obtained from a harmonic analysis of 60 days' worth of data from the ECLH climatology run (01/05 - 30/06). These harmonic components control the timing of the spring-neap cycle, and their combination is considered to give a good measure of average spring (and neap) tides. The data was also used to calculate the mean neap tidal range as:

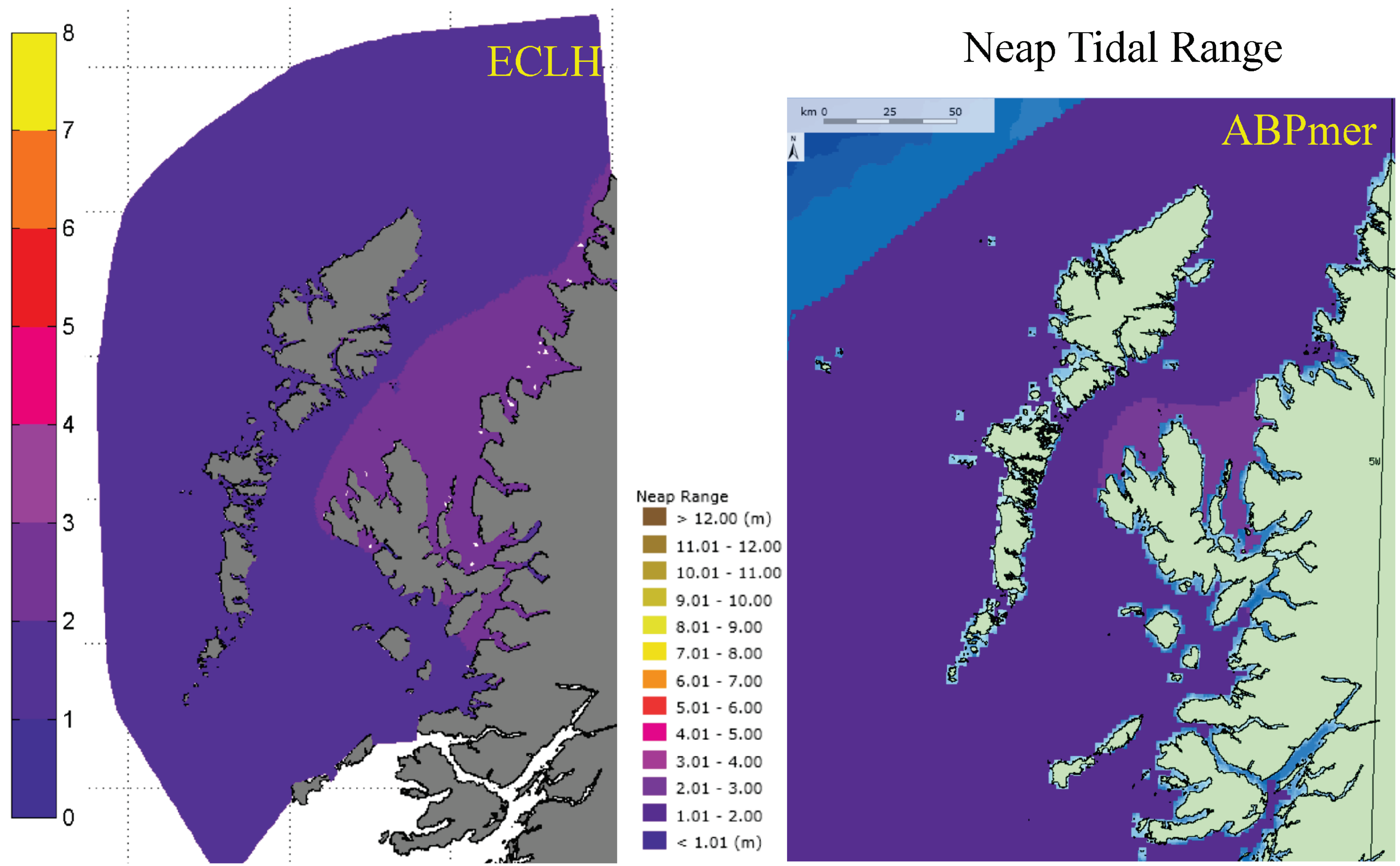
mean high-water neaps = $Z_0 + (H_{M2} - H_{S2})$
mean low-water neaps = $Z_0 - (H_{M2} - H_{S2})$
neap tidal range = mean high-water neaps – mean low-water neaps

A map of the mean spring results are shown, along with the equivalent tidal range from the ABPmer / NOC Atlas of Marine Energy Resources (http://www.renewables-atlas.info/) in Figure 3-13a. The corresponding plots for mean neap tidal range are shown in Figure 3-13b. The spring tidal range from the ECLH FVCOM model is lower than that shown in the ABPmer tidal atlas in the area between the Outer Hebrides and the mainland. The comparison of neap tidal range in Figure 3-13b shows that the calculated tidal range is greater for the ECLH model. Further comparisons were made at a number of locations where the M2 and S2 constituents are available from the Admiralty tide tables (Figure 3-14a). Due to the lower resolution of the ABPmer model comparison was not possible at a number of points around the Kyle of Lochalsh. The spring tidal ranges from the admiralty charts support the results of the ECLH model at most locations (Figure 3-14b). Agreement is particularly good around the area of interest, i.e. Stornaway to Bays Loch, the ABPmer model tends to overestimate the spring tidal range. The neap tidal ranges at the admiralty locations are overestimated by both the ABPmer and ECLH models. However the comparison between the two models between East Loch Tarbert and Castle Bay (the east coast of the Hebrides) are good. (Figure 3-14c)

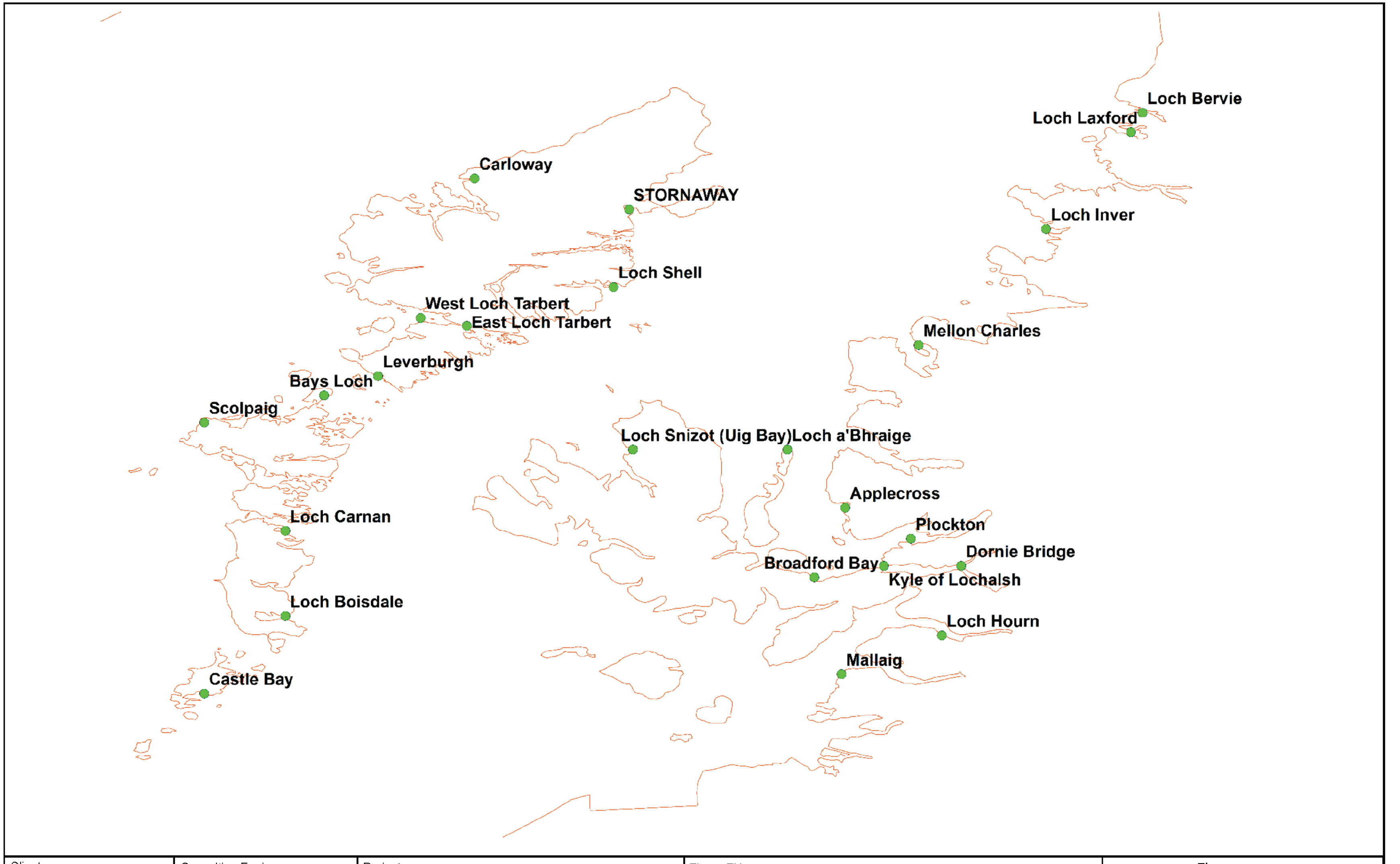
The differences between the two model results are likely to be related to the variation in the model resolutions. In the ABPmer model the Isle of Skye is attached to the mainland and the openings between the Hebridean Islands is not well resolved. In fact the tidal ranges calculated in the shelf model which also has Skye attached to the mainland compare well to the ABPmer model results (Wolf et al. 2015). This highlights the benefit of the nested ECLH model.



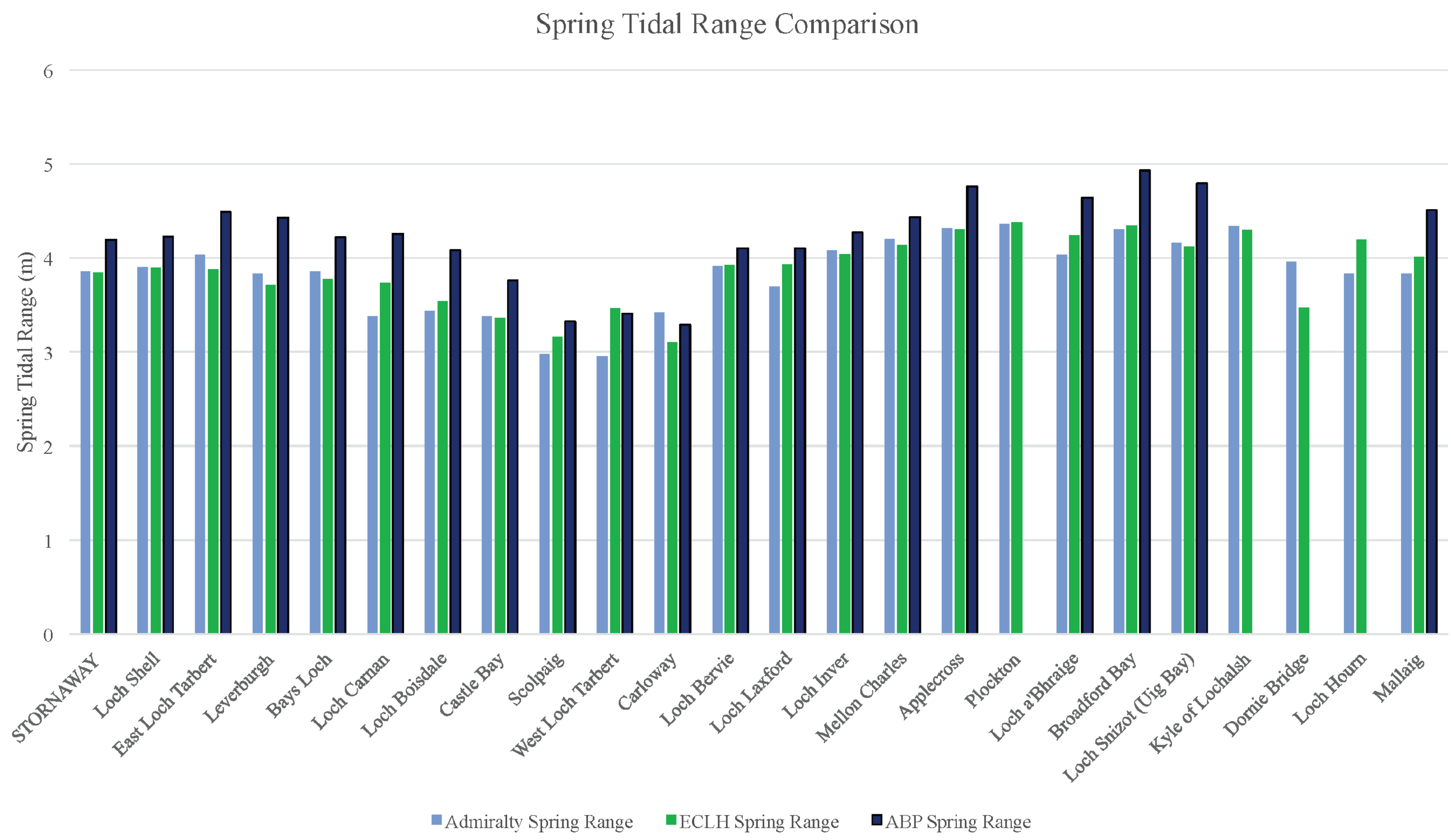
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-13a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Spring Tidal range calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



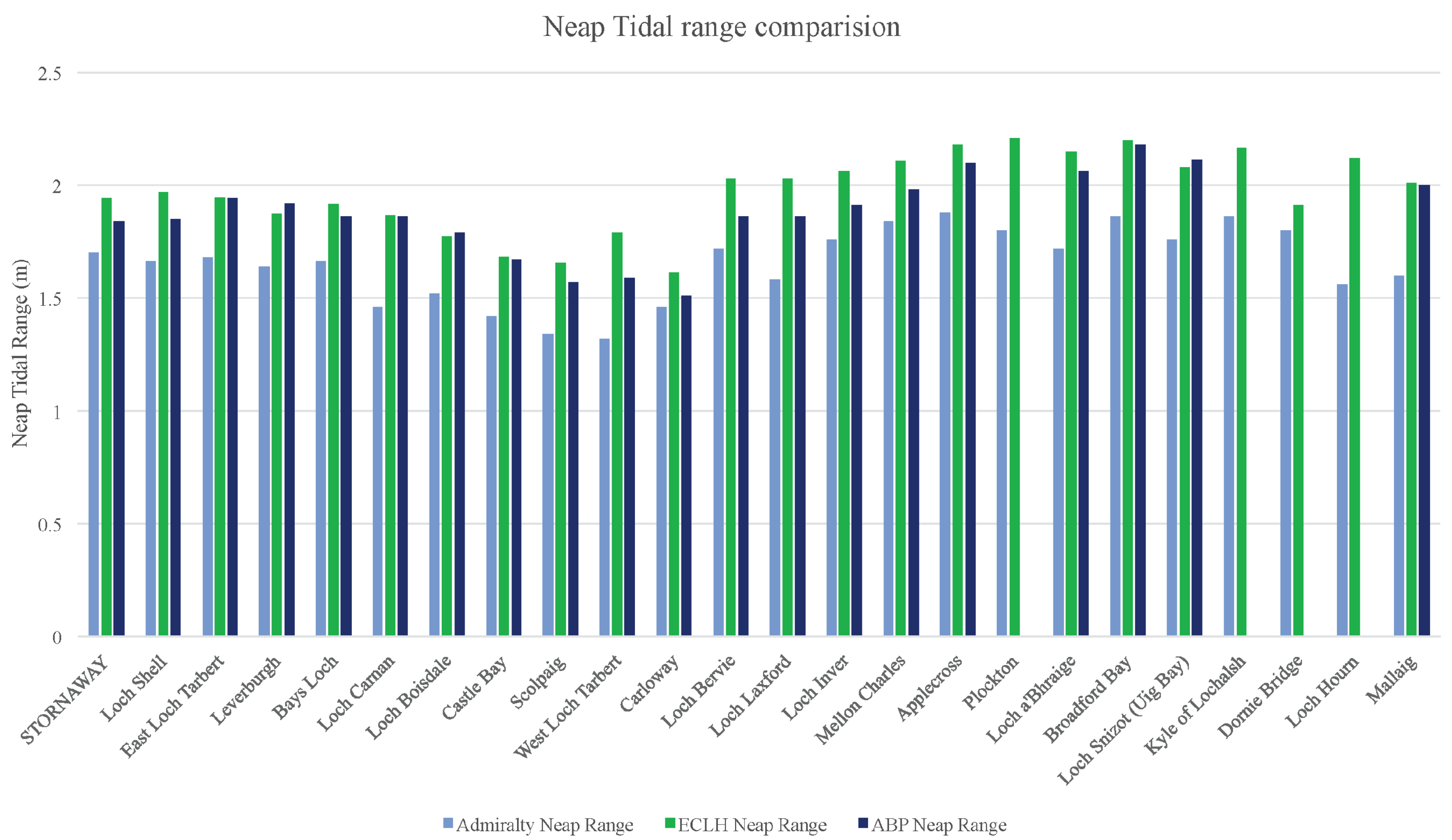
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-13b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Neap Tidal range calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Location of Admiralty Tidal data	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Spring Tidal range calculated from the Admiralty tide tables, FVCOM model and the ABPmer/ NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-14c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Neap Tidal range calculated from the Admiralty tide tables, FVCOM model and the ABPmer/ NOC Atlas of Marine Energy Resources	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.6.3.3 Mean Spring/Neap Currents

Mean peak current speeds have been calculated from a harmonic analysis of 60 days of depth averaged tidal velocities, from the ECLH climatology run (01/05 - 30/06. The east and west components of velocity were analysed using T_TIDE to give the M_2 and S_2 amplitudes and phases. These were in turn analysed to give the semi-major axis amplitudes for each ellipse. The mean peak spring current was then computed as:

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

The mean neap spring current was computed as:

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

A map of the results for mean spring current is shown, along with the equivalent peak currents from the ABPmer / NOC Atlas of Marine Energy Resources, in Figure 3-15a. Corresponding plots for the mean neap current are shown in Figure 3-15b. The peak spring flow data from the ABPmer Atlas is taken from a higher resolution model. The spatial variations in peak flow are consistent between the two data set however the ABPmer Atlas give higher values of peak flow, particularly at the southern tip of the Hebrides (Barra Head) and the northern tip of Skye. The neap peak flows from the ABPmer Atlas are from the lower resolution model (Figure 3-15b). There is good agreement between the CH2M and ABPmer data sets for neap peak flows, again the ABPmer data gives higher peak flows at the northern tip of Skye.

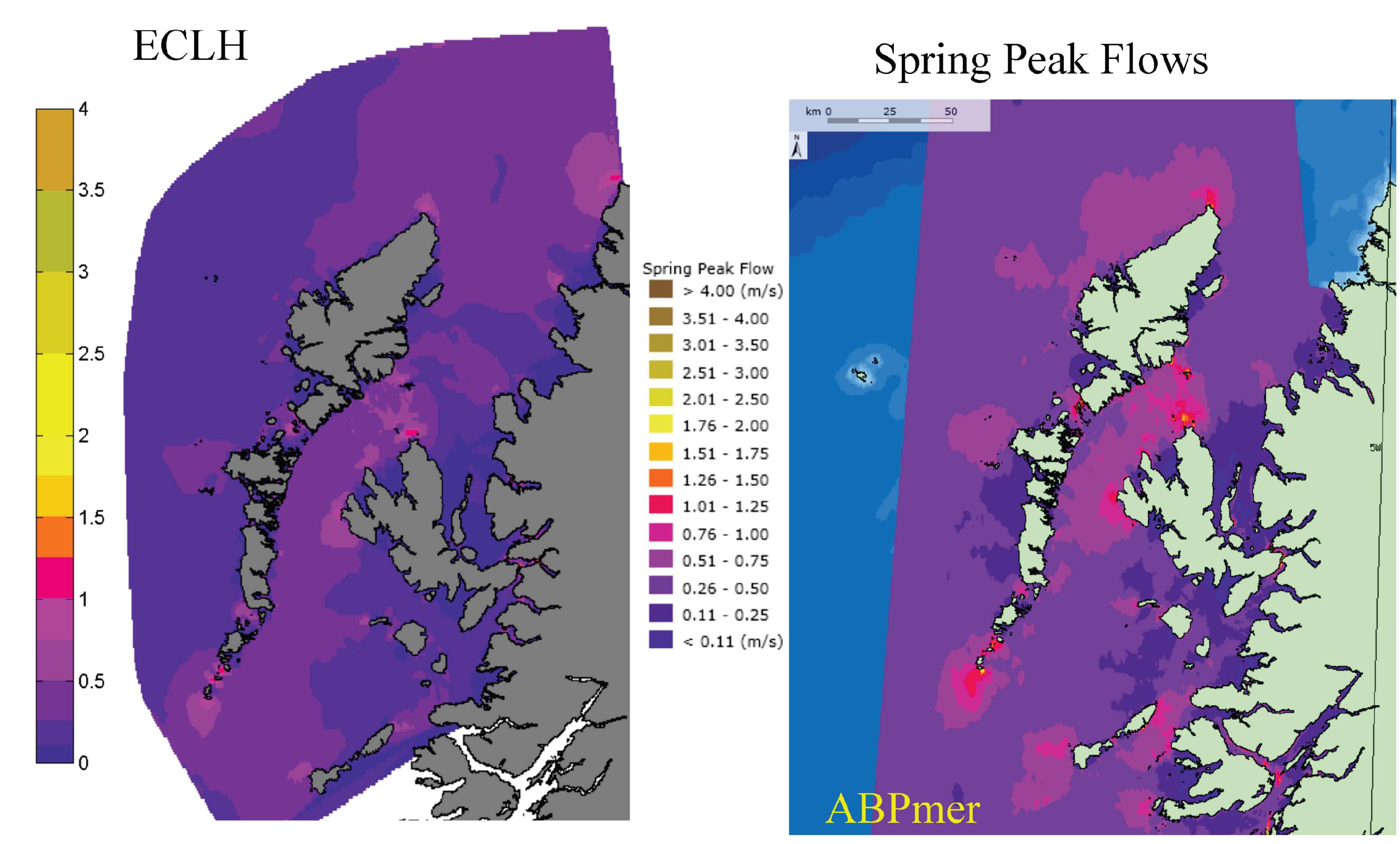
3.6.4 Results

The channel between the Outer Hebrides and the Scottish Mainland known collectively as the Minch is an area with complex topography and a complex coastline shown in Figure 3-16. The North Minch is separated from the sea of the Hebrides (referred to as the South Minch in this report) by the Little Minch. This area has complex hydrodynamics, influenced by the interaction of three water masses: 1) High salinity (>35.0psu) Atlantic water, 2) Low salinity (<35.0psu) Irish and Clyde Sea water transported northwards by the Scottish Coastal Current and 3) fresh coastal water derived from river runoff from the Scottish Mainland (Gillibrand et al. 2003, Hill et al, 1997). The results of the ECLH FVCOM climatology runs are presented here. The results are discussed with reference to existing studies in an attempt to further validate the model results and enhance the understanding of the hydrodynamics of this region.

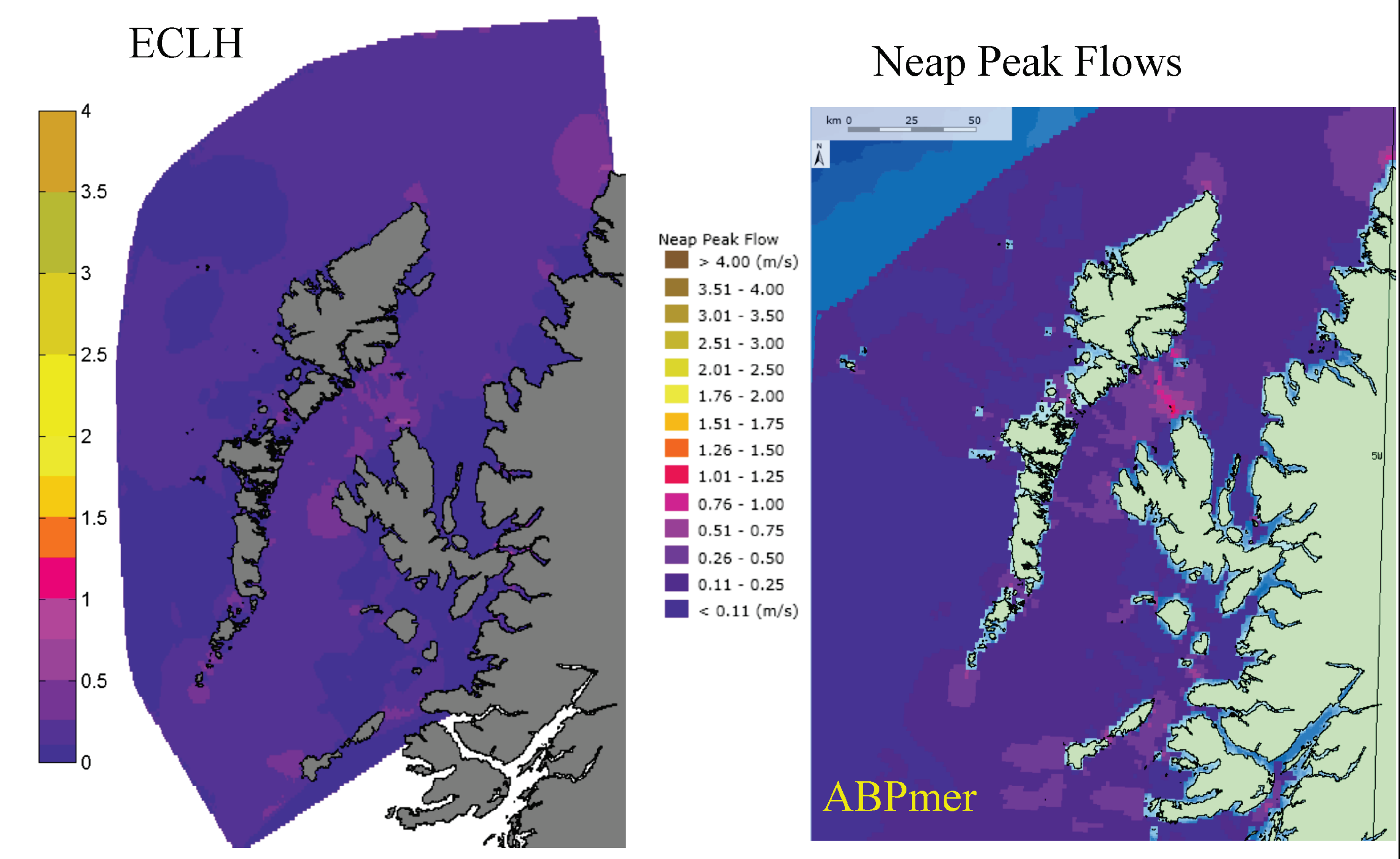
3.6.4.1 Temperature

The average monthly sea surface and bottom temperatures are presented in Figure 3-17a and b respectively. Minimum temperatures are seen in May increasing to their peak in August and dropping off again towards October. Between May and September the average sea surface temperature in the North Minch is lower than the South Minch. This variation is also seen in the sea bottom temperatures between May and June, but from July to September the temperatures in the North Minch exceed those in the South Minch. A report from the Fisheries Research Service (Gillibrand et al., 2003) presents the results of CTD surveys in the Minches in July 1996 and September 1998, these results have been reproduced in Figure 3-17c. The spatial variation seen in the June averages match well with those seen in the summer (July) surveys for both surface and bottom temperature variations. Comparison with the autumn (September) surveys and the ECLH results show a similar spatial variation in the bottom temperatures, however the surface temperature variations seen in the survey, i.e. uniform with a slight drop in temperatures through the Little Minch are not seen in the ECLH averages. The absolute temperatures presented do not match well but this can be explained by the fact that the surveys represents a snapshot in time while the model results are monthly averages from a climatological (averaged meteorological forcing) model run.

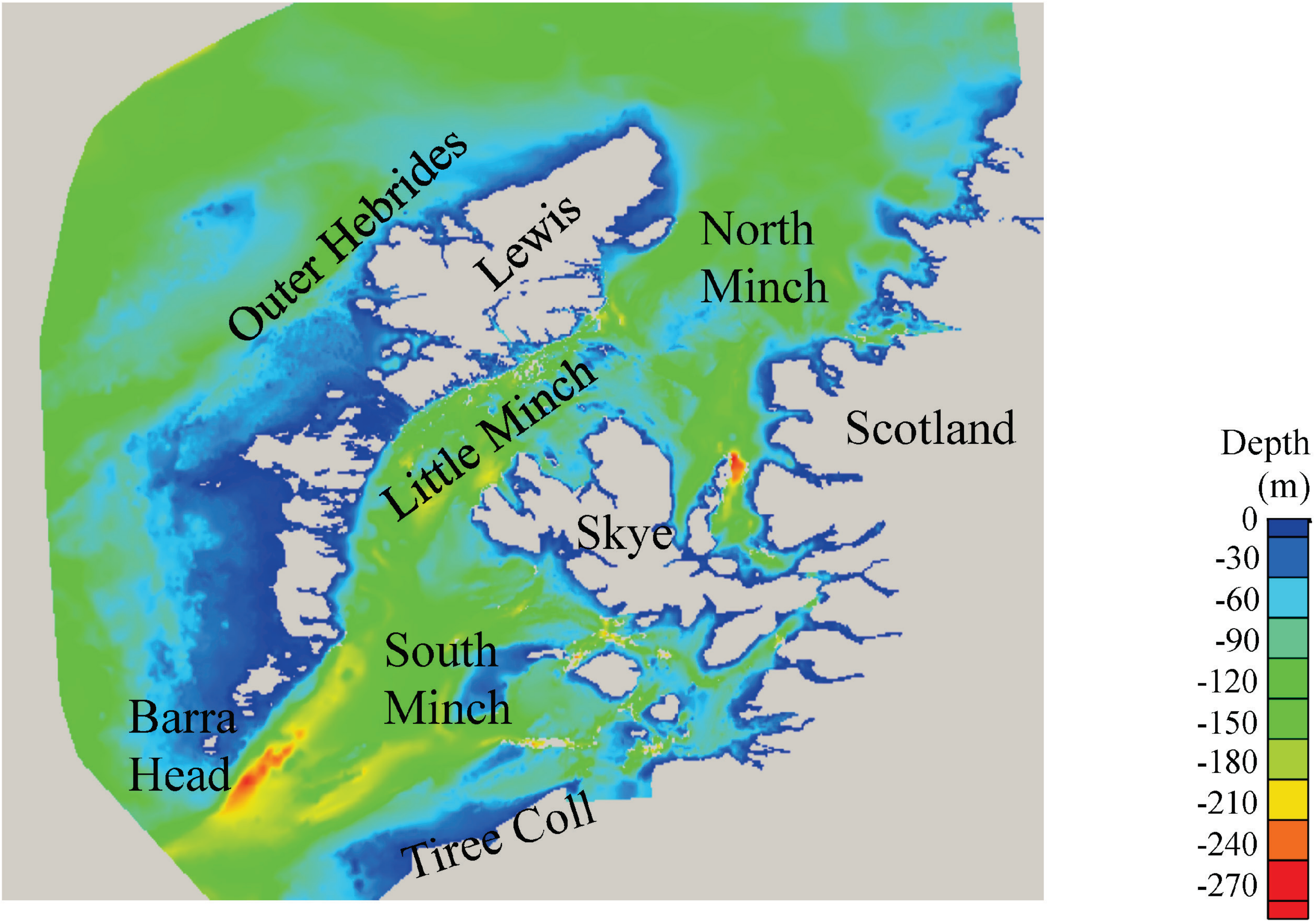
The plots in Figure 3-17d show the difference between the sea surface and sea bottom temperatures, giving an indication of the stratification of the water column. The differences in surface and bottom temperatures increase from May to August up to a maximum difference of 5-6 degrees. Differences reduce to close to zero in October. Interestingly areas of the North Minch show little vertical temperature variations, while the Little Minch shows increasing variations towards July/August, when the Little Minch is thought to be well mixed due to high current velocities.



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Spring Peak Currents calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed:	Drawn:	Date: 23/09/2014

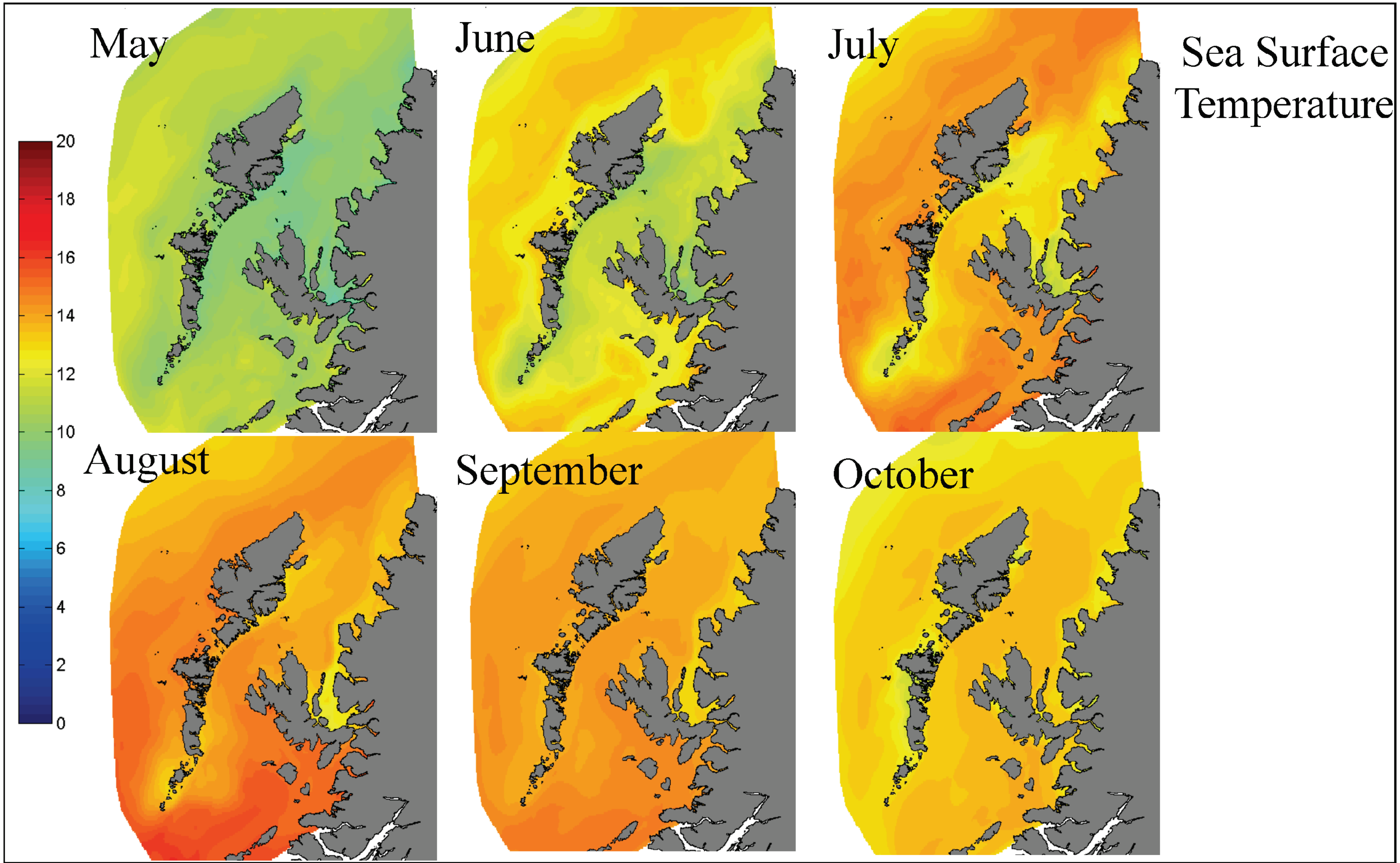


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-15b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Comparison of Mean Neap Peak Currents calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed:	Drawn:	Date: 23/09/2014

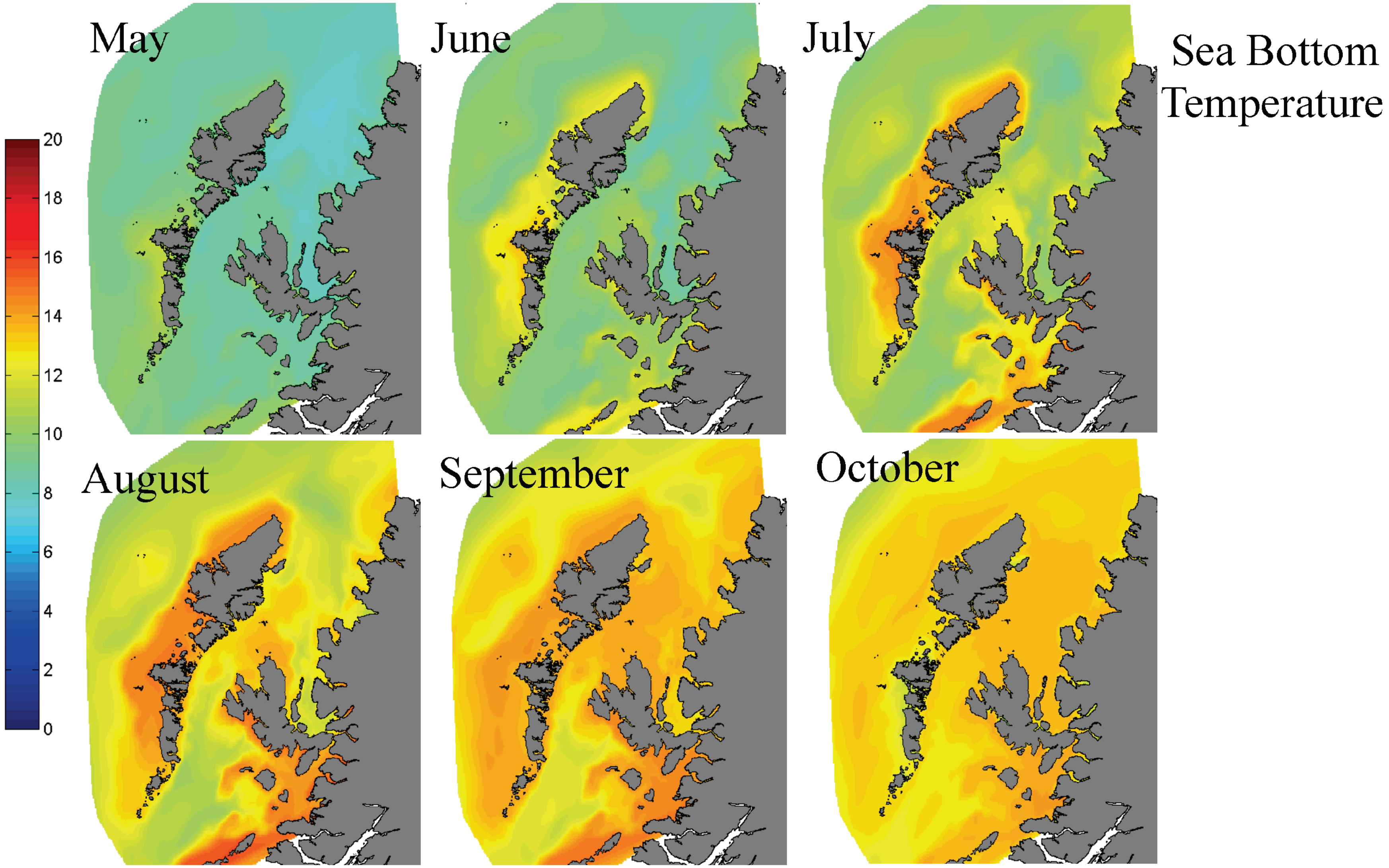


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-16		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Bathymetry and notable locations in the ECHL model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

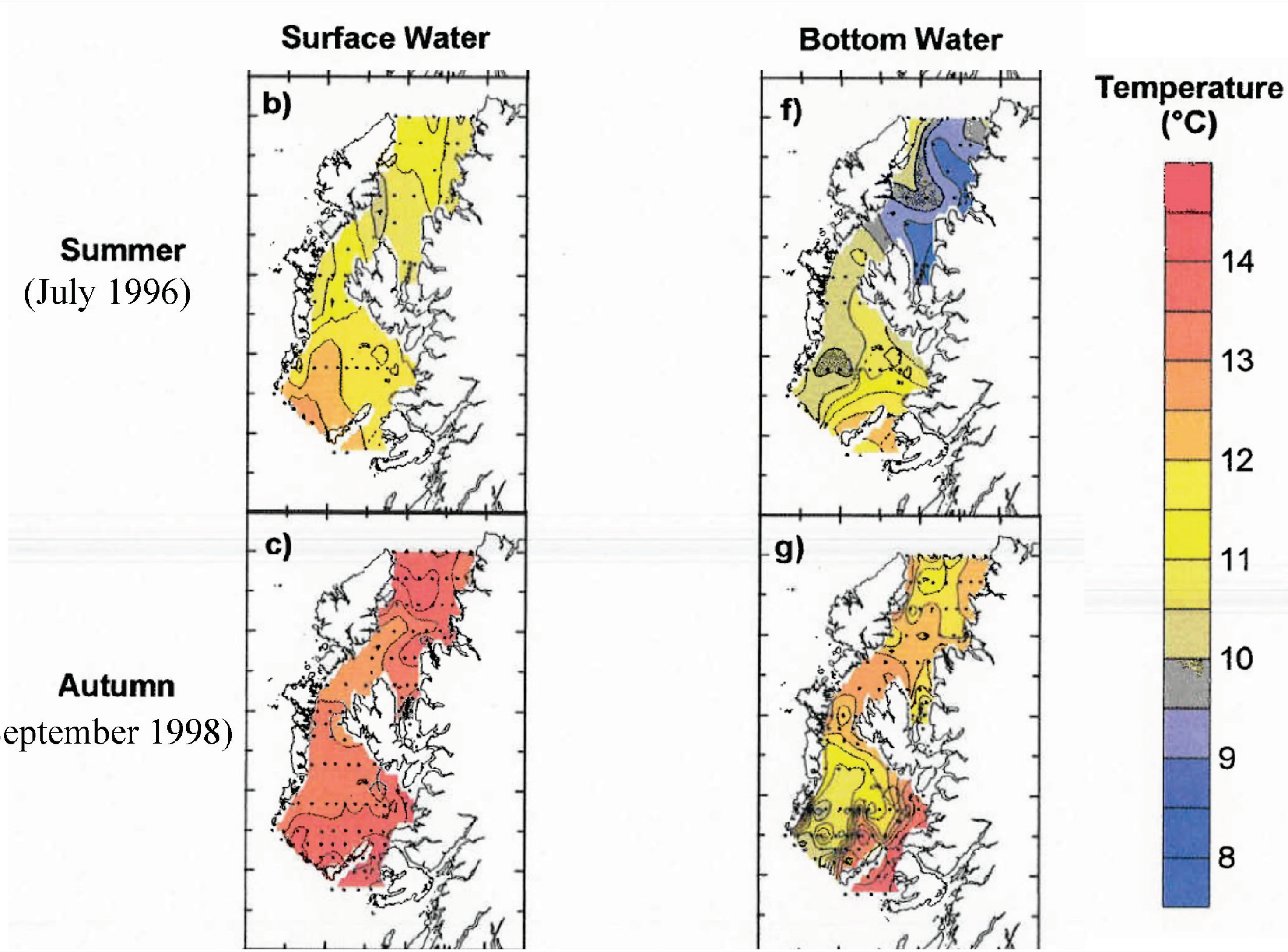
ch2m



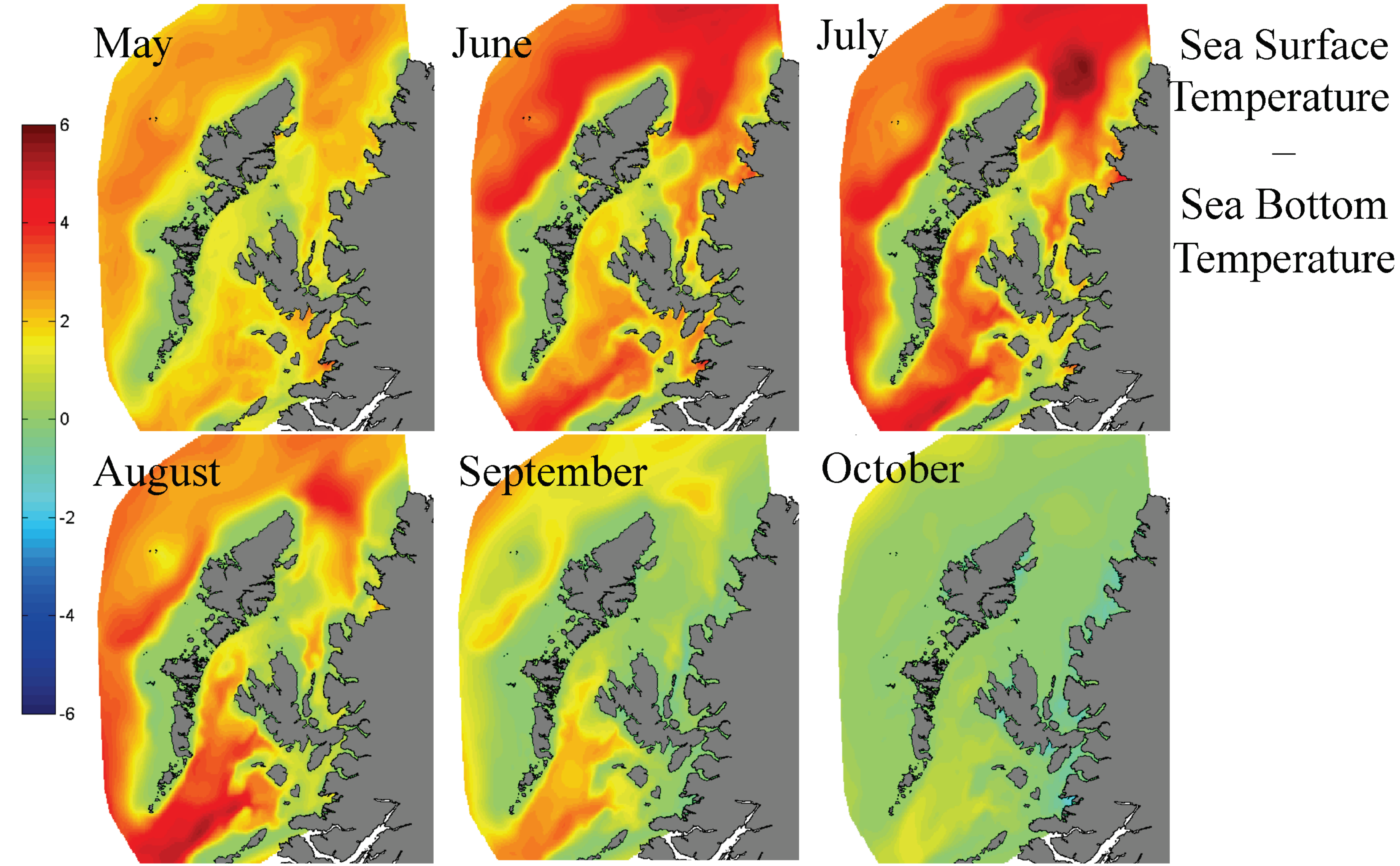
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly average sea surface temperature from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17b		
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Monthly average sea bottom temperature from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Sea surface and sea bottom temperature from CTD surveys. Taken from Gillibrand et al., 2003	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



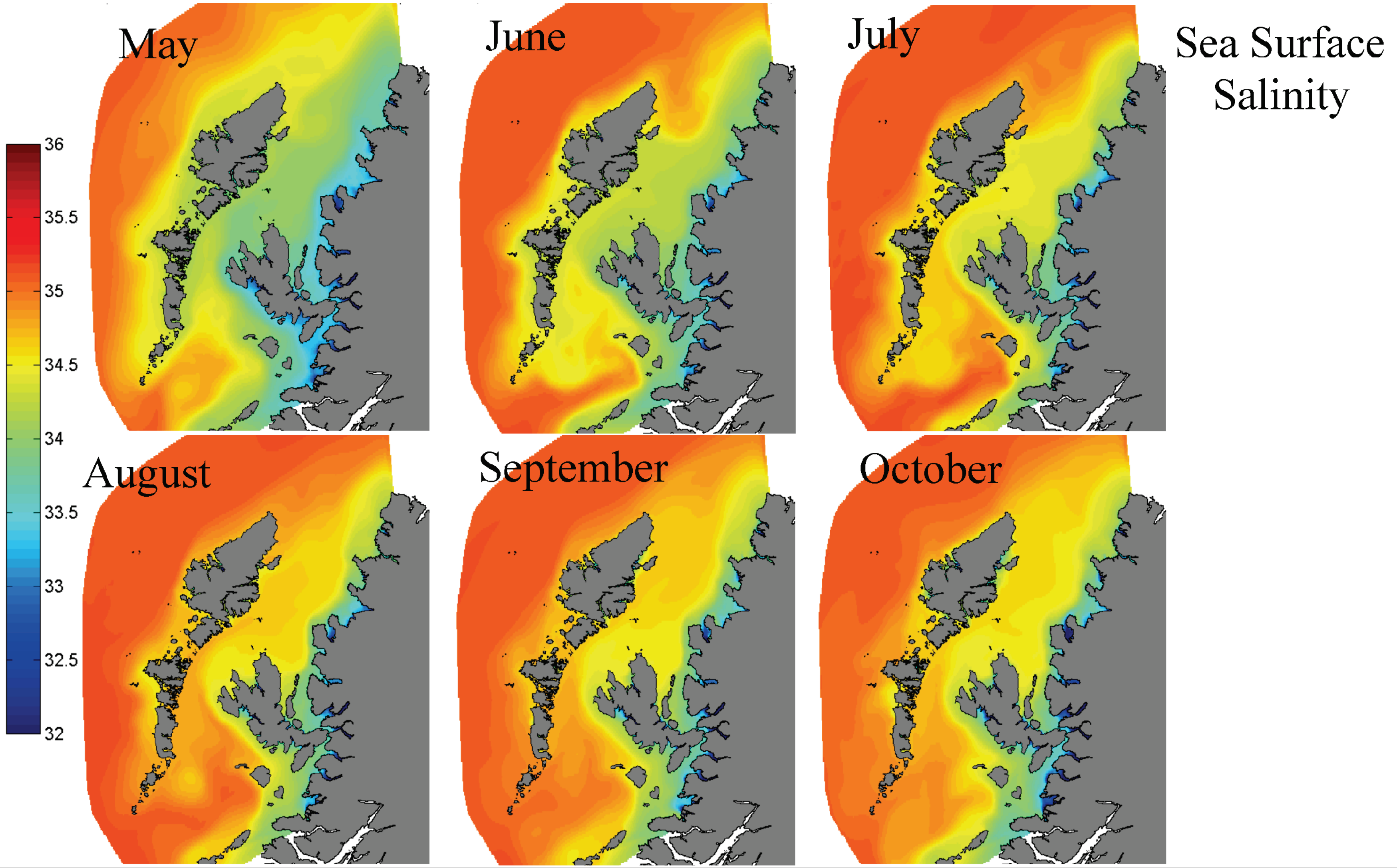
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-17d		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Difference in monthly average sea surface and sea bottom temperature from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.6.4.2 Salinity

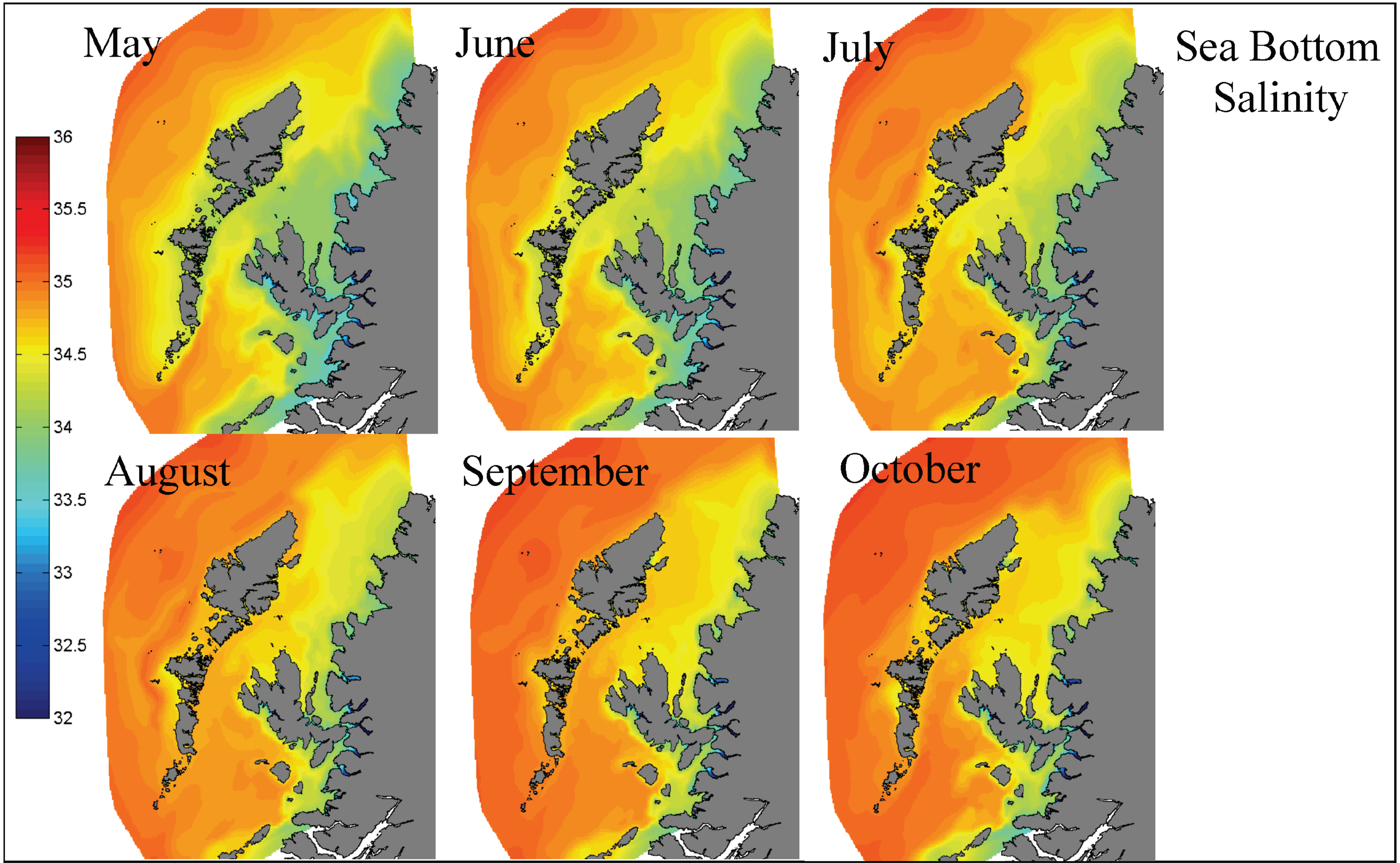
The average monthly sea surface and bottom salinities are presented in Figure 3-18a and b respectively. The blue/green area of low salinity water along the west coast of the Scottish mainland represents the input of fresh water from river run off both within the model area and the area to the south which is brought into the model area by the northward Scottish Coastal current. The size of this low salinity area is at its greatest in May and reduces through the summer as rain fall decreases.

A tongue of high salinity Atlantic water in the South Minch is visible in both the surface and bottom salinities, creating a salinity gradient from the South Minch to the North Minch. This incursion of high salinity water was observed in the surveys by Gillard et al. (2003) (Figure 3-18c), although the incursion was not as defined in the surface salinities. The presence of this incursion was also documented by Hill et al. (1997) and appears to be a persistent feature. In the ECLH results the extent of this saline incursion seems to increase from May to September.

Figure 3-18d shows the difference between the surface and bottom salinities, as with the temperature differences this gives an indication of potential for stratification. The yellow and orange areas show where surface water has a higher salinity compared to the bottom water. Generally higher salinity water would be denser and therefore sink. The reason for this unusual behaviour may lie with the relatively higher temperature of the high salinity Atlantic water. Figure 3-17d shows that the surface waters in these areas are considerably warmer (around 3 to 6 degrees). The scale of the salinity variation in these areas increases from May to July reducing again towards October. The blue areas show where the surface water is fresher than the deep water giving an indication of the movements of fresh water within the model. In May a large area of the Minches and an area off the west coast of Lewis have lower salinity water at the surface than at depth, this coincides with high inputs of fresh water over the preceding months. These areas with fresher surface water (blue) reduce in size through the summer and increase again in September and October.

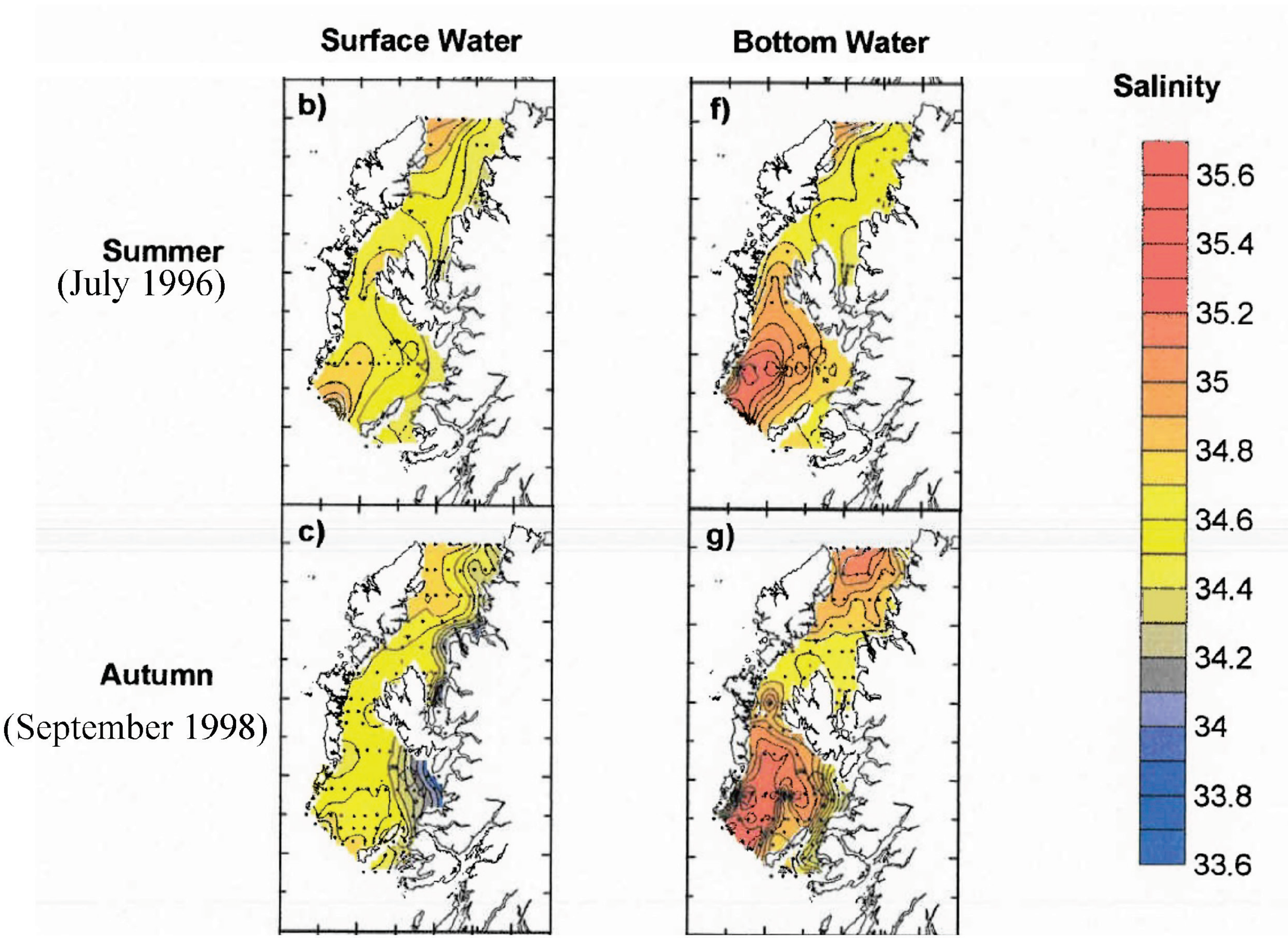


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly average sea surface salinity from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

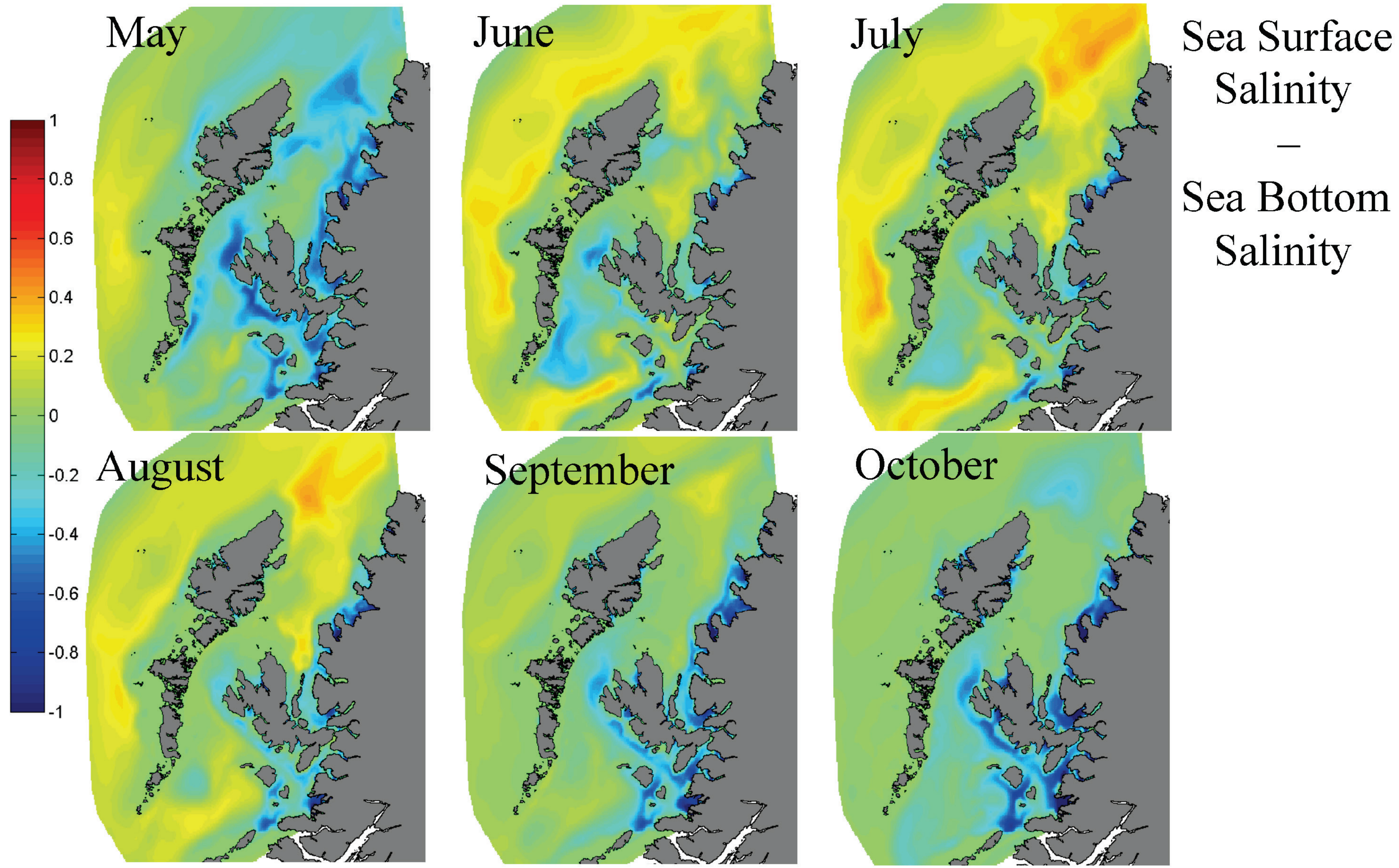


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly average sea bottom salinity from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

ch2m



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18c		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Sea surface and sea bottom salinity from CTD surveys. Taken from Gillibrand et al., 2003	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



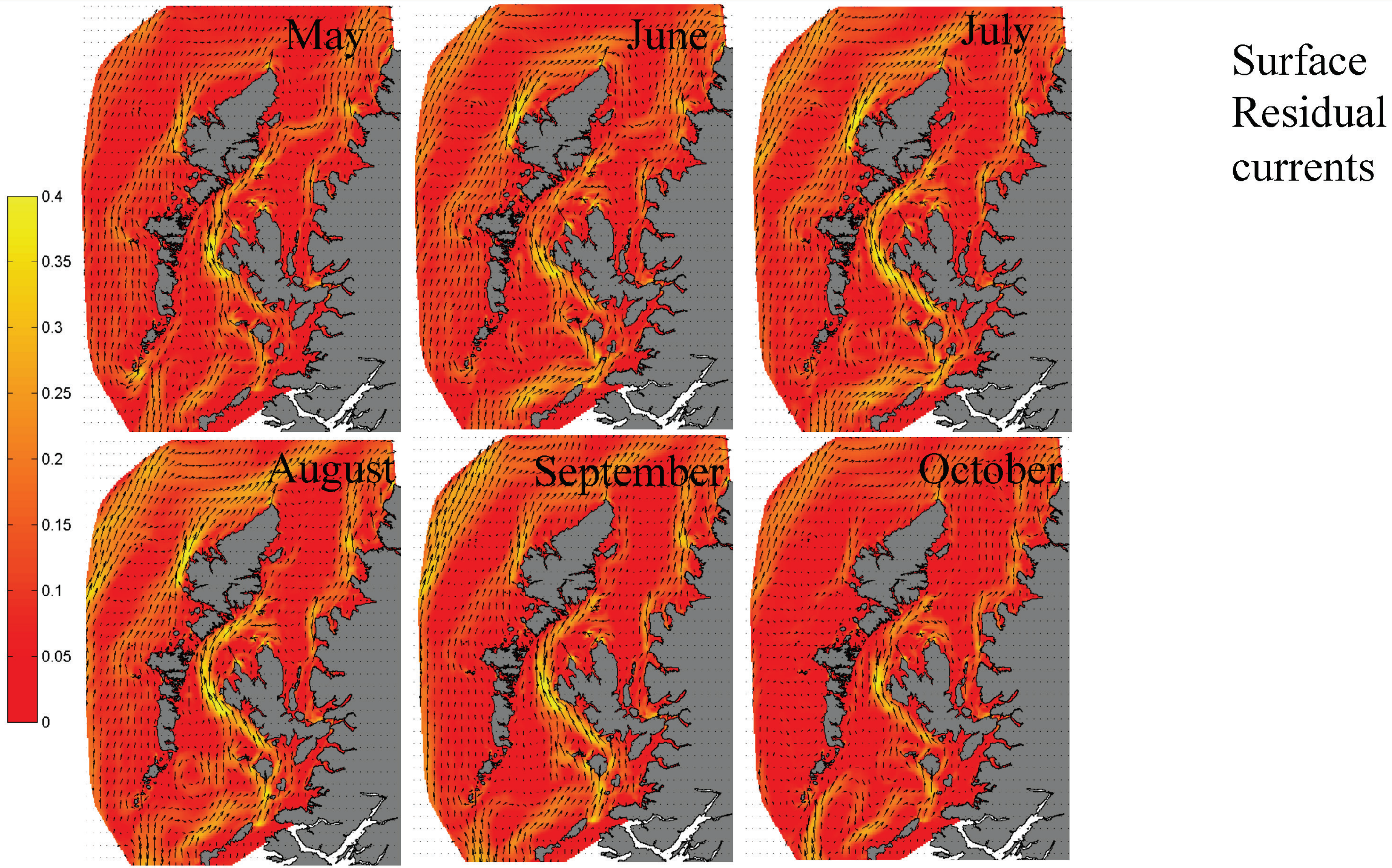
Client	Consulting Engineer	Project:	Figure Title:	Figure 3-18d		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Difference in monthly average sea surface and sea bottom salinity from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.6.4.3 Residual Currents

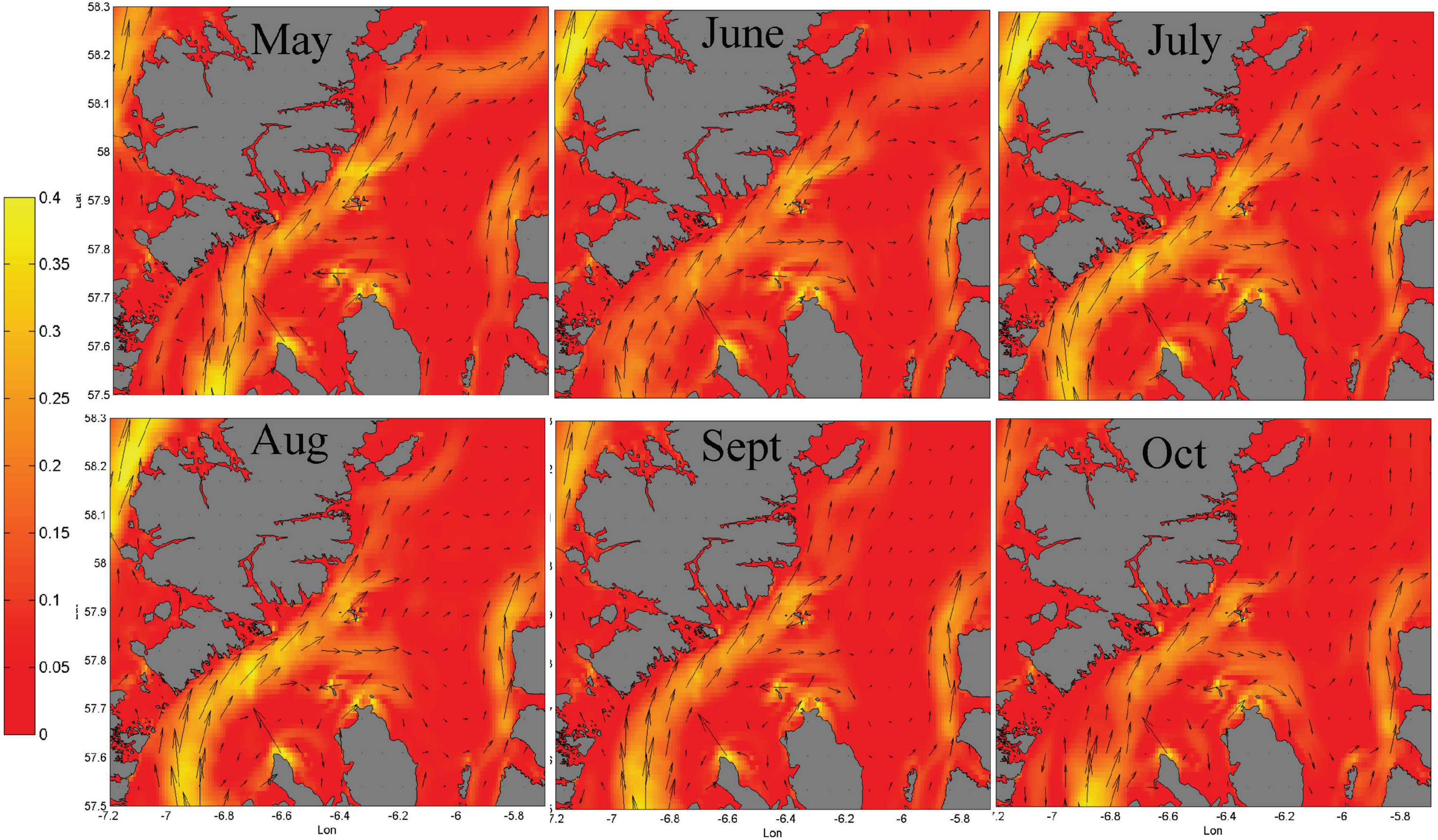
The surface residual currents for each month for the whole model area and zoomed into the area of interest are shown in Figure 3-19a and b respectively. For all months the overall residual flow is to the north, with slower circulating flows in the North and South Minch. The strength of the residual flow does vary, with the peak in residual flows seen in July, reaching 0.4 m/s along the west coast of Skye through the Little Minch. The path that this peak flow takes varies from month to month as does the pattern of circulation in the South and North Minch. In May the northward residual current splits west of Tiree, the western branch head north towards Barra before turning east forming a clockwise circulation in the South Minch. The eastern branch travels along the east coast of the Little Minch, close to Skye reaching the east coast of Lewis and Harris just south of East Loch Tarbert. It flows along the coast turning to the east near Stornaway toward the Mainland then north along the coast. A weak anticlockwise circulation is formed in the North Minch above the peak current flow path. Where the north flowing residual current reaches the east coast of Harris some of the water is diverted south along the east coast of the Hebrides to Barra Head where the current turns northwards once more.

In June the northward residual current follows the coast of Tiree and the Small Islands more closely, passing the Isle of Skye and flowing through the Little Minch to the west of the channel reaching the east coast of North Uist before continuing north along the path it followed in May. The shift in the northward residual in the Little Minch appears to have weakened the southward flow from North Uist to Barra Head and an anti-clockwise circulation around the South Minch begins to develop which strengthens in July and August. In July the pattern of the residuals in the South and Little Minch are similar to that seen in June, however the residual no longer turns east to the mainland in the North Minch, but continue north up the centre of the channel. The pattern of the residual flows within the Minches remains unchanged until September when the northward flowing current begins to migrate to the east side of the Little Minch, the anti-clockwise circulation in the South Minch breaks down to be replaced by a clockwise circulation in October. The east ward shift in the northern flows coincided with a strengthening of the southward flow along the east coast of the North and South Uist and Barra.

The bottom residual currents for each month for the whole model area and zoomed into the area of interest are shown in Figure 3-20a and b respectively. The residual currents in the bottom layer are much lower than at the surface. And the flow patterns are not so well defined. There is still a general northward trend in the residual flows in all months between May and October. There seems to be a northward flow up the western side of the South Minch, through the Little Minch to the North Minch and beyond to deeper water (Figure 3-16) and a southward flow in the shallower water of the east coast of the Hebrides. The southward residual flow is strongest in June and July and weakest in October.

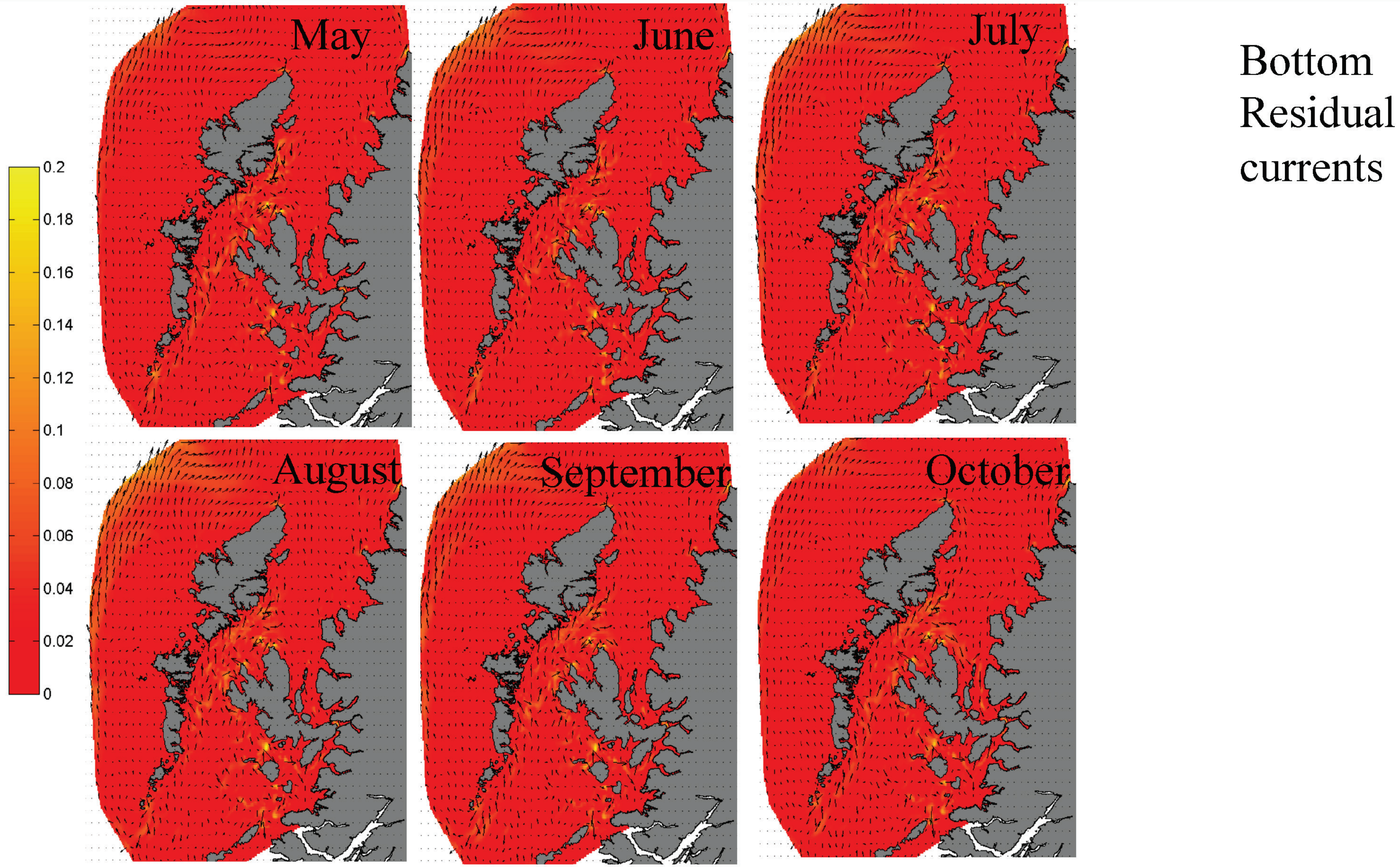


Client	Consulting Engineer	Project:	Figure Title:	Figure 3-19a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly surface residual currents from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

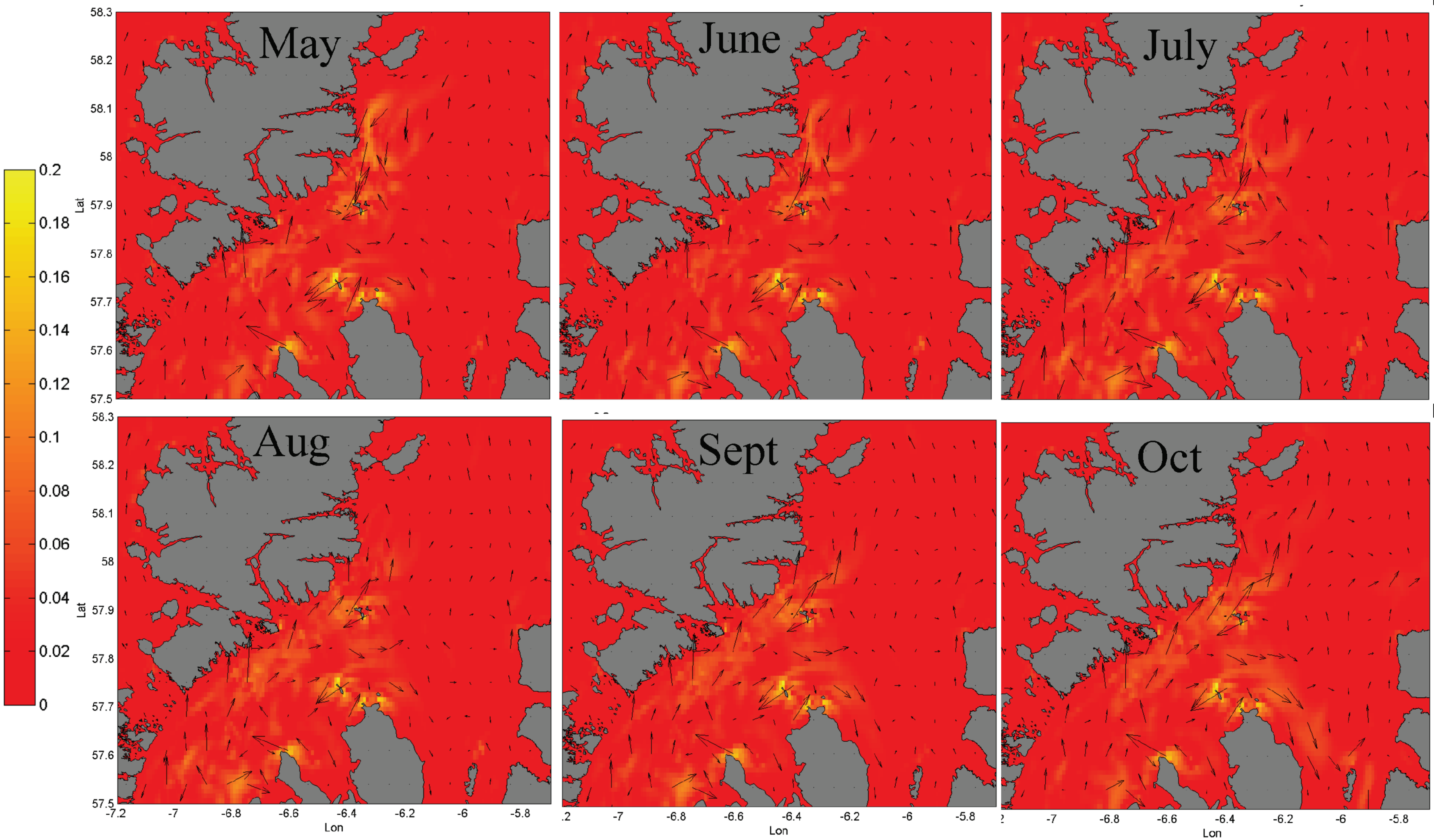


Surface Residual currents

Client	Consulting Engineer	Project:	Figure Title:	Figure 3-19b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly surface residual currents from May to October from the ECLH model. Zoomed into the area of interest	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure 3-20a		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly bottom residual currents from May to October from the ECLH model	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Bottom Residual currents

Client	Consulting Engineer	Project:	Figure Title:	Figure 3-20b		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Monthly bottom residual currents from May to October from the ECLH model. Zoomed into the area of interest	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014

3.6.5 Discussion

Previous research into the hydrodynamics and seasonal characteristics of the area covered in the ECLH model have highlighted a number of interesting features. Most notably the presence of low salinity water around the Outer Hebridean Islands and the intrusion of high salinity Atlantic water into the South Minch. The small amount of freshwater discharge the Outer Hebrides produces indicates that the source of the low salinity water is not local. The distribution of radiocaesium (^{137}Cs) released from the Sellafield nuclear reprocessing plant in Cumbria showed that the source of this low salinity water around the Outer Hebridean Island chain was not only the west coast of Scotland but also a proportion from the Irish Sea waters. The existing research indicates that the mechanisms by which this low salinity water can be transported to the Outer Hebrides is advection by residual currents (Gillibrand et al., 2003, Hill et al., 1997). Based on drifter experiments and the modelling results of Xing and Davies (1996), Hill et al., hypothesised that the circulation in the South Minch was a result of baroclinic density fields around the intrusion of high salinity Atlantic water.

The FVCOM model reproduces the intrusion of high salinity Atlantic water. The surface residual currents do show evidence of anti-clockwise circulation around the South Minch (Figure 3-19). The surface and bottom salinity difference plots in Figure 3-18d do show the distribution of low salinity surface water around the Minches which coincide with the patterns of the surface residual currents indicating that the fresh water is transported by the residual currents to the Outer Hebrides. The seasonal variations seen in the residual currents and the temperature and salinity fields indicate that the strength of the circulation is greatest in May and October, reducing in the summer months when the supply of low salinity water for river discharge into coastal waters is at its lowest.

3.6.6 Summary

Section 3.4 describes the climatology run for the ECLH model. The input data used was taken from the Shelf Model for boundary conditions, CEH for rivers and ECMWF averaged data for the meteorological forcing. The model was run for six months (May to October) the results have been compared with sea surface temperature and salinity climatological data sets for the months of May, August and October. The mean neap and spring tidal ranges and peak speeds were calculated and compared with the ABPmer tidal Atlas. There is some variations between the ECLH results and the available validation data but these variations are thought to be related to the difference in model resolution. ECLH has a finer resolution and includes a number of Lochs that are not included in the lower resolution models including Loch Alsh, the narrow stretch of water between the Isle of Syke and the mainland.

Consideration of the seasonal variations in temperature, salinity and residual currents in the context of existing studies has shown that the ECLH model can reproduce the spatial variations in temperature and salinity fields. Its results support the findings of previous research into the hydrodynamics of the area and provide further insights into the residual flows around this complex region.

4 Summary and Conclusions

4.1 Introduction

This report documents the work carried out in developing the East Coast of Lewis and Harris (ECLH) model. This work includes: data collated for the numerical modelling, setup and calibration of the flow model, and the longer term six month climatological simulation required for this study.

The FVCOM model was chosen because of its capabilities as well as it being freely available, which then fulfils the aim for this and other models developed under the same project to become community models.

4.2 Hydrodynamic model calibration

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

The model mesh was created with the SMS mesh generator using a spherical coordinate system (latitude and longitude). The model was run with 10 vertical sigma layers with a vertical datum of Mean Sea Level (MSL).

An analysis of the data available for forcing the hydrodynamic (HD) model showed that periods in 2009 were the most appropriate providing all of the necessary forcing data required by the model. Datasets for calibration and validation of the model in the form of timeseries of water levels and current speeds were available close to shore and at various locations throughout the model domain. Additionally temperature and salinity profiles were available for comparisons with the model.

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

Celsius which was felt appropriate when considering the observed sea water temperatures.

Comparisons between the model results and measurements of water level and current speeds showed generally good agreement. Comparisons of the 10 layer baroclinic model showed that salinity comparisons with data were generally within the 1 psu in line with our target. Temperature was within 1 degree Celsius, although most of the time it was in the order of 0.5 degrees.

4.3 Climatological simulations

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

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

Mean spring and neap tidal ranges and currents were also calculated using M2 and S2 water level and current constituents and then compared against an ABPmer model of the area. Comparisons are generally good, with the main difference found around Skye; here both the Shelf Model and the ABPmer model have similar tidal ranges, but both models do not resolve the channel between Skye and the mainland. The ECLH model does however resolve this channel and therefore this is likely to be the reason for the differences observed and the benefit of the finer resolution ECLH model.

Consideration of the seasonal variations in temperature, salinity and residual currents in the context of existing studies has shown that the ECLH model can reproduce the spatial variations in temperature and salinity fields. Its results support the findings of existing research into the hydrodynamics of the area and provide further insights into the residual flows around this complex region.

5 References

ABPmer, 2012. Pentland Firth and Orkney Waters Strategic Area: Marine Energy Resources. Report R.1936. The Crown Estate.

Bartlett, J.M., 1998. Quality Control Manual for Computational Estuarine Modelling. R & D Technical Report W168, Environment Agency. Section A.4.2.1.

Baston, S. and Harris, R., 2011.Modelling the Hydrodynamic Characteristics of Tidal Flow in the Pentland Firth. Proceedings of the 9th European Wave and Tidal Energy Conference, 5-9 September, Southampton, UK.

Chen, C., R.C. Beardsley, G. Cowles, J. Qi, Z. Lai, G. Gao, D. Stuebe, Q. Xu, P. Xue, J. Ge, S. Hu, R. Ji, R. Tian, H. Huang, L. Wu, H. Lin, Y. Sun and L. Zhao, 2013. An Unstructured Grid, Finite-Volume Community Ocean Model FVCOM User Manual, v3.1.6, Fourth Edition, SMAST/UMASSD-13-0701, July 2013.

GEBCO_08 Grid – artefact along 0°E in the North Sea region http://www.bodc.ac.uk/help_and_hints/errata/gebco/documents/gebco_errata_north_sea.pdf

http://www.bodc.ac.uk/help_and_hints/errata/gebco/documents/gebco_08_grid_artifact_north_sea.pdf

ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources And Analysis, Christopher Amante , NOAA Technical Memorandum NESDIS NGDC-24.

The GEBCO_08 Grid, version 20100927, http://www.gebco.net

The GEBCO_08 SID Grid, version 20100927, http://www.gebco.net

Gillibrand, P.A., Sammes, P.J., Slesser, G. and Adams, R.D., 2003. Seasonal water column characteristics in the Little and North Minches and the sea of the Hebrides. I. Physical and Chemical parameters. Fisheries Research Services Internal Report No 08/03.

Halcrow, 2012. Data review, Hydrodynamic Model of Scottish Shelf Waters. Report prepared for Marine Scotland, November 2012.

Hill, A.E., Horsburgh, K.J., Garvine, R.W., Gillibrand, P.A., Slesser, G., Turrel, W.R. and Adams, R.D. 1997. Observations of a density-driven recirculation of the Scottish coastal currents in the Minch. Est. Coast. Shelf Sci., 45, 473-484.

Holt, J.T., Allen, J.I., Proctor, R.and Gilbert, F. 2005. Error quantification of a high-resolution coupled hydrodynamic–ecosystem coastal–ocean model: Part 1 model overview and assessment of the hydrodynamics. Journal of Marine Systems, 57, 167-188.

Holt, J., Butenschön, M., Wakelin, S.L., Artioli, Y. and Allen, J.I. 2012. Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. *Biogeosciences*, 9 (1). 97-117. 10.5194/bg-9-97-2012

Hughes, S. L. 2014, Appendix E: Quality Control of Bathymetry Data *in:* Inflow of Atlantic Water to the North Sea: Seasonal Variability on the East Shetland Shelf, 333 pp, PhD Thesis, University of Aberdeen, Aberdeen.

Inall, M. and Griffiths, C. 2003. The Tiree Passage Time Series: 1981 - 2003, Marine Environmental Change Network. http://www.mba.ac.uk/mecn/mecn_members/downloads/mecn%20publications/tiree%20passage%20review.pdf

Ivanov V., Dale A., Inall M. A high-resolution baroclinic model of Loch Linnhe, EGU General Assembly 2011, Geophysical Research Abstracts, Vol. 13, EGU2011-4461, 2011.

McKinley, I.J., Baxter, M.S., Ellett, D.J. and Jack, W. 1981. Tracer applications of radiocaesium in the Sea of the Hebrides. Est. Coast. Shelf Sci., 13, 69-82.

O'dea, E.J., Arnold, A.K., Edwards, K.P., Furner, R., Hyder, P., Martin, M.J., Siddom, J.R., Storkey, D., While, J., Holt, J.T. and Liu, H. 2012. An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf. *Journal of Operational Oceanography*, 5 (1). 3-17.

Ordnance survey landform, user guide and technical specification, Ordnance Survey 2010.

OS Vectormap District, User guide and technical specification, Ordnance Survey 2011.

Wakelin, S.L., Holt, J.T., Blackford, J.C., Allen, J.I., Butenschön, M. and Artioli, Y. 2012. Modelling the carbon fluxes of the northwest European continental shelf: Validation and budgets. *Journal of Geophysical Research*, 117 (C5). C05020. 10.1029/2011JC007402

Wolf, J. and Woolf, D. K. 2006. Waves and climate change in the north-east Atlantic, Geophysical Research Letters, 33, L06604, doi:10.1029/2005GL025113

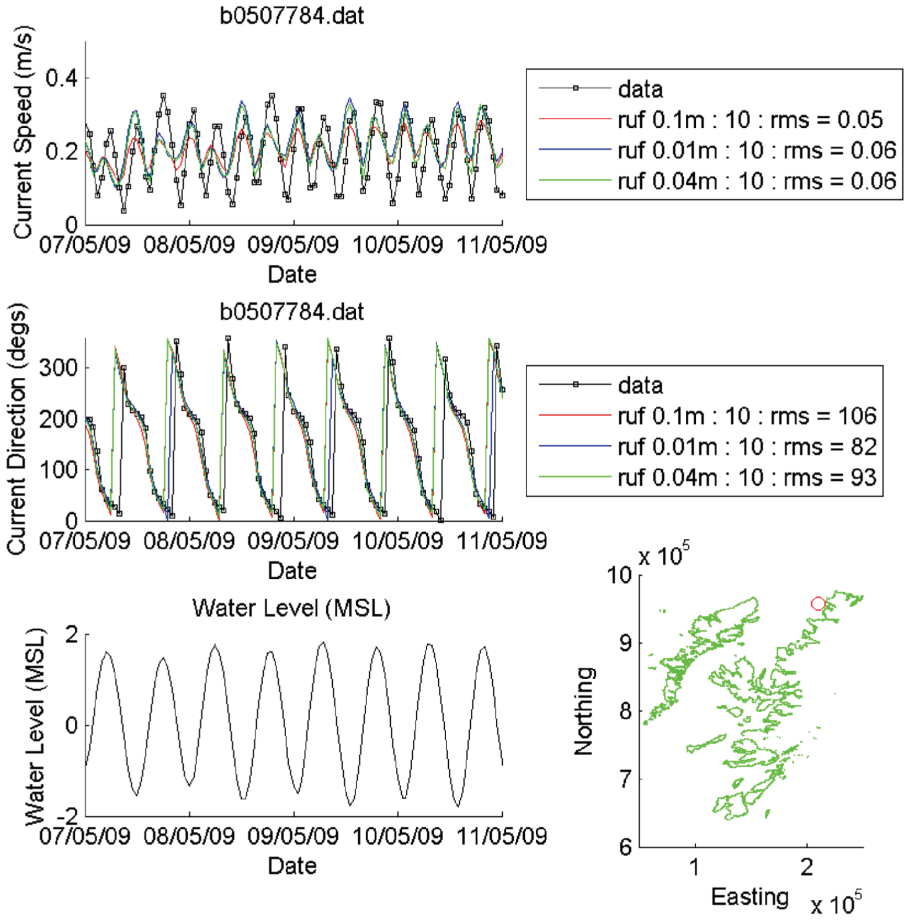
Wolf, J., Yates, N., Brereton, A., Buckland, H., De Dominicis, M., Gallego, A., O'Hara Murray, R. 2015. The Scottish Shelf Model. Part 1: Shelf-Wide Domain. Scottish Marine and Freshwater Science Vol 7 No 3. Prepared by CH2M on behalf of Marine Scotland. Marine Scotland Science, 151pp.

Xing, J. and Davies, A.M., 1996. A numerical model of the long term flow along the Malin-Hebrides shelf. Journal of Marine Systems. 8, 191-218.

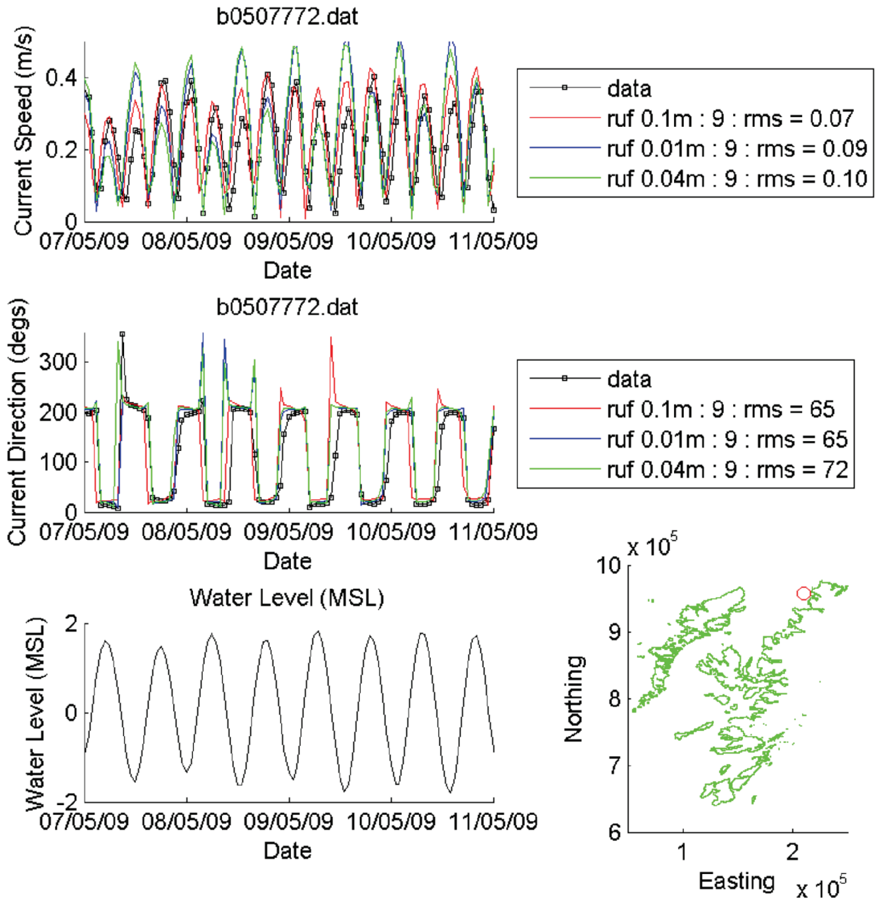
Zijderveld, A., Verlaan, M., 2004. Towards a new gridded bathymetry for storm surge forecasting in the North Sea. EGU 1st General Assembly, Nice, France, 25–30 April 2004, Geophysical Research Abstracts 6, EGU04-A-05177.

Appendix A

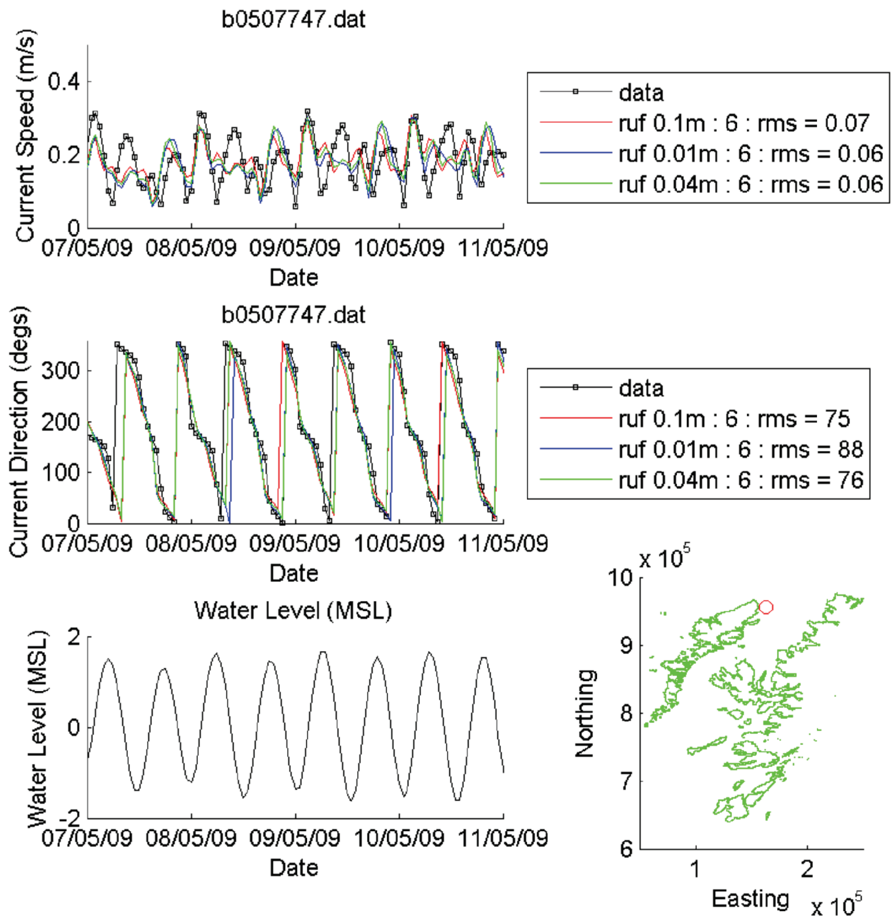
Additional Figures



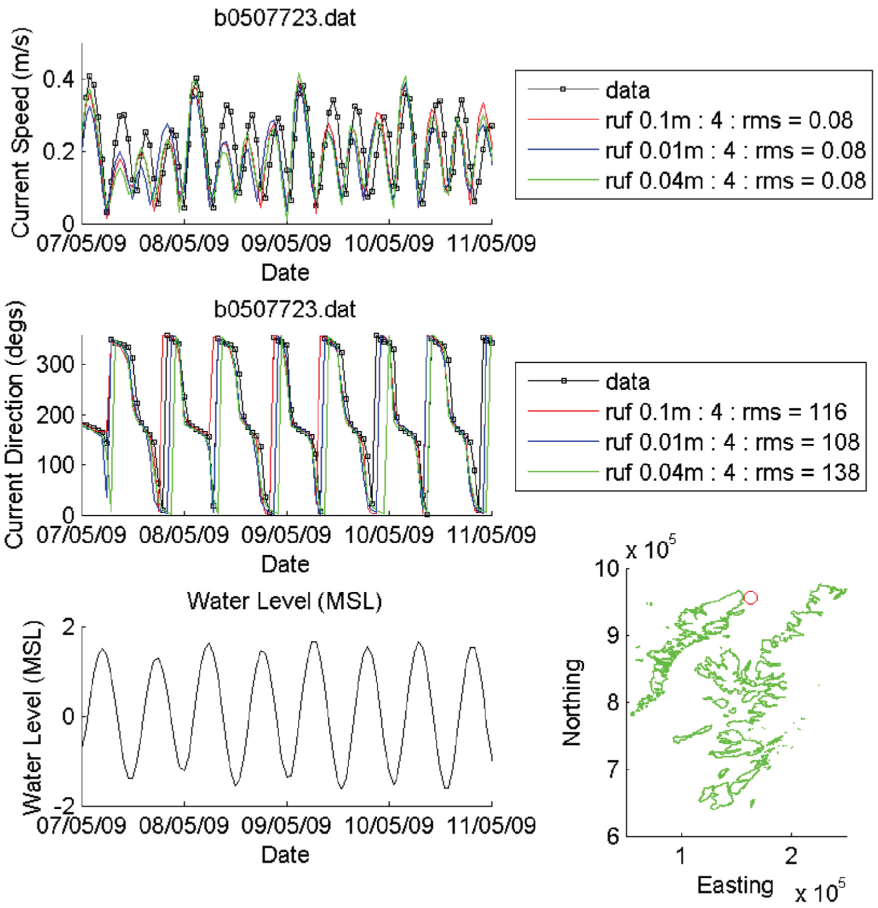
Client	Consulting Engineer	Project:	Figure Title:	Figure A-1		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



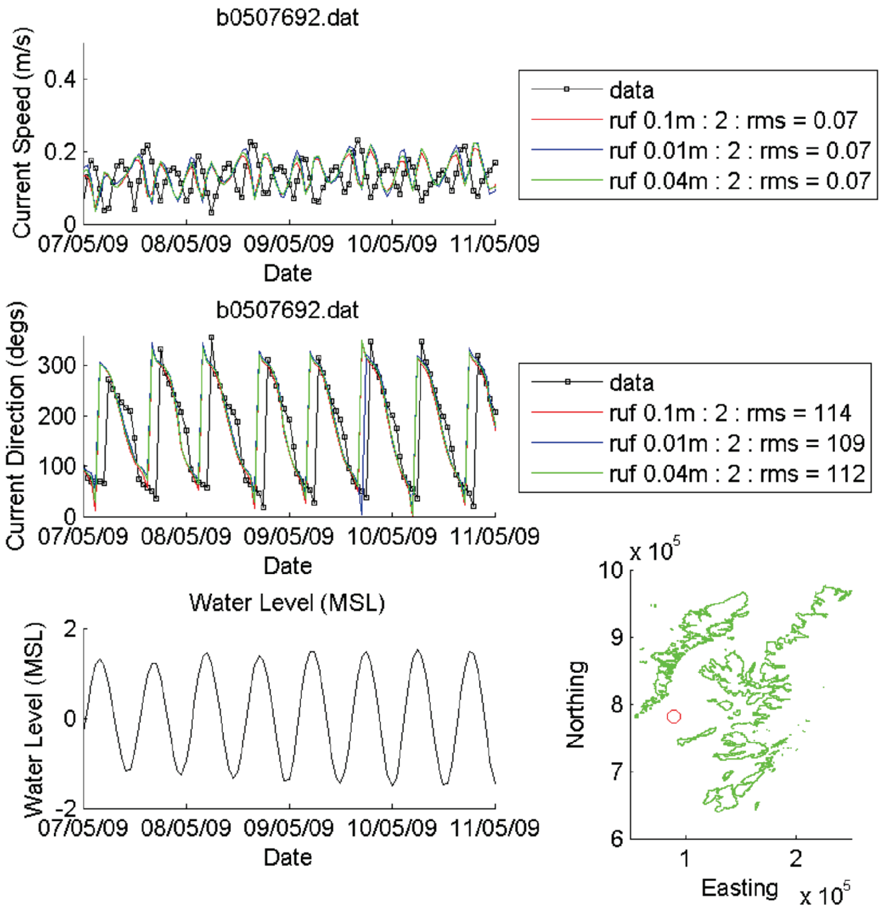
Client	Consulting Engineer	Project:	Figure Title:	Figure A-2		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014



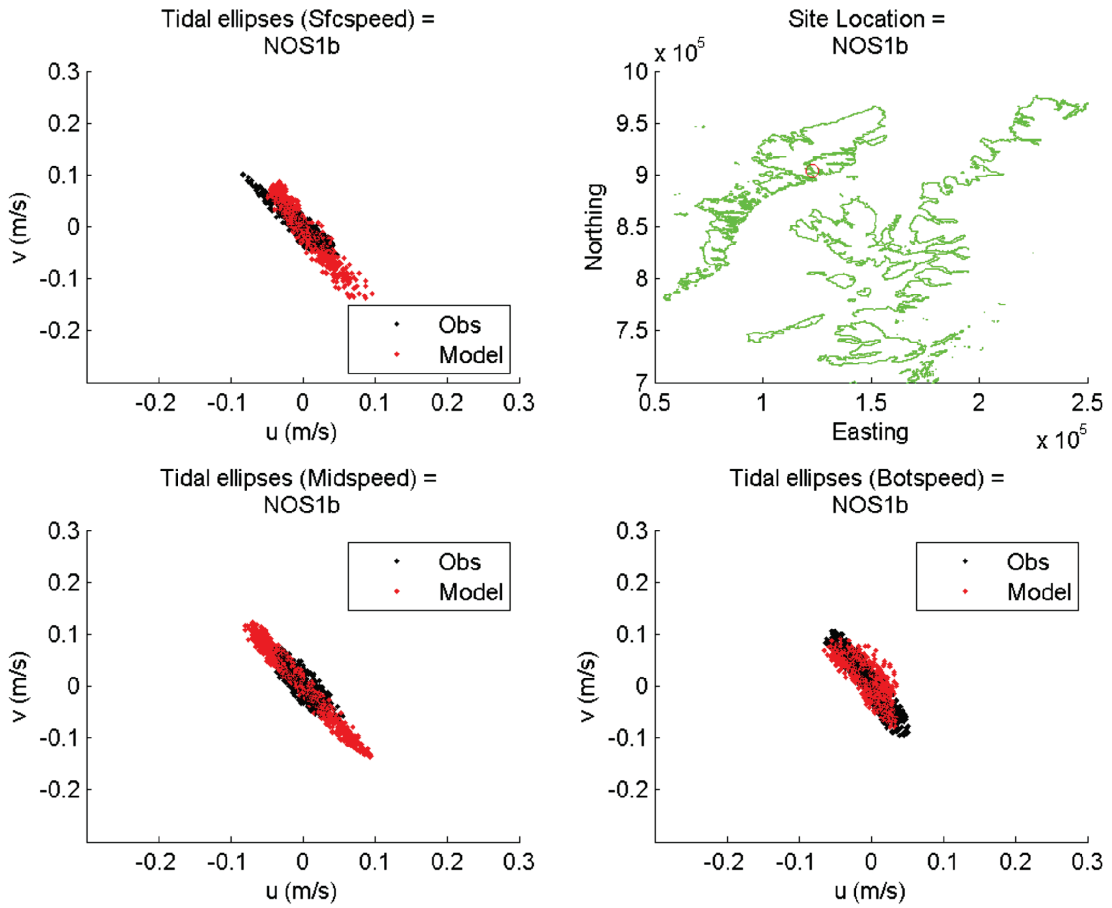
Client	Consulting Engineer	Project:	Figure Title:	Figure A-3		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



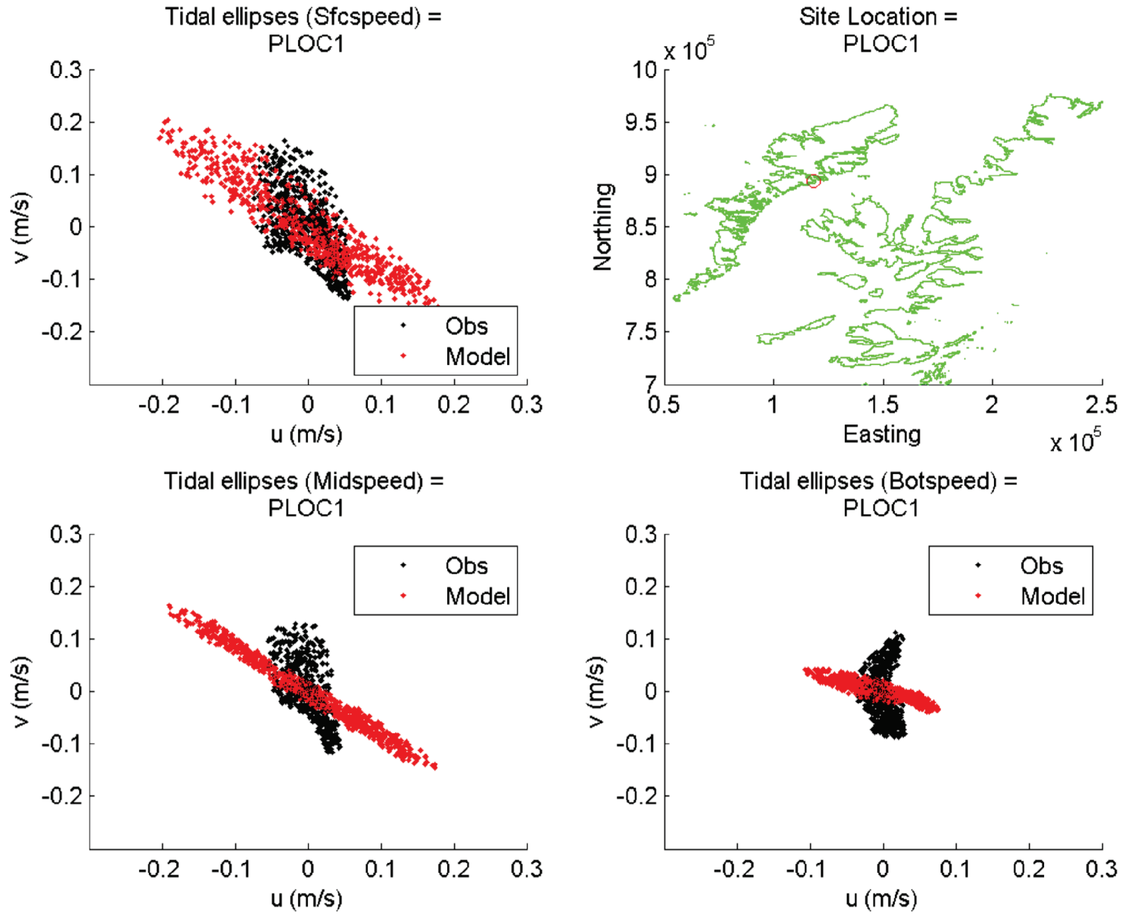
Client	Consulting Engineer	Project:	Figure Title:	Figure A-4		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014



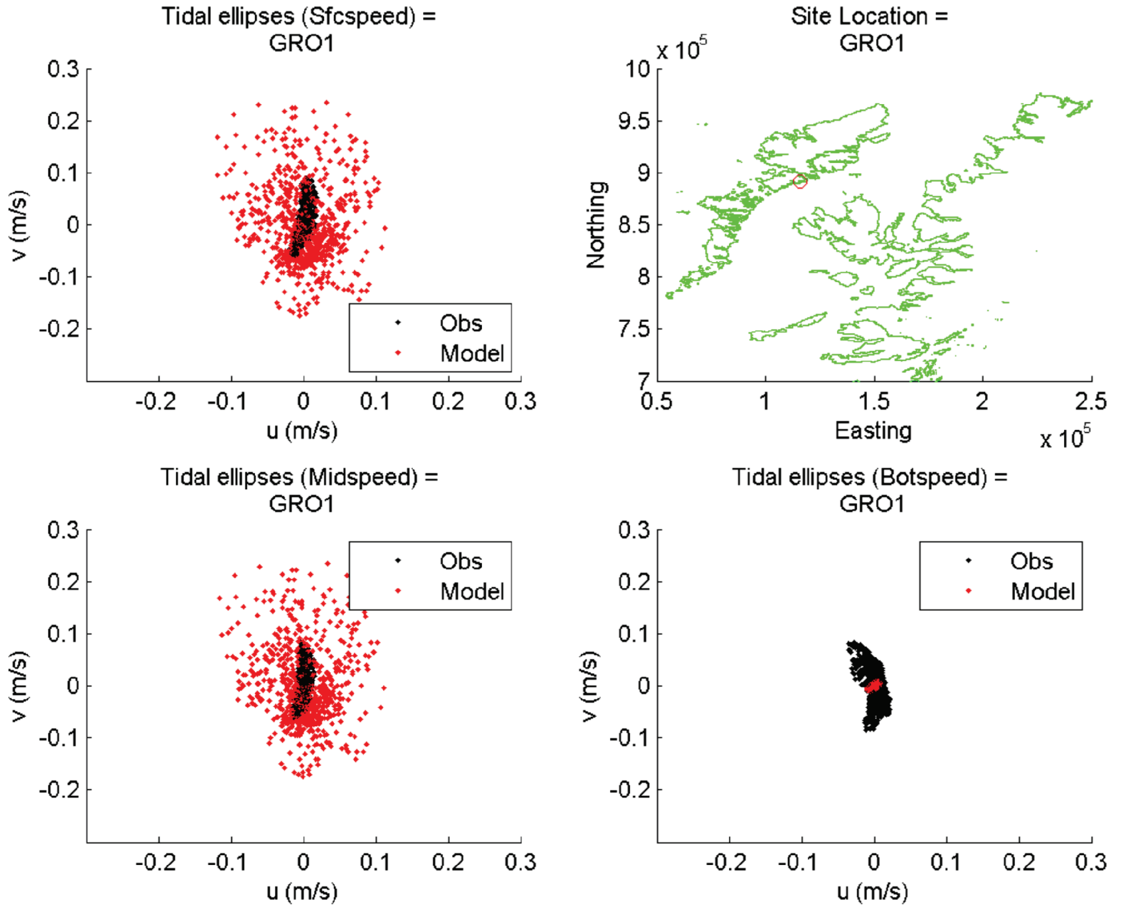
Client	Consulting Engineer	Project:	Figure Title:	Figure A-5		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Current speed comparison between BODC data and three model runs with roughness lengths of 0.1m, 0.04m and 0.01m	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



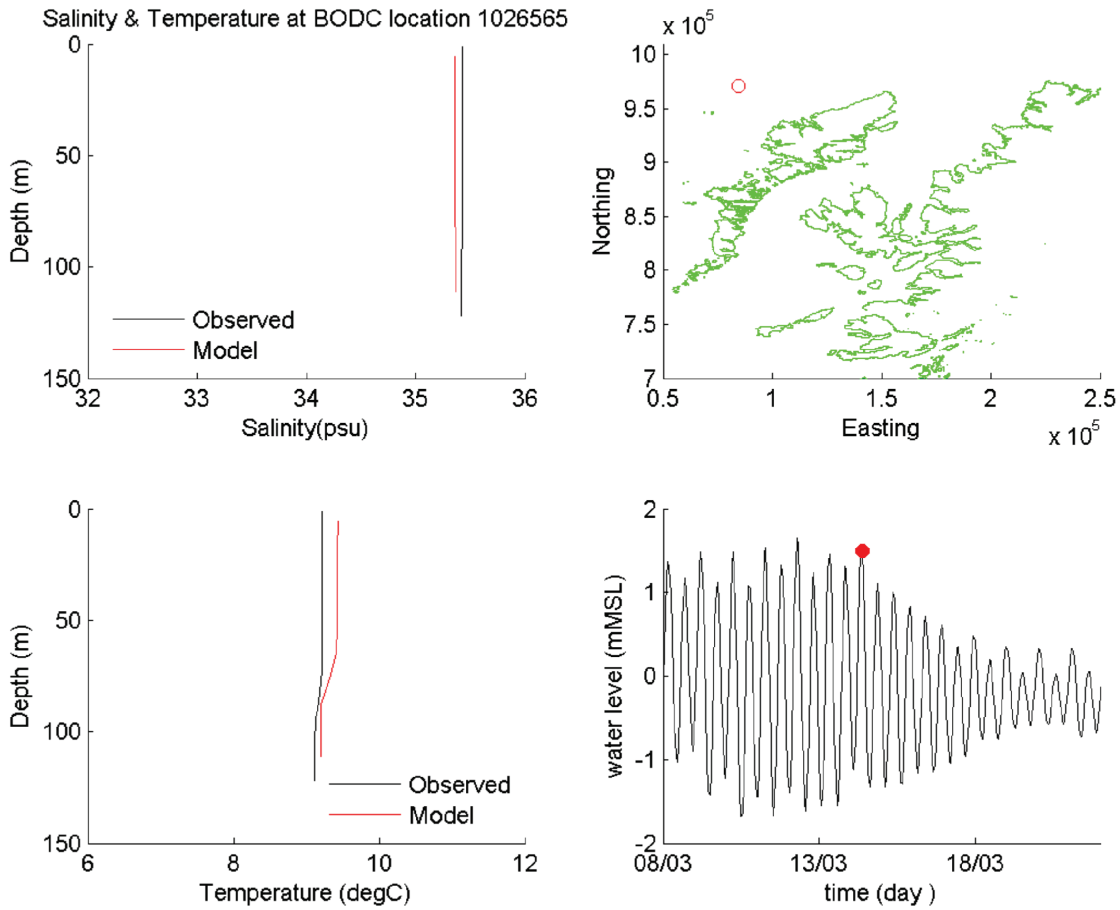
Client	Consulting Engineer	Project:	Figure Title:	Figure A-6		
Marine Scotland	ch2m:	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



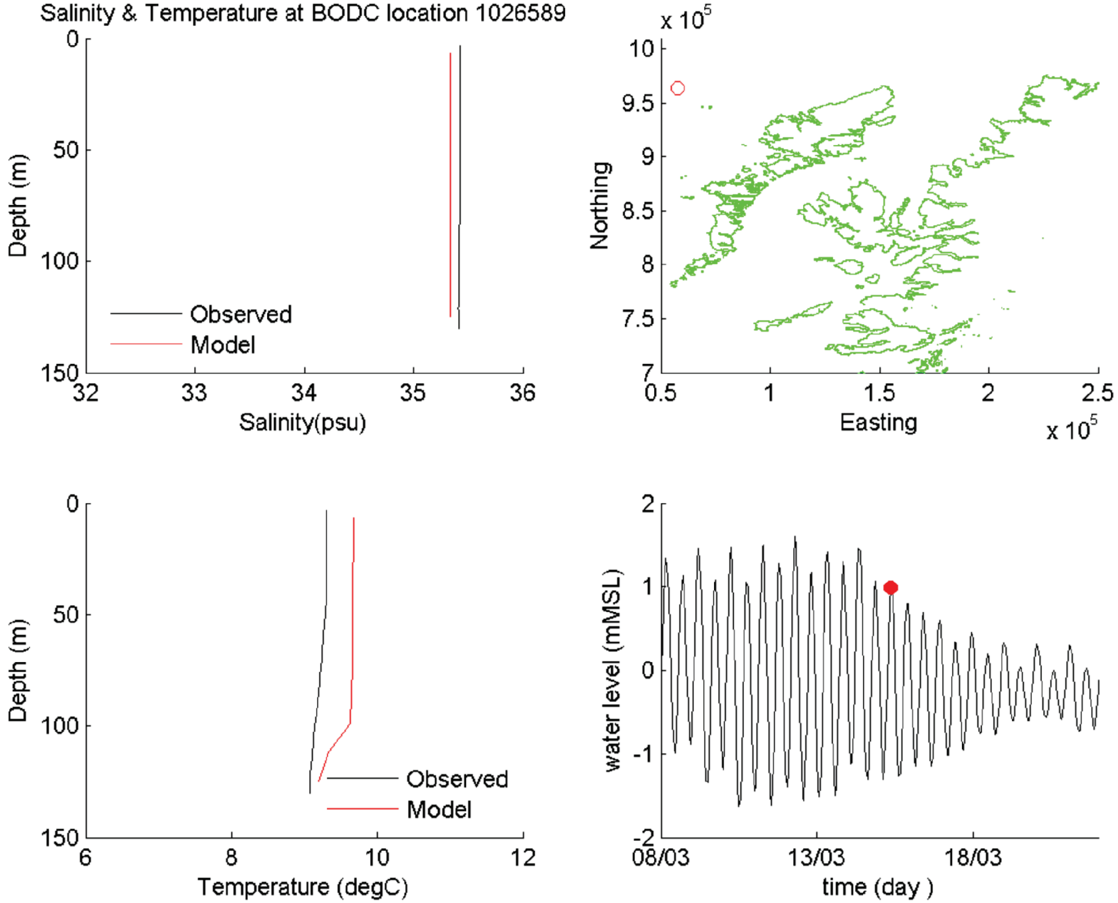
Client	Consulting Engineer	Project:	Figure Title:	Figure A-7		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



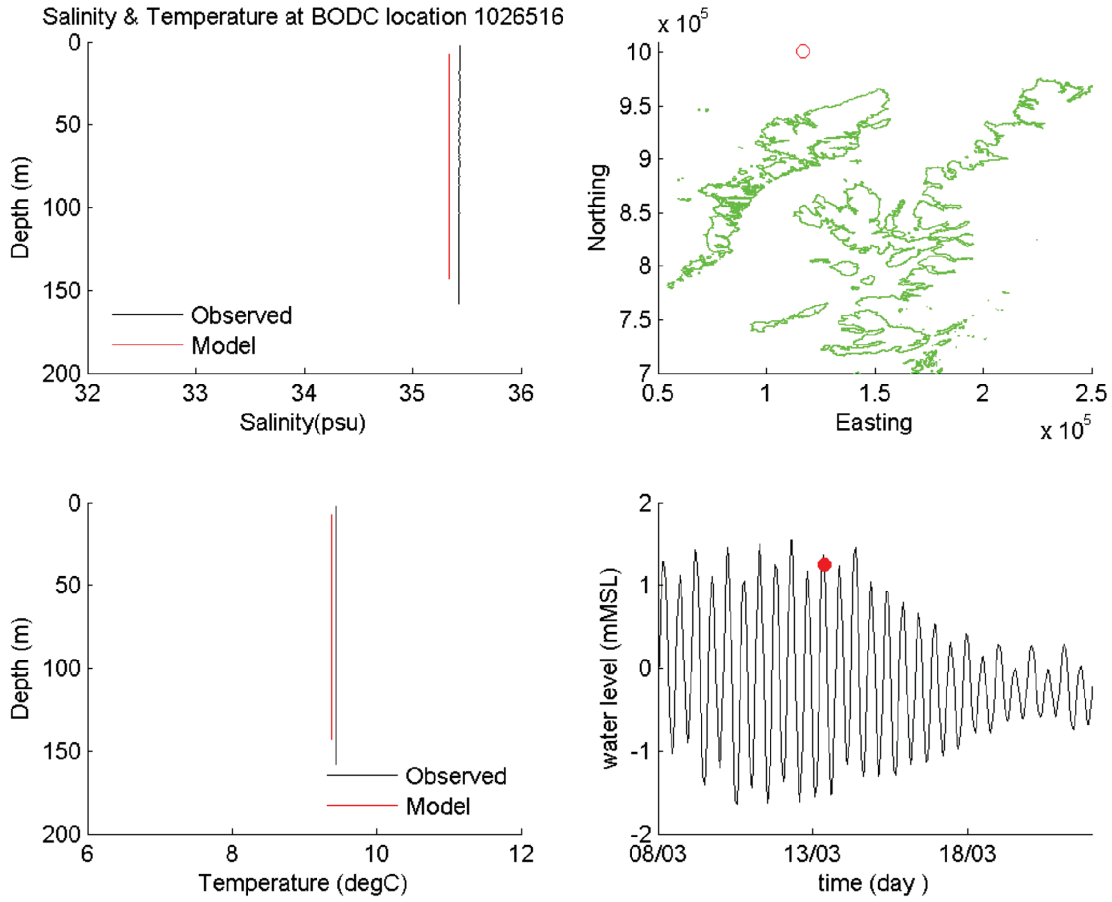
Client	Consulting Engineer	Project:	Figure Title:	Figure A-8		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Tidal ellipse comparison between SEPA data (black) and model run (red). Model results and SEPA data reconstructed to be on the same timeframe	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure A-9		
Marine Scotland		East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure A-10		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked DMP	Scale Not to scale	Rev. 0
				Designed	Drawn	Date 23/09/2014



Client	Consulting Engineer	Project:	Figure Title:	Figure A-11		
Marine Scotland	ch2m	East Coast Lewis and Harris Model	Temperature and salinity comparison between BODC data (black) and model run (red).	Checked: DMP	Scale: Not to scale	Rev.: 0
				Designed	Drawn	Date: 23/09/2014

The Scottish Government
Riaghaltas na h-Alba

This publication is available at **www.gov.scot**

Any enquiries regarding this publication should be sent to us at
The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-78544-971-0 (web only)

Published by The Scottish Government, February 2016

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS63337 (02/16)