The Scottish Government
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# The Scottish Shelf Model.
# Part 3: St Magnus Bay Sub-Domain

## Scottish Marine and Freshwater Science Vol 7 No 5

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

marine scotland

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# The Scottish Shelf Model. Part 3: St Magnus Bay sub-domain

## Marine Scotland

04 Sep 2015

City Park, 368 Alexandra Parade, G31 3AU
tel 0141 552 2000
fax 0141 552 2525
halcrow.com

# Document history

## The Scottish Shelf Model: Part 3: St Magnus Bay sub-domain

Marine Scotland

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**The Scottish Shelf Model. Part 3: St Magnus Bay sub-domain.**

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

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The FVCOM model has been developed by the Marine Ecosystem Dynamics Modeling 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.

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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.

# 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 |
| EMODnet | European Marine Observation and Data Network |
| FVCOM | Finite Volume Community Ocean Model |
| G2G | Grid-to-Grid |
| GEBCO | General Bathymetric Chart of the Oceans |

| Abbreviation | Meaning |
| --- | --- |
| GSHHS | Global Self-consistent, Hierarchical, High-resolution Shoreline |
| ICES | International Council for the Exploration of the Sea |
| IRS | Irish Sea model |
| MHW | Mean High Water |
| MHWS | Mean High Water Spring |
| MRV | Marine Research Vessel |
| MS | Marine Scotland |
| MSL | Mean sea level |
| NDBC | National Data Buoy Center |
| NGDC | National Geophysical Data Centre |
| NOAA | US National Oceanic and Atmospheric Administration |
| NOC-L | National Oceanography Cerntre - 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 |

| Abbreviation | Meaning |
|---|---|
| OS | Ordnance Survey |
| PFOW | Pentland Firth and Orkney Waters |
| POL | Proudman Oceanographic Laboratory |
| POLCOMS | Proudman Oceanographic Laboratory Coastal Ocean Modelling System |
| POL HRCS | Proudman Oceanographic Laboratory High Resolution Continental Shelf |
| SEPA | Scottish Environment Protection Agency |
| SMB | St Magnus Bay |
| SMHI | Swedish Meteorological and Hydrological Institute |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |
| UKHO | United Kingdom Hydrographic Office |
| VMADCP | Vessel Mounted Acoustic Doppler Current Profiler |
| 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.

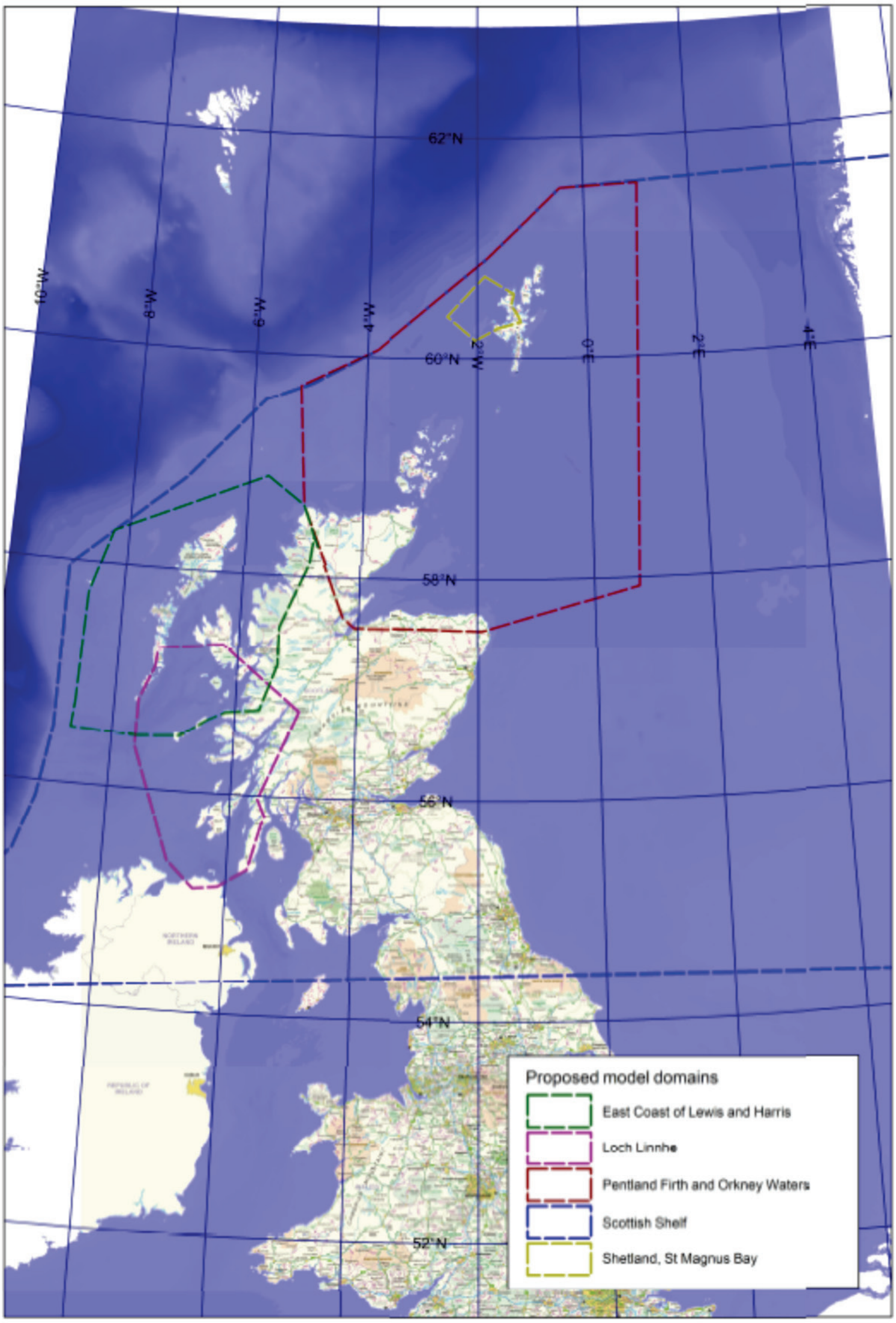
## 1.2 Study areas

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 (PFOW)
Case Study 2: Wider Loch Linnhe System
Case Study 3: East Coast of Lewis and Harris
Case Study 4: Northwest Shetland mainland – St Magnus Bay (SMB) 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 | St Magnus Bay 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 in the region. It also includes a description of methods for assessing the impact of extracting some of that energy upon the physical environment.

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

## 1.4 Project Team

The project team delivering this study consists of:

- Halcrow Group Ltd as the main contractor, responsible for co-ordination of 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 development of connectivity indices.

## 1.5 This Report

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

## 1.6 Datums

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

- All horizontal co-ordinates are referenced to lattitude and longitude, however the model itself is referenced to Ordnance Survey of Great Britain (OSGB).
- 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.
- CEFAS for the provision of wave data from their WAVENET website. Thanks to David Pearce at CEFAS for his help with clarifying the terms of use of these data.
- Dr Susana Baston Meira and Dr David Woolf at Heriot-Watt University for their help with obtaining ADCP data in the Pentland Firth.
- Professor Chen at the University of Massachusetts (Dartmouth) and his team for making the FVCOM software available for this project.

We also acknowledge with thanks the owners of the internet websites mentioned below for the valuable data downloaded from them for this study.

- Tide gauge data (class 'A') from the National Tide and Sea Level Facility (NTSLF – available from 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 St Magnus Bay area (SMB), the following data have been collated and/or identified:

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

This section of the report describes the data collated/identified for the SMB model area. Where appropriate, reference is made to the overall project data review report (Halcrow, 2012) and the Pentland Firth and Orkney Waters modelling report (Price et al. 2015). As the SMB model is set within the PFOW model area, there are common datasets being used by both models as time was spent during the PFOW model setup to make sure data was also suitable for the SMB model. 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. These are at higher spatial resolution than the GSHHS shoreline dataset. 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, such as for St Magnus Bay.

### 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 Island (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. There does not appear to be any discontinuities in the immediate area of St Magnus Bay.

#### 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.

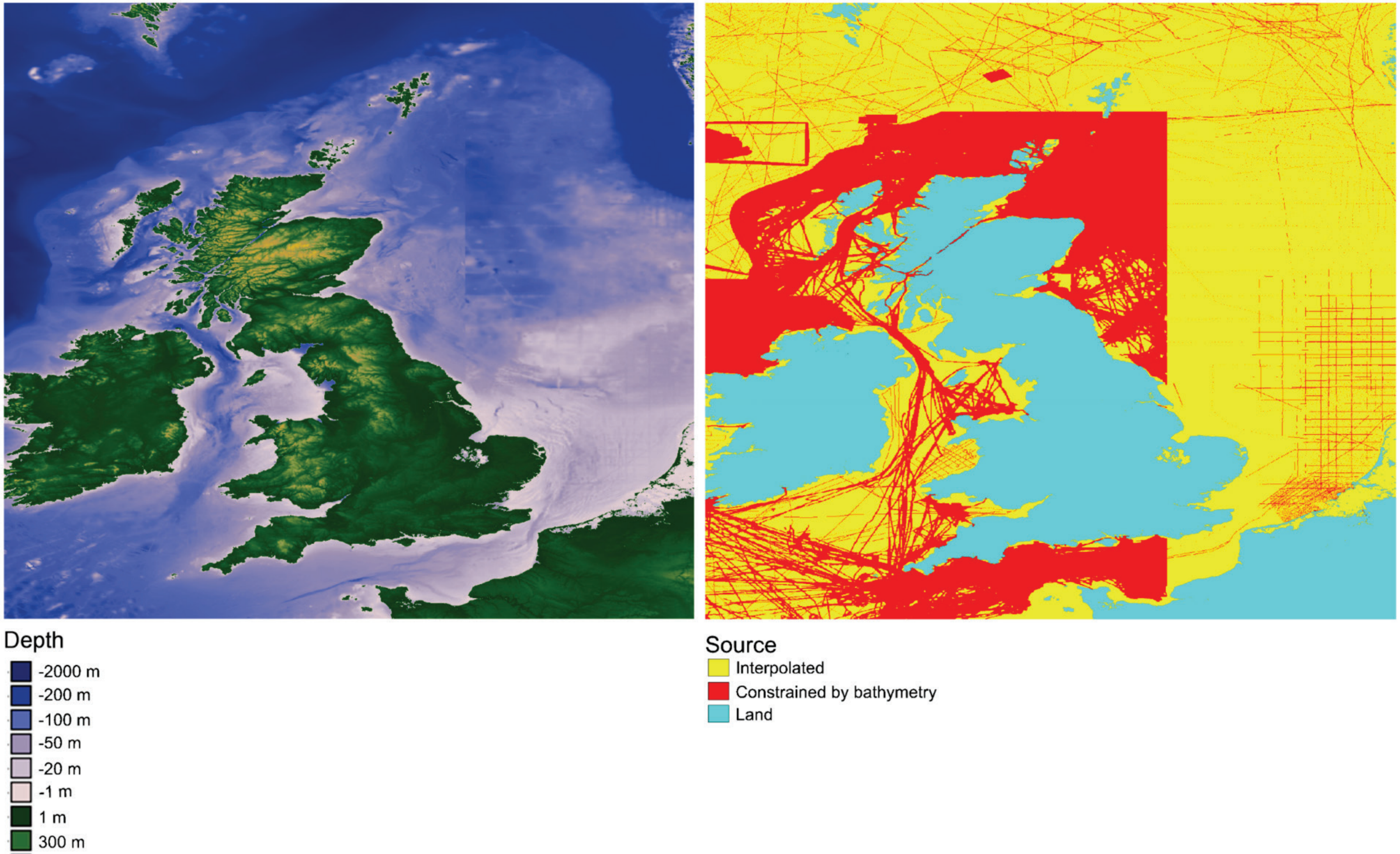
#### 2.2.2.3 European Marine Observation and Data Network (EMODnet)

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/

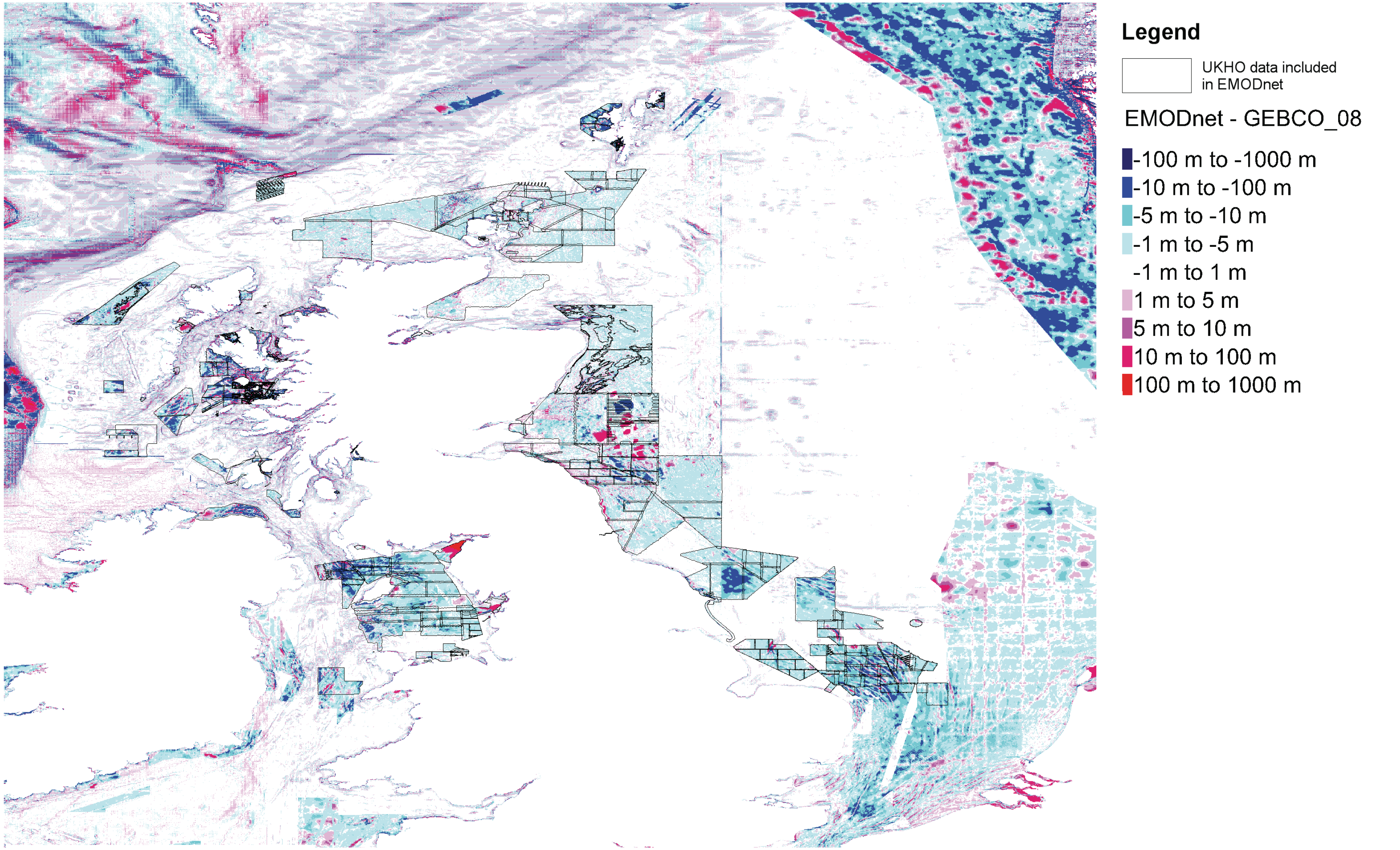
Further details of EMODnet are provided in Halcrow (2012).

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. It can be seen in Figure 2-2 that there is more detailed bathymetry in St Magnus Bay from UKHO data.

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 | St Magnus Bay Model | Data sources used in the GEBCO data set. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



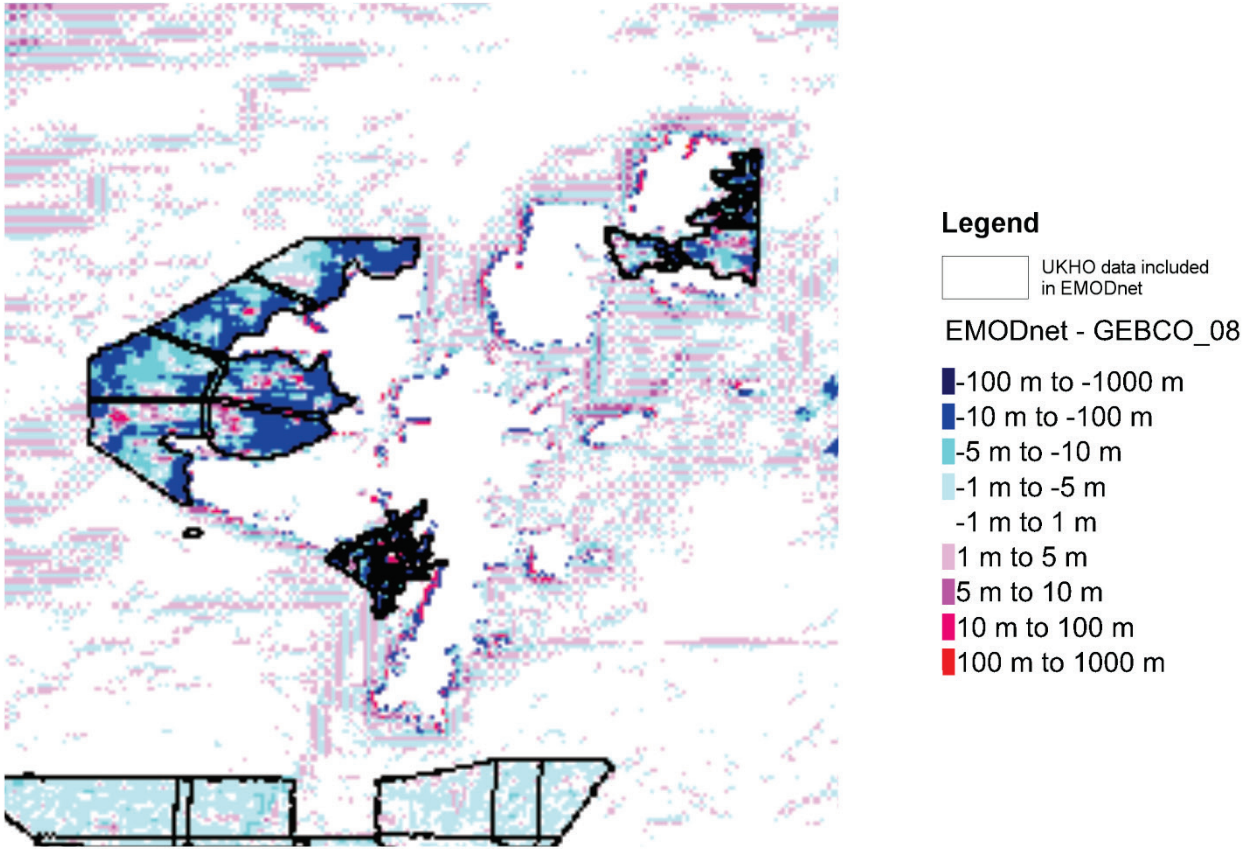

| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-2 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | EMODnet data sources and difference between EMODnet and GEBCO_08 bathymetry. | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: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

### 2.2.3 Hydrographic Data

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

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

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




| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-3 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Location of EMODnet and UKHO Bathymetry data for the St Magnus Bay model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

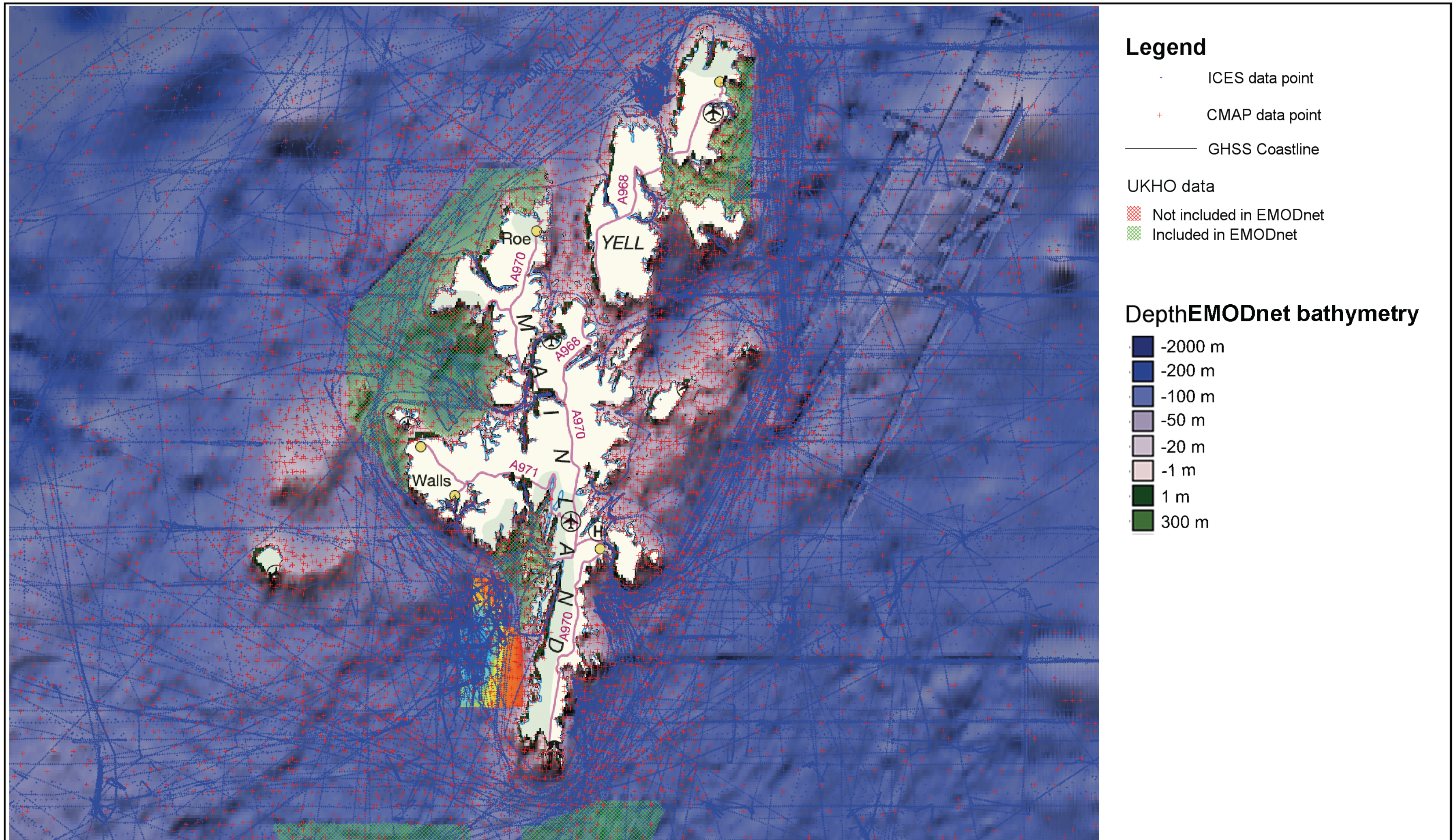
### 2.2.4 Other data sources

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 SMB model.

### 2.2.5 Summary of bathymetry data availability for the St Magnus Bay Area

A map of data availability for the Shetland Islands, including the proposed model domain in and around St Magnus Bay, is shown in Figure 2-4. For the Shetland Islands there is no high resolution data east of the Mainland and through the Yell Sound, however this area is not within the SMB model domain. UKHO bathymetry data does exist within St Magnus Bay and was used in preference to other datasets, Admiralty Chart data being the second preference followed by the coarser EMODnet data. Admiralty Chart data is required in the margins of the Bay and in the smaller channels.

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






| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-4 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Detailed view of available bathymetry for the Shetland Islands. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

## 2.3 Forcing Data

### 2.3.1 Introduction

Forcing data is required for a six month climatological model run of the SMB flow model and for calibration using observed data for approximate 1 month period. 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

As the SMB model lies wholly within the PFOW model domain, the boundary conditions came directly from that model for the calibration runs and from the shelf model for the climatology.

### 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 could be 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.

### 2.3.3 Meteorological observations

The Marine Scotland Science survey vessel MRV Scotia undertook two surveys for this project, including one in St Magnus Bay, Shetland (October 2012). During these surveys wind measurements were made from the vessel.

### 2.3.4 Hydrological Data (Fresh Water Inflows)

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

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.

### 2.3.5 Tide

For the SMB Model, the boundary data was derived from the PFOW model which in turn gets its boundary data from NOC-L's Atlantic Margin Model (AMM) with a 12km resolution. Water levels along with temperature and salinity timeseries was 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 the 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, salinity and surface waves. In addition validation is required for the 1 year climatological runs against accepted general flow characteristics including residual current speed and direction (seasonal variability) and seasonal temperature and salinity cycles.

### 2.4.2 Water Level

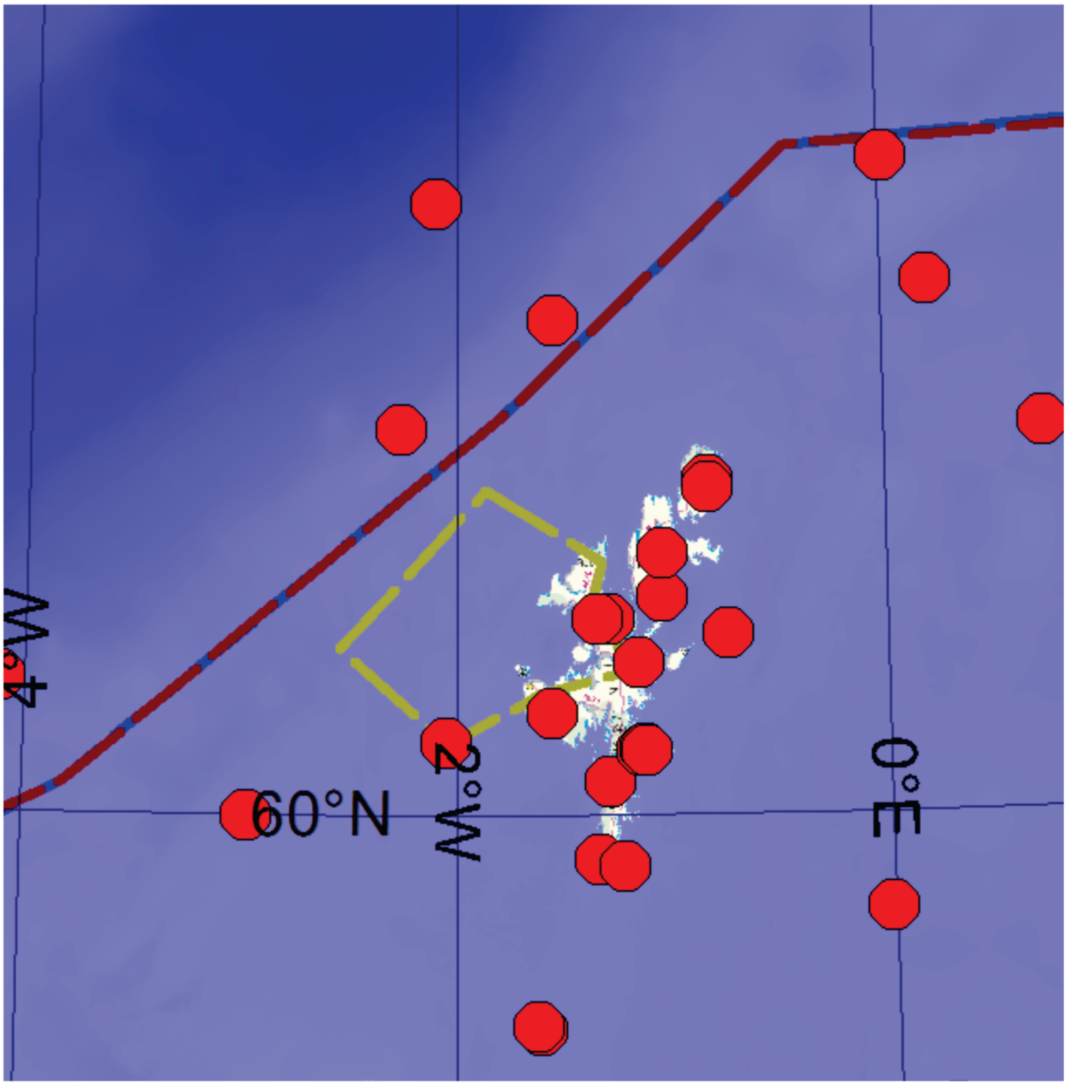
Figure 2-5 shows all the locations of water level observations that are available in the SMB region. These come from three main sources: tide gauge data from the BODC National Oceanographic Database (NODB) and bottom pressure data from the NODB, analysed tidal data from NOC. Those data which are available post year 2000 are shown in Figure 2-6.

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 2-7. 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 2-8.

### 2.4.3 Currents

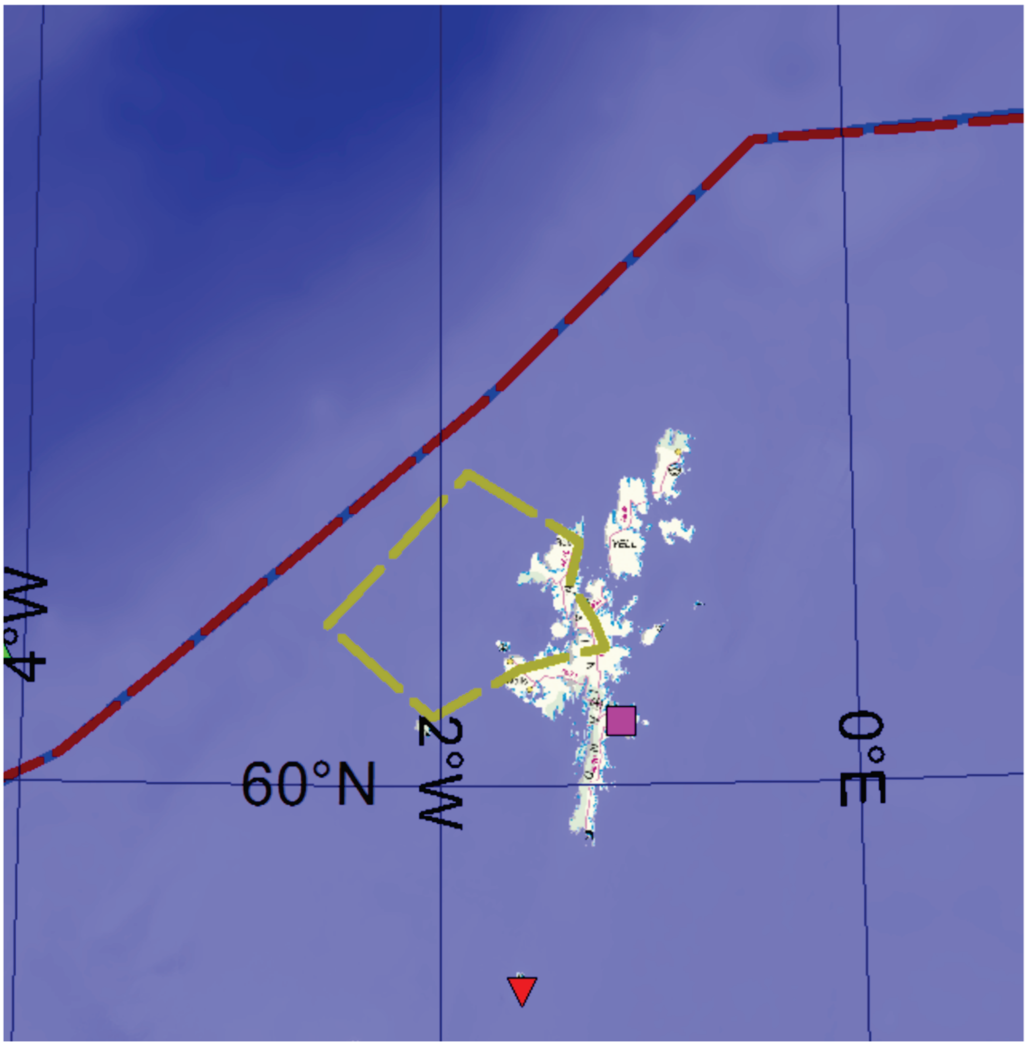
Datasets on currents have been found from a number of sources; locations of many of these are shown in Figure 2-9. These come from the BODC National Oceanographic Database (NODB) and the TotalTide software, from UK Hydrographic Office. As Figure 2-10 shows, there are only a few datasets from the BODC National Oceanographic Database since year 2000. In addition, some of these datasets (shown in red) may not be freely available. In some cases, vertical current profiles are available; these are shown in Figure 2-11.

Fish Farm data was also obtained from Alan Hills of SEPA. This data consisted of 30 days of current measurements at three depths (surface, mid and bottom). This data has proved to be useful for comparison with the model within the SMB area.

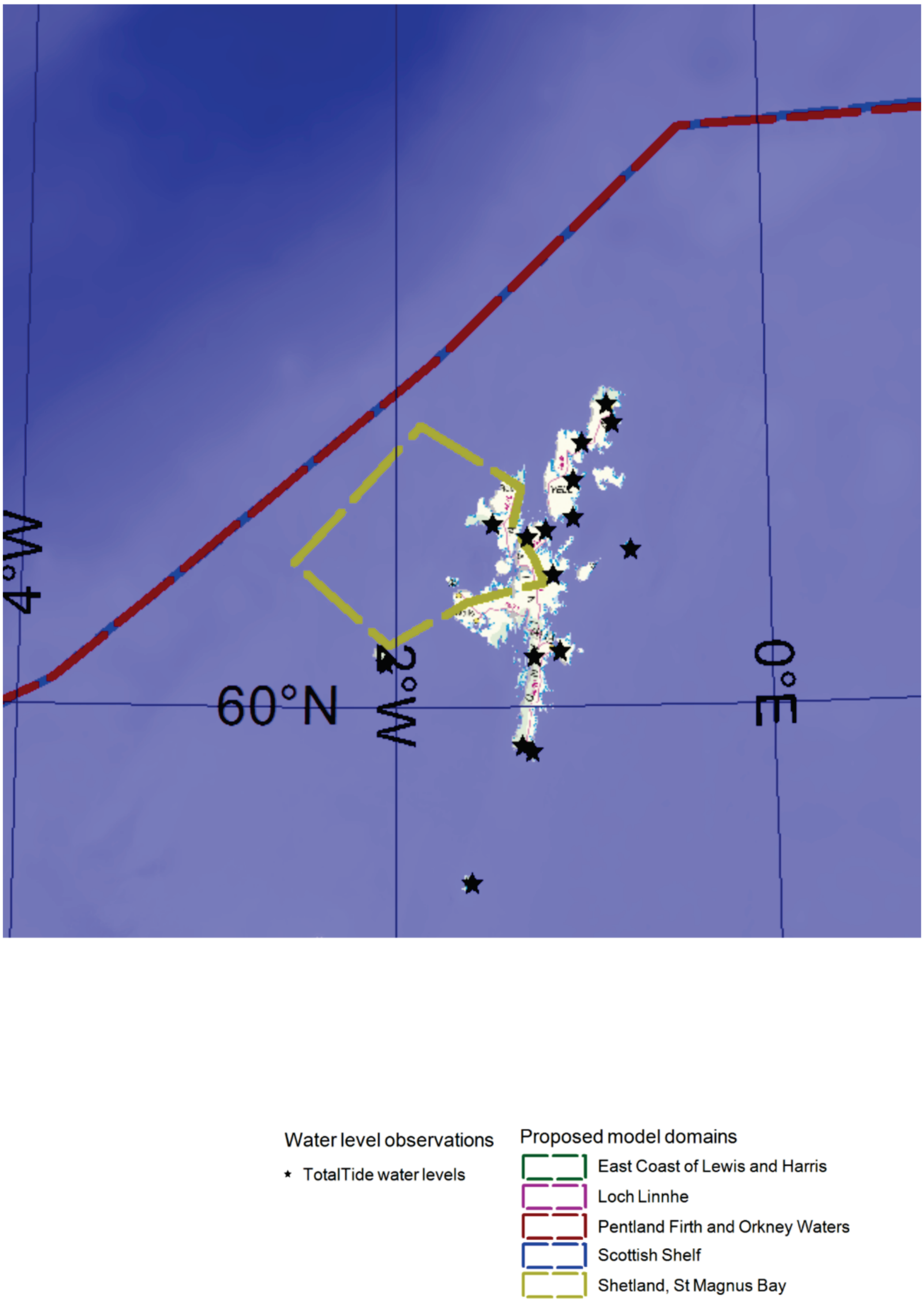




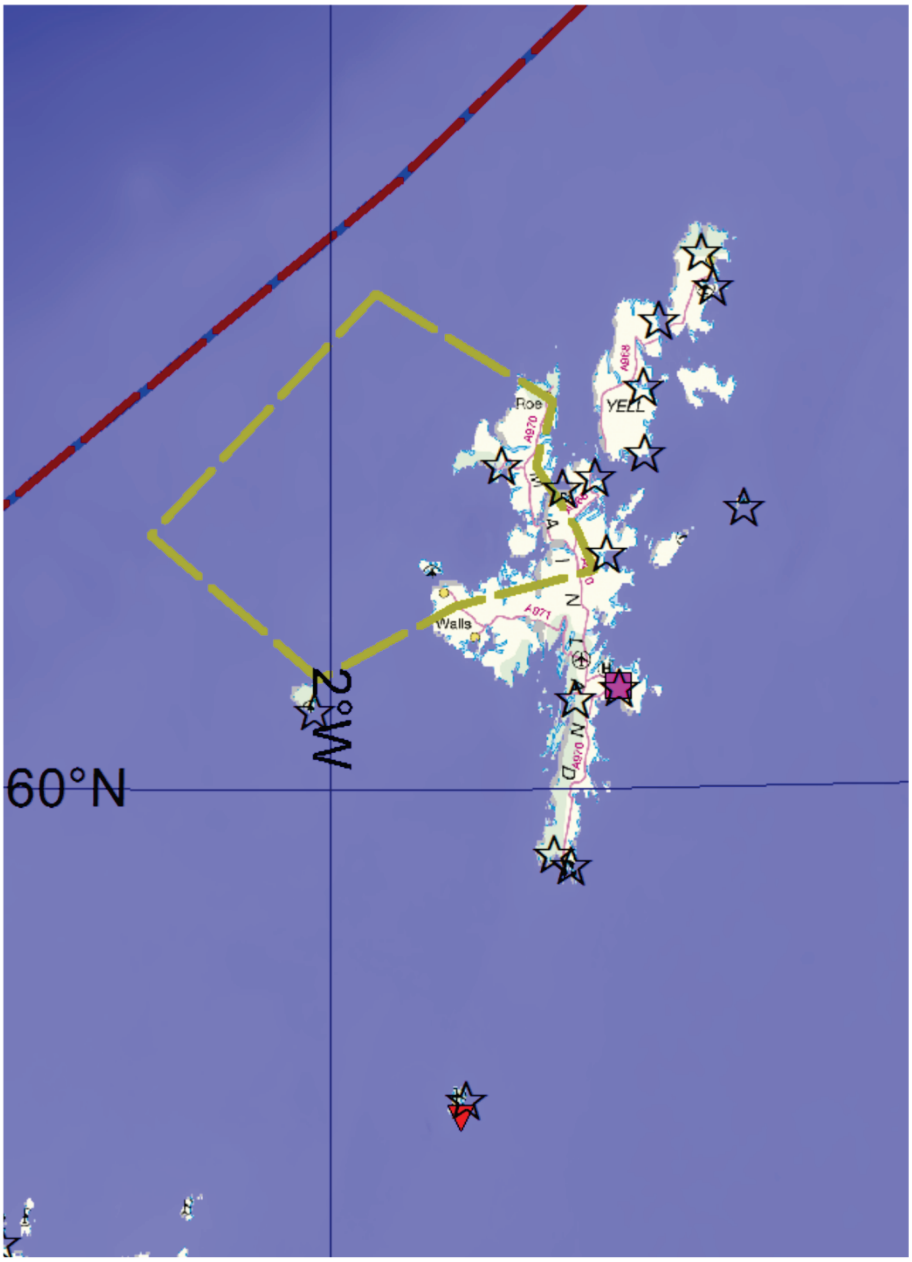

| Client | Consulting Engineer | Project: | **Figure 2-5** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Water level observations in the Shetland Waters |




| Client | Consulting Engineer | Project: | **Figure 2-6** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Post-2000 water level observations |




| Client | Consulting Engineer | Project: | **Figure 2-7** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Total-tide water level locations |



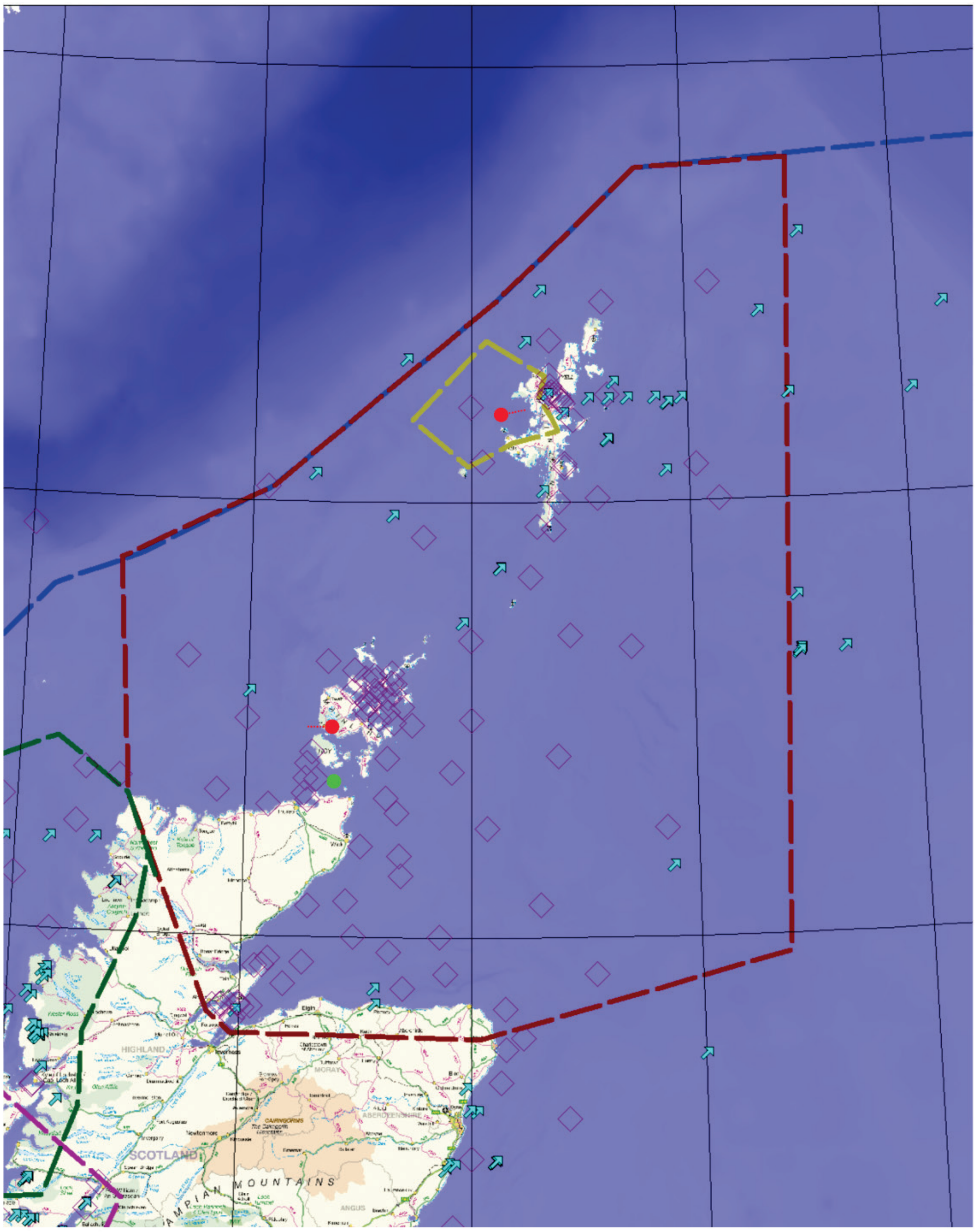

Water level observations post-2000

- 1/4-hourly tide gauge data from BODC
- NOC analysed tidal data
- TotalTide water levels
- Bottom pressure data - possible restrictions
- Bottom pressure data - unrestricted

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 2-8** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Post-2000 water level observations in the Shetland Waters |




All TotalTide locations

All current observations

Proposed model domains

East Coast of Lewis and Harris

Loch Linnhe

Pentland Firth and Orkney Waters

Scottish Shelf

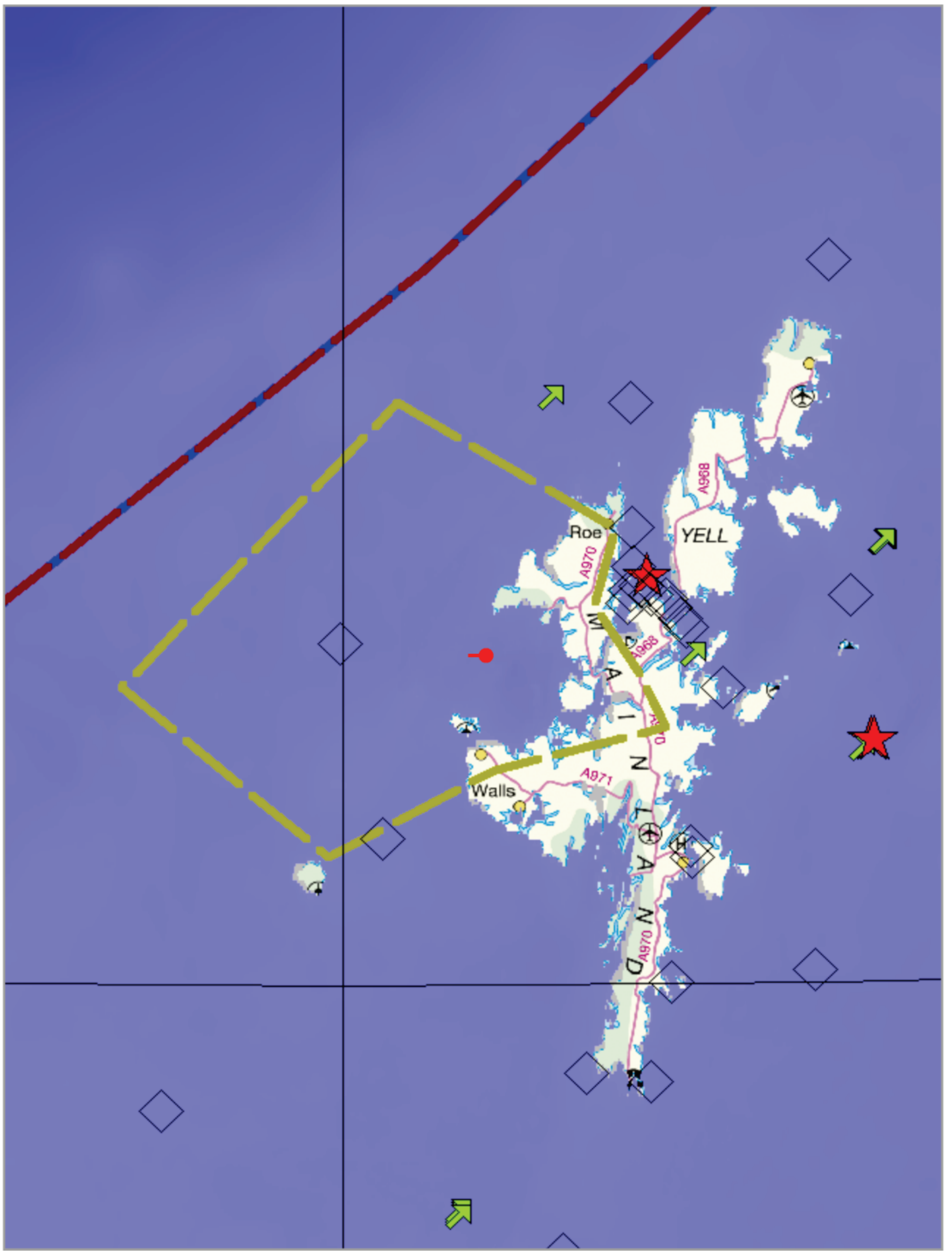
Shetland, St Magnus Bay

ADCP Data from Pentland Firth

ADCP Data from MV Scotia



| Client | Consulting Engineer | Project: | **Figure 2-9** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | All current observations and TotalTide tidal stream locations |




Currents observations from BODC post-2000
Unrestricted

Currents observations from BODC post-2000
Possible restrictions

TotalTide tidal stream data

ADCP Data from MV Scotia

Proposed model domains

East Coast of Lewis and Harris

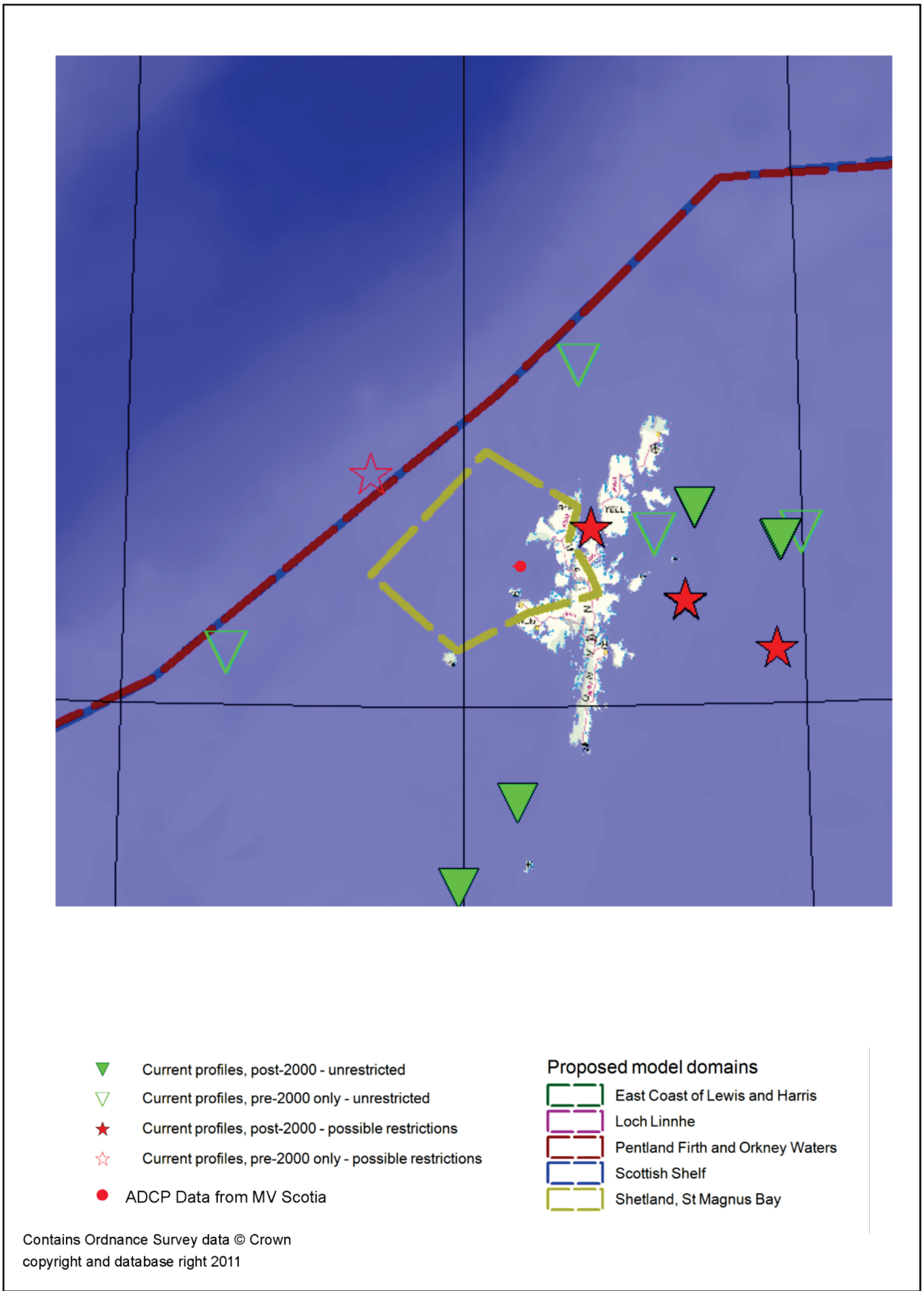
Loch Linnhe

Pentland Firth and Orkney Waters

Scottish Shelf

Shetland, St Magnus Bay

| Client | Consulting Engineer | Project: | **Figure 2-10** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Post-2000 current observations in the Shetland Waters |




| Client | Consulting Engineer | Project: | **Figure 2-11** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Pre and Post-2000 current profiles |

The methodology used by TotalTide for calculating currents is not known exactly but is likely to be an interpolation of tidal diamond chart data to cover different range tides. In addition, these data have been estimated for the use of shipping; therefore, a greater weighting may be placed on surface currents than currents near the sea bed.

Additionally the MRV Scotia collected current and CTD measurements in and around St Magnus Bay in Shetland in October 2012 (shown as ADCP Data from MRV Scotia on Figure 2-9, 2-10 and 2-11 with more detail shown on Figure 2-12). These data are considered essential for the calibration of the SMB model.

The Atlas of UK Marine Renewable Energy Resources (www.renewables-atlas.info) contains information on peak tidal current speeds over a mean spring and a mean neap tide. The dataset was derived from the POL HRCS Model, with peak spring and neap current speeds calculated from the major 2 or 4 tidal harmonics. Although this dataset is limited, it is freely available on a 0.0167° x 0.025° (latitude x longitude) grid throughout the region shown in Figure 2-13.

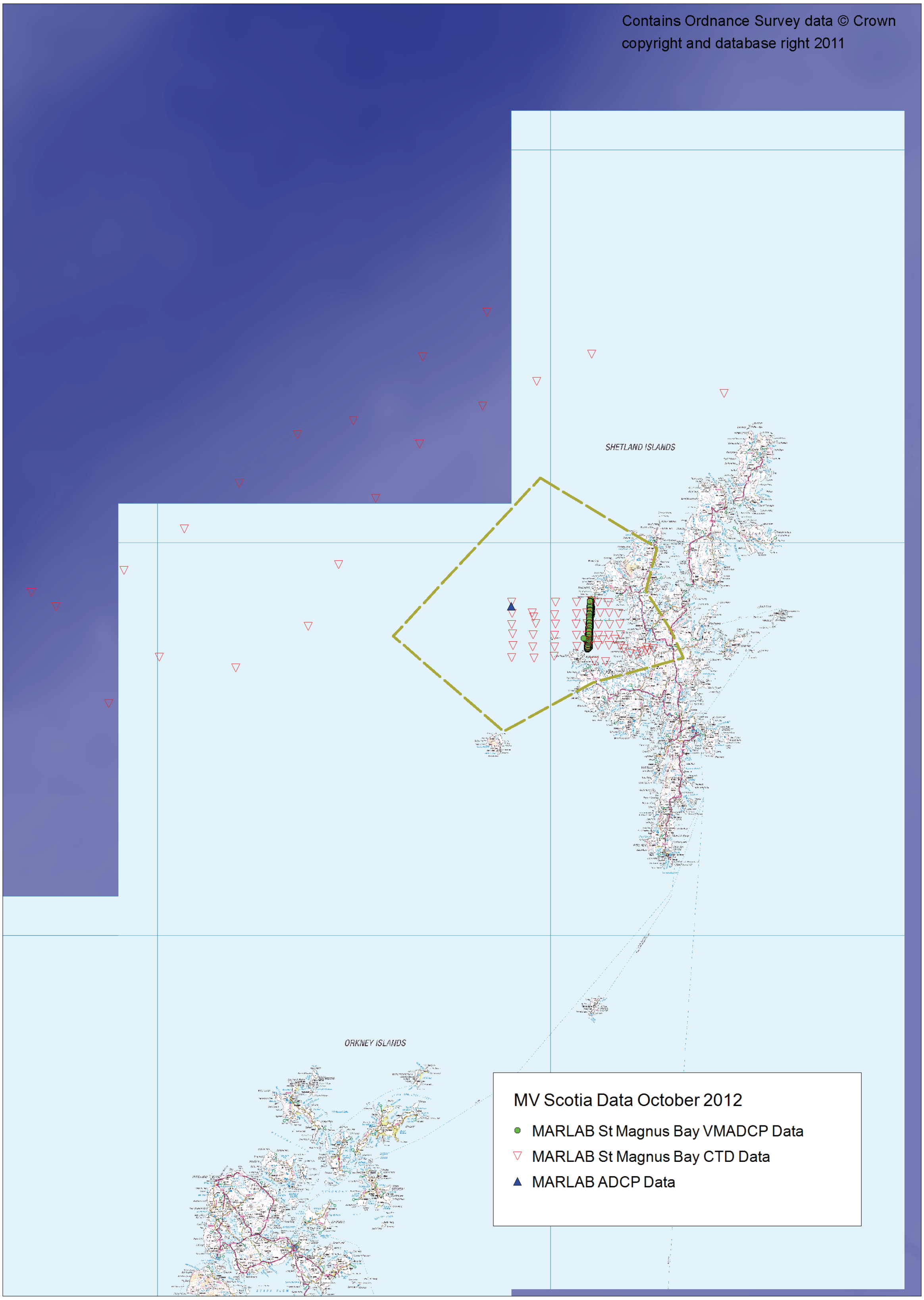
### 2.4.4 Temperature and Salinity

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. Additionally the Marine Scotland survey in SMB also provides temperature and salinity data, which together with the ADCP data was the data used for model calibration.

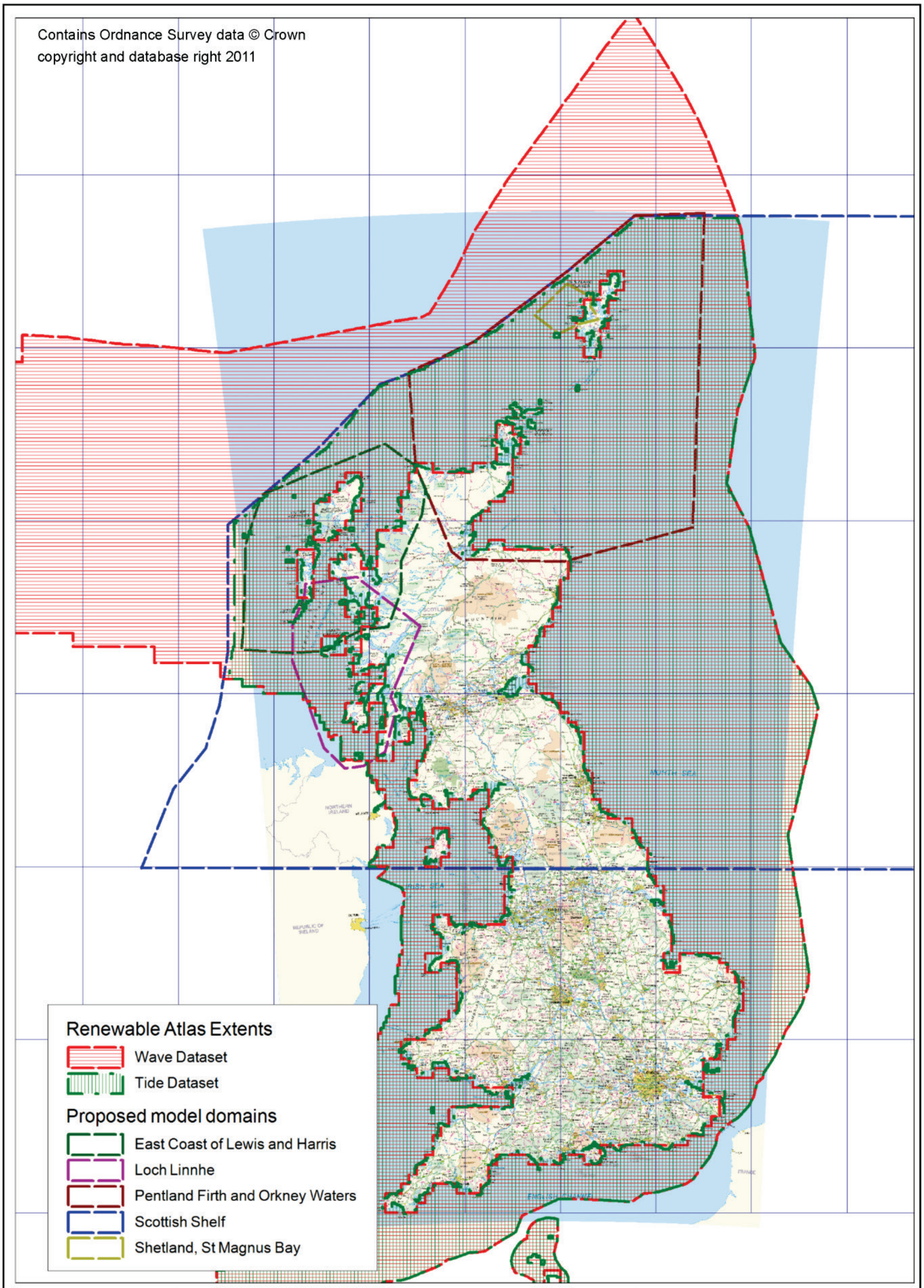
Figure 2-14 shows the locations of the temperature observations and Figure 2-15 shows the locations of the salinity observations. As Figure 2-16 shows, the temperature and salinity observations have occurred throughout the last two decades, with many observations throughout all model domains having occurred over the last few years. Figure 2-17 shows which of these observations include profiles over the entire water depth. Most temperature and salinity observations occurred at the same location and time.

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

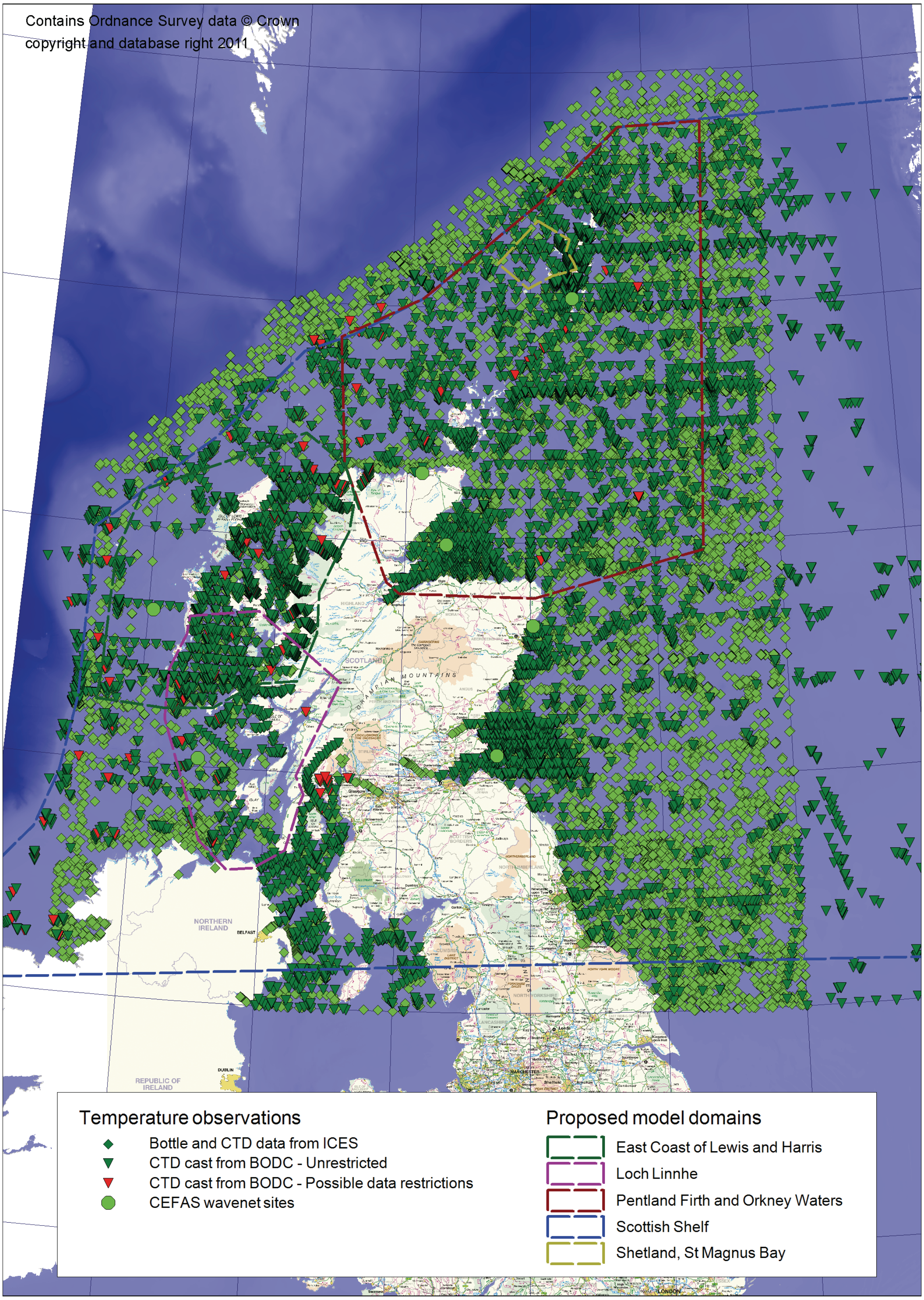
The results from the climatic run were compared with climatological atlas information for temperature and salinity, from the World Ocean Atlas (WOA) and International Council for Exploration of the Seas (ICES) climatological datasets.



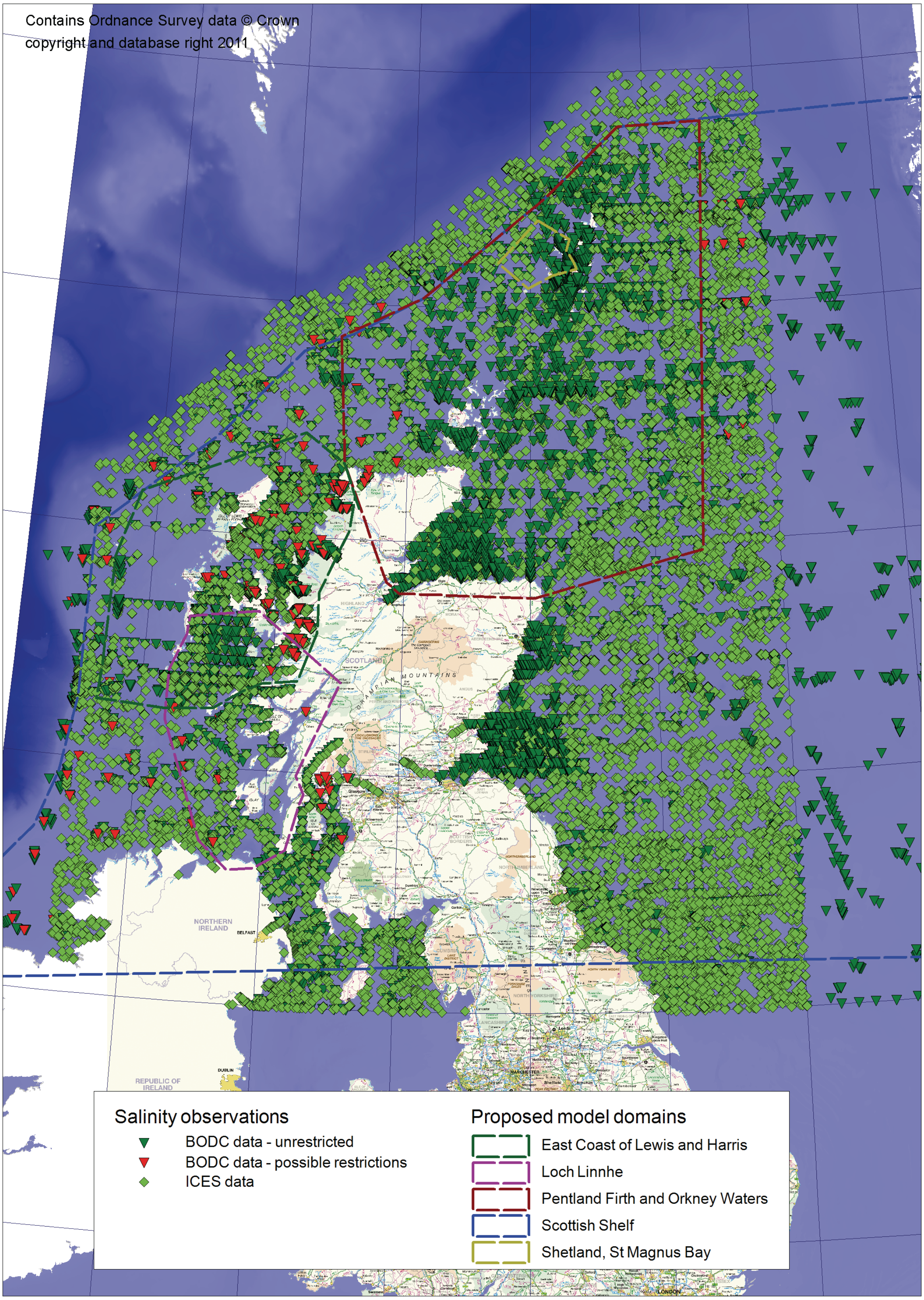

| Client | Consulting Engineer | Project: | **Figure 2-12** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Observations from MV Scotia in St Magnus Bay, Shetland in October 2012 |



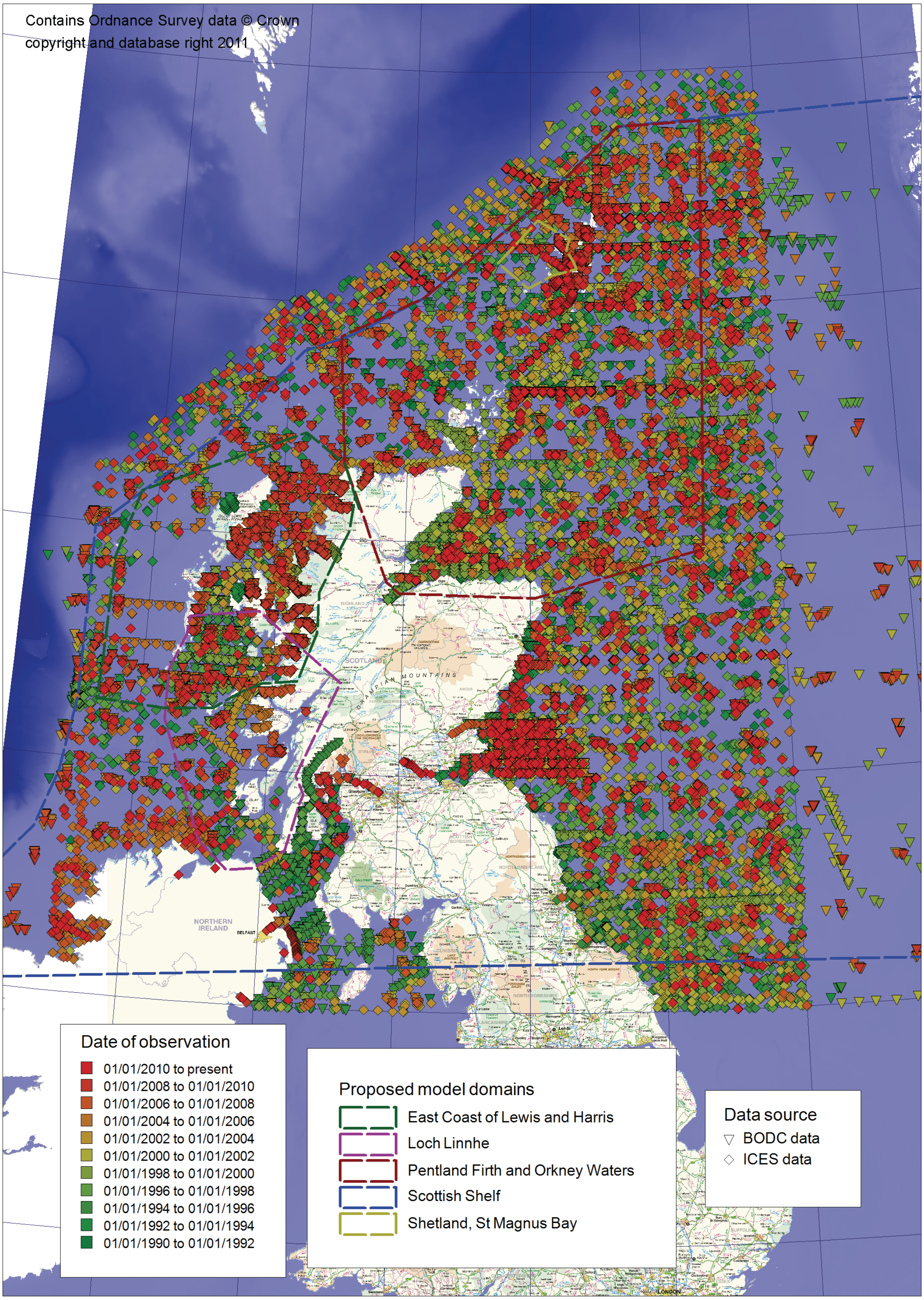

| Client | Consulting Engineer | Project: | **Figure 2-13** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Wave and tidal domains from the Renewables Atlas |



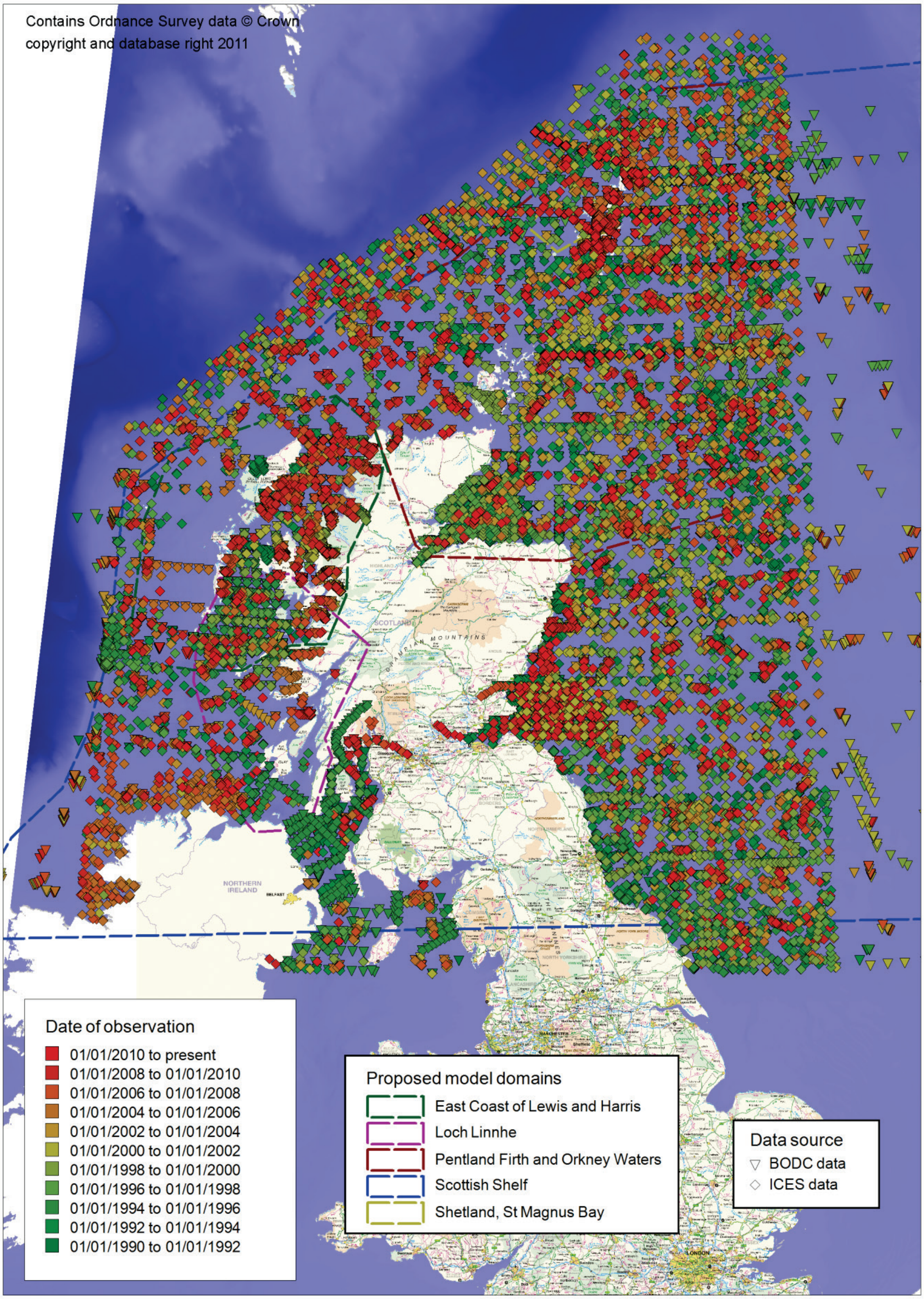

| Client | Consulting Engineer | Project: | **Figure 2-14** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | All temperature observations |




| Client | Consulting Engineer | Project: | **Figure 2-15** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | All salinity observations |




| Client | Consulting Engineer | Project: | **Figure 2-16** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Temperature and salinity observations by date, including surface observations and profiles |




| Client | Consulting Engineer | Project: | **Figure 2-17** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Temperature and salinity profile observations by date |

### 2.4.5 Summary of data availability for the SMB model

This section summarises the availability of calibration and validation data for the SMB 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 SMB model. It shows that for all three years sufficient data exists for tidal hydrodynamic calibration, however 2009 is the only year suitable for the baroclinic calibration. Calibration of the model is carried out using 2012 while 2009 and 2001 are used for temperature/salinity and tidal currents validation respectively.

*Table 2-1 Case Study models and available data*

| Sub model | Year | Water level | Currents | Temperature /salinity | Meteorological | Wind | River |
|---|---|---|---|---|---|---|---|
| St Magnus Bay | 2001 | ✓ | ✓ | ✓ | X | X | X |
| | 2009 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 2012 | ✓ | ✓ | ✓ | X | ✓ | X |

## 2.5 Conclusions and Recommendations

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

### 2.5.1 Bathymetry

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

Further UKHO data 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 PFOW model which in turn obtained its boundary conditions from the NOC-L AMM model.

**Meteorological forcing** for the SMB 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. Therefore for the model calibration only wind forcing was available (coincident with the MRV Scotia data in St Magnus Bay).

**Fluvial inputs** were derived from G2G river flow data obtained from CEH for the SMB area for the 2009 validation. Additional G2G runs were undertaken to provide missing data in Shetland although this is not coincident with the 2012 survey but was useful for climatological simulations.

### 2.5.3 Calibration Data

Section 2.4.5 presents information about which data are available for the SMB model. In general there is sufficient data with which to undertake calibration for, water level, currents, temperature and salinity, with the main period for comparison being in October 2012 when the MRV Scotia made her measurements. In summary we believe that there are sufficient data for the calibration of the SMB model.

# 3 Hydrodynamic Model Development

## 3.1 Introduction

This section of the report describes the setting up of the SMB model mesh, bathymetry 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 SMB flow model setup

### 3.2.1 Model bathymetry

The SMB model mesh has been created using the MIKE21 mesh generator, as was the case for the PFOW model, although for both models the mesh was loaded into SMS mesh generator in order to use its mesh QA capability. The area of the mesh is contained within the Pentland Firth and Orkney Waters (PFOW) model, allowing boundary conditions to drive the SMB model to be extracted from the results of the PFOW model.

The bathymetry data used for the SMB model was the same as that used for the PFOW model, as care had been taken to provide sufficient resolution in this area. The bathymetry was constructed from the following data sources (which are ordered with the highest priority/resolution data first):

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

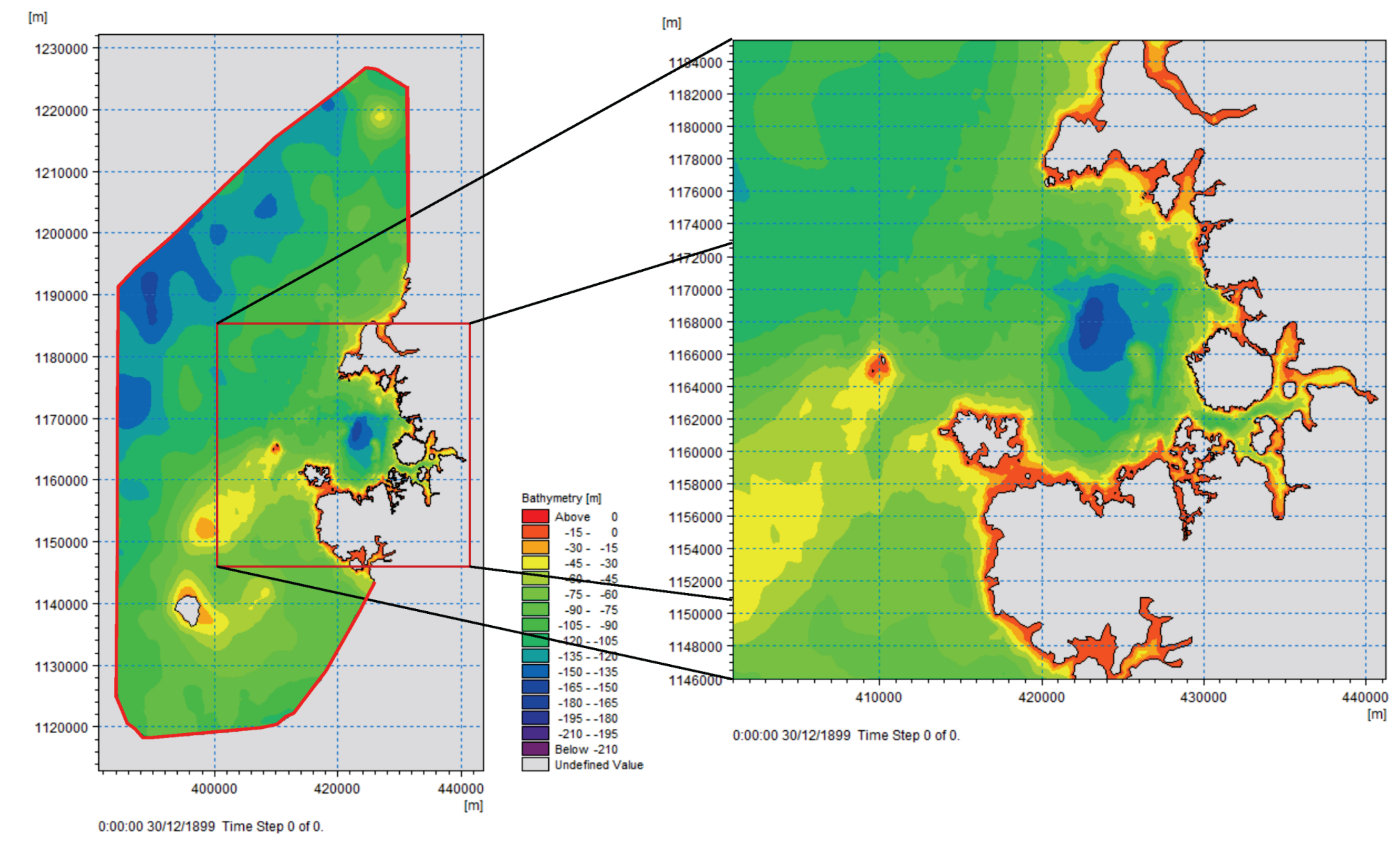
The coastline was derived from Ordnance survey coastline data.

Figure 3-1a shows the extent of the model domain in the left hand frame. The open boundary is highlighted in red. The contours on this and subsequent images are of the model bathymetry which is relative to MSL. Figure 3-1b shows a closer view of SMB in the left hand frame, and a closer view of the eastern part of SMB in the right hand frame.

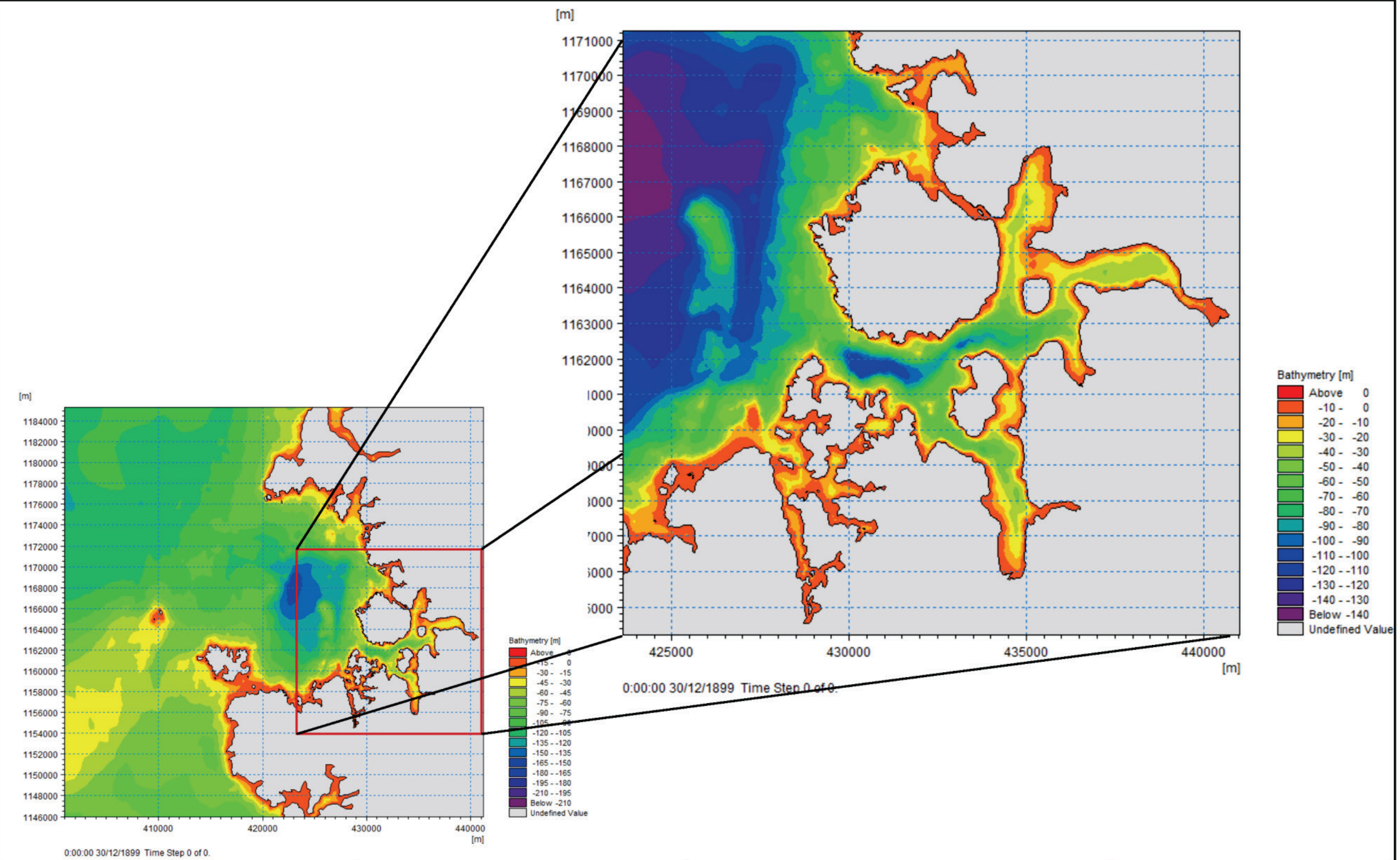
### 3.2.2 Model mesh

The model mesh was created to provide sufficient resolution within SMB and especially the narrower channels. The mesh was edited to make sure there were no nodes connected to nine or more others. Figures 3-2a-c show the mesh at different zoom levels. Resolution in the offshore region of the model is in the order of 1000m, within the central part of SMB it is 200m, with most of the rest of the area within SMB has a resolution in the order of 50-75m. The channel between Muckle Roe and the mainland has a resolution of 25m in order to be able to resolve the flow through this narrow channel.

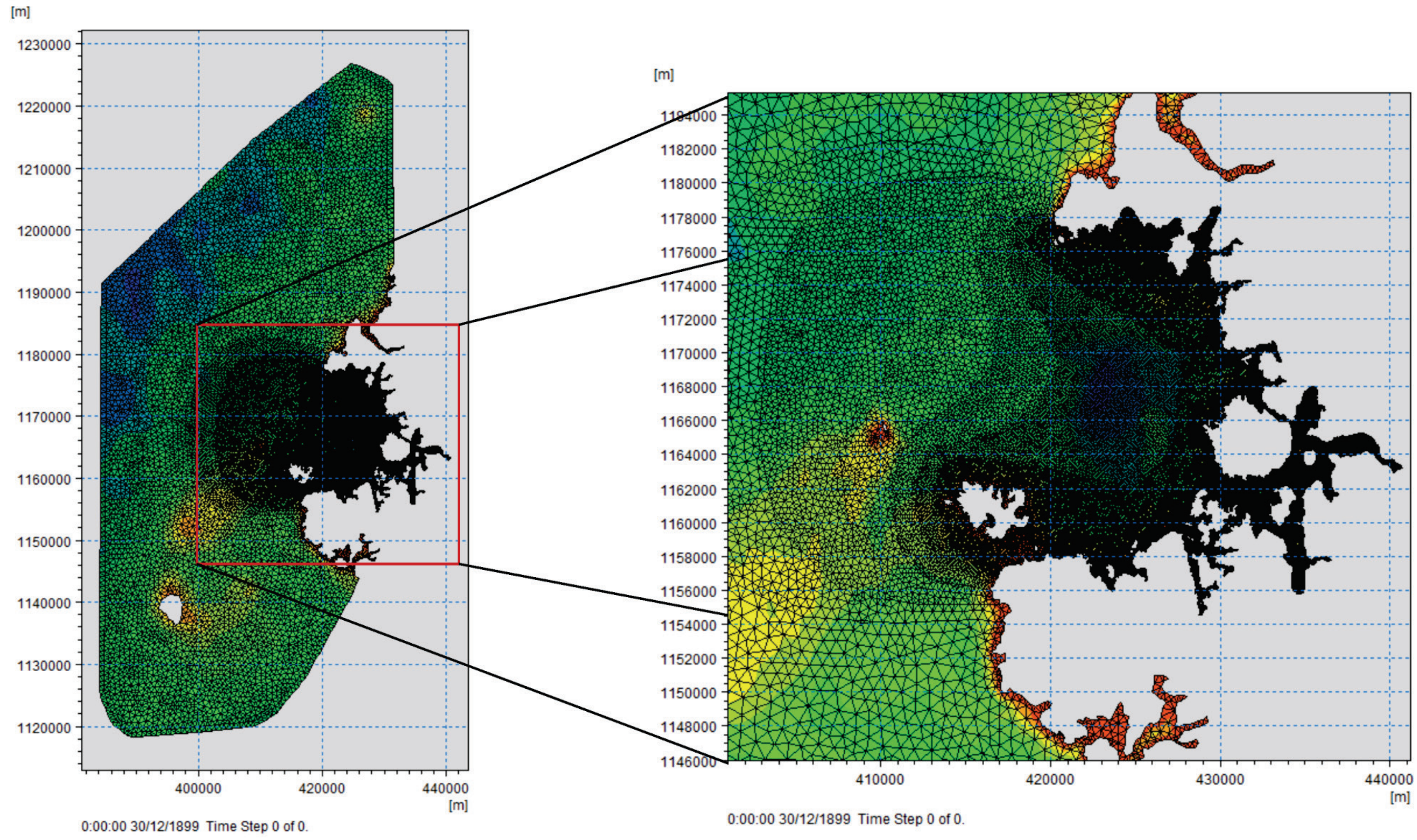
It can be seen in Figure 3-2d that there is a polyline inside the outer open boundary. The nodes along this line were defined so that edges of boundary elements were normal to the open boundary. The purpose of this is to reduce interpolation along the boundary for when the model applies water level, currents, temperature and salinity nudging. The simulations undertaken with this model mesh used 10 vertical sigma layers (11 levels), each with an equal 10% proportion of the total water depth.



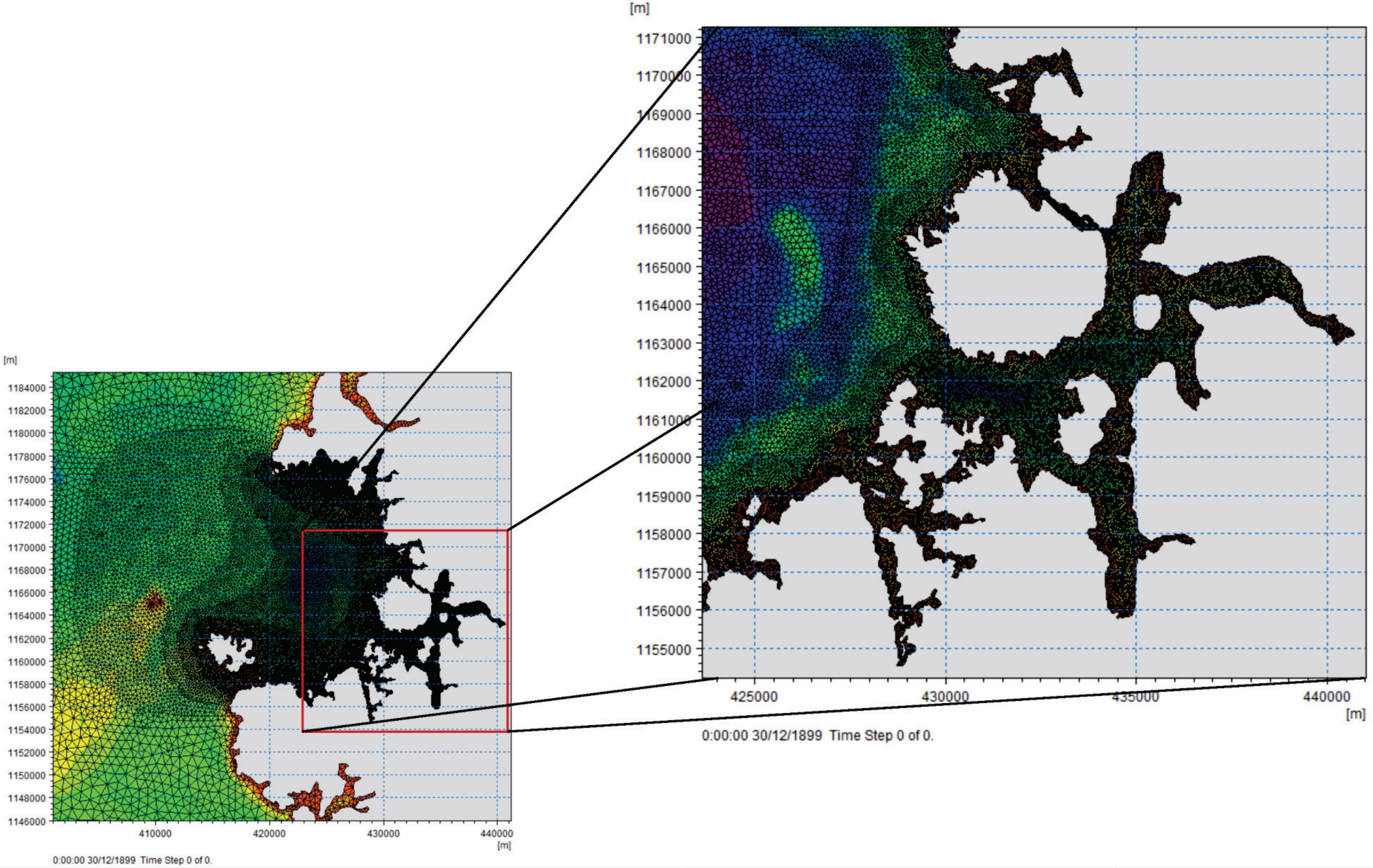

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-1a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | SMB model bathymetry relative to MSL showing model open boundary with thick red line | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



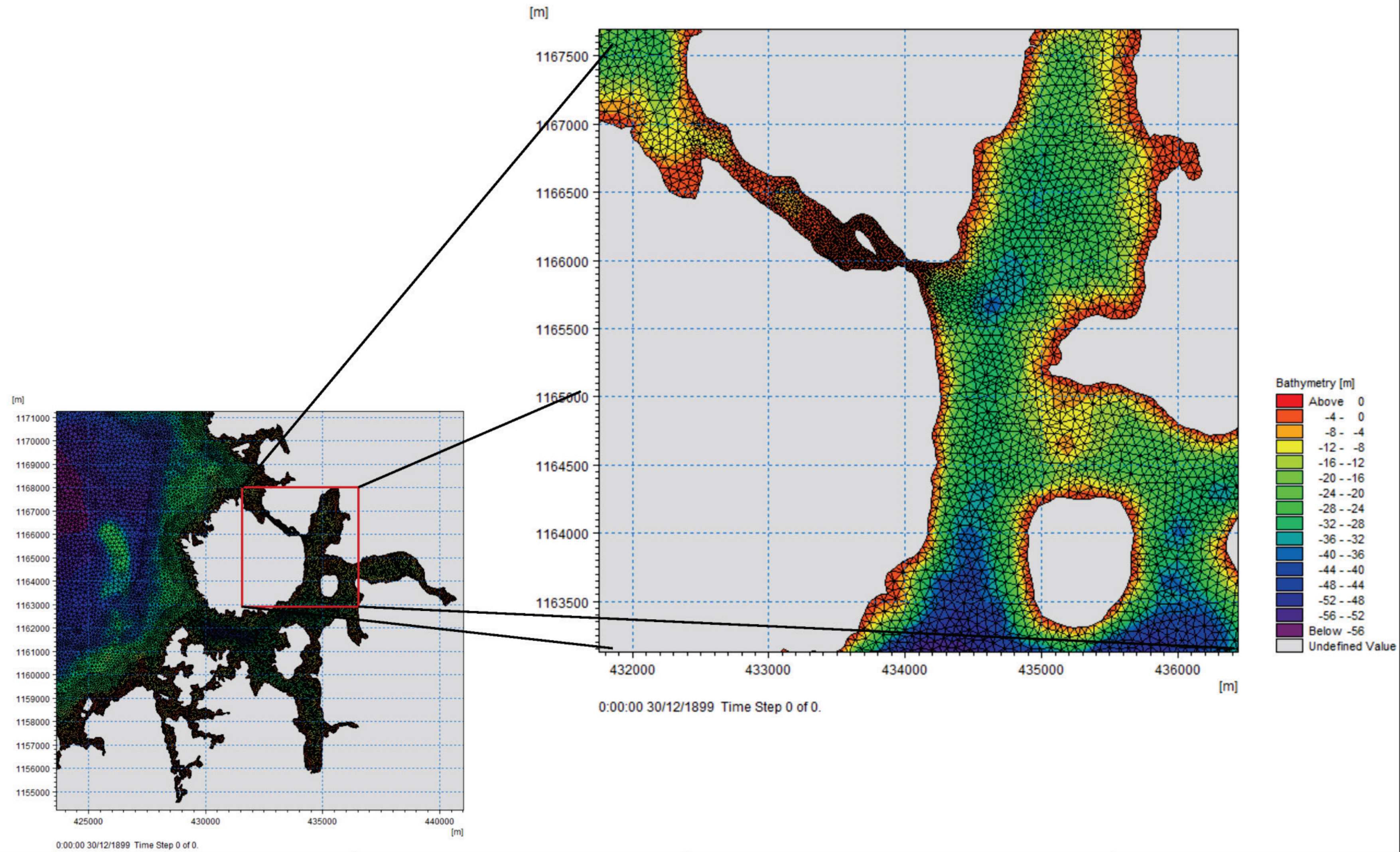

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-1b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | SMB model bathymetry relative to MSL | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



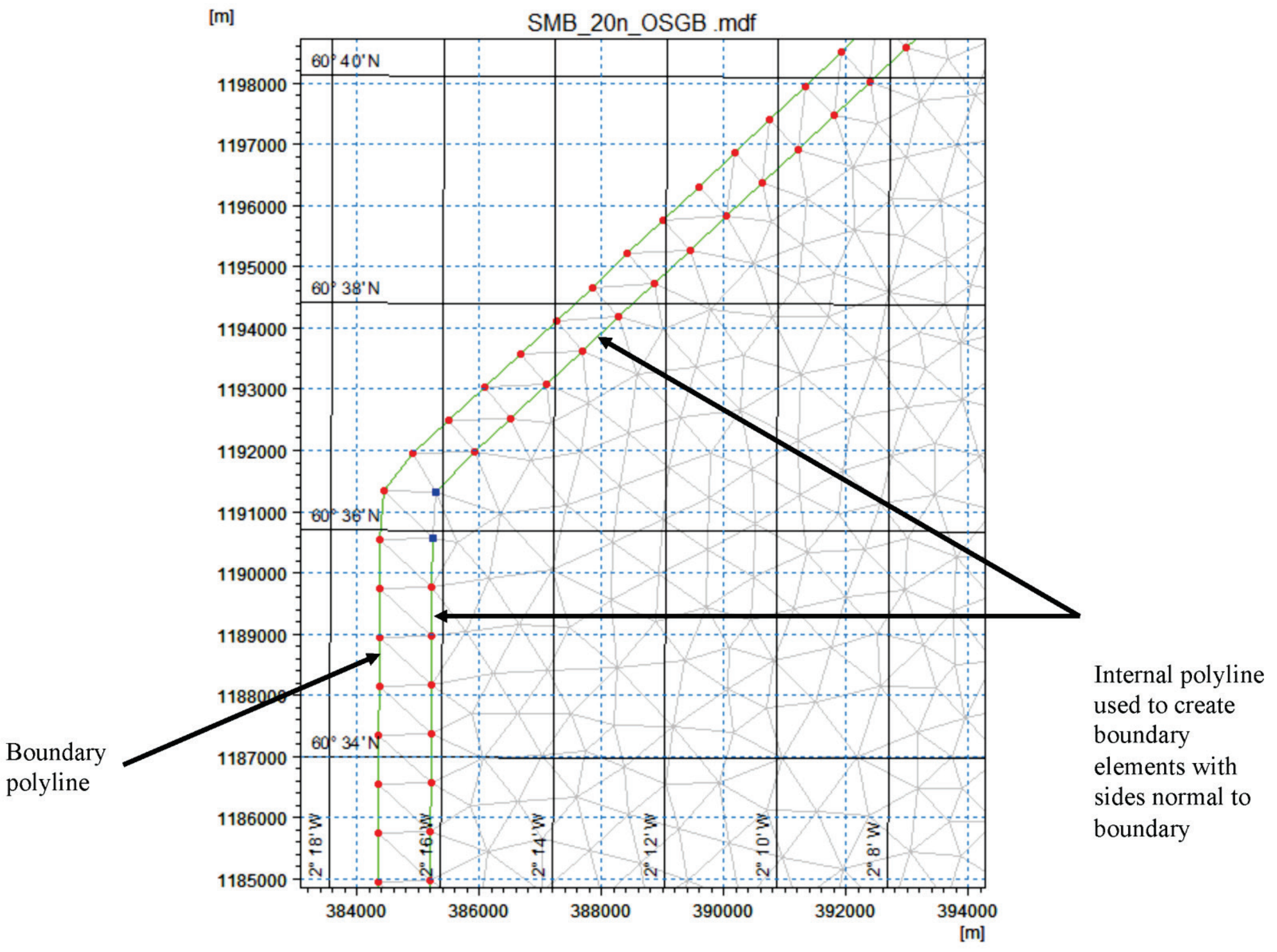

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | SMB model mesh | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | St Magnus Bay Model | SMB model mesh | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | SMB model mesh | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | SMB model mesh – boundary element detail | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

### 3.2.3 Boundary data

The nested boundary approach was used to specify the boundary data applied to the SMB model. Water levels relative to MSL, current speeds, temperature and salinity are applied at the centres of all the elements attached to the open boundary (for currents) and all of the attached nodes (water levels, temperature and salinity). These were obtained from simulations of the PFOW model for three specific periods.

Sometimes there can be problems with obtaining boundary conditions from a coarser model and supplying it to a higher resolution local model. The flows within the higher resolution model may be different to the larger scale model due to factors such as mesh size dependent wave celerity, different representations of bed features and physical features such as eddies as examples. FVCOM lets weight factors be applied to the nested boundary nodes and elements, this allows a proportion of the nested boundary values to be factored into the existing values calculated within the model thus reducing and dispersing any sharp gradients and differences. Please see Section 6.4 in the FVCOM manual (Chen et al, 2013) for more detail.

A Matlab script was developed which reads the PFOW results, and creates the SMB nested boundary file. A type 3 nested boundary (which uses the weighting factors mentioned above) was applied to all of the simulations presented in this report using extracted results from PFOW simulations.

The SMB 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 SMB model hot start conditions to match those applied at the boundary and to have suitable temperature/salinity within the model domain.

### 3.2.4 Meteorological forcing data

Wind data from the Met Office 12km Unified model was available for certain periods of time but not for the period in 2012 when the MS survey data was recorded. Initially wind for this period was obtained from the MRV Scotia but was subsequently found to be problematic, so wind data from the Met Office UK Waters wave model was used. Data was purchased at 4 points around the PFOW model area and interpolated over the model domain. For further details see the PFOW report (Price et al. 2015). There is no data however for short and long-wave radiation for the period of October 2012 when the calibration data is available. Therefore for this period the model was run for just hydrodynamics alone in order to compare against water level and current speeds. It was subsequently run with time-varying temperature and salinity boundaries but with no further heat input/loss apart from wind as a surface forcing factor; HEATING_CALCULATED was turned off.

The simulation itself (currents/CTD measurements) was of a short duration (4 days) as the data also covered a short period. Therefore the temperature and salinity comparisons provided in section 3.3.2 are the result of advection/mixing from the initial conditions and boundary inputs of temperature and salinity alone, without any heat exchange with the atmosphere. Without the necessary data this was deemed the best approach. A full baroclinic simulation over the month of May 2009 has been undertaken and compared with a number of vertical profiles of temperature and salinity.

### 3.2.5 3.4.6 River input

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

A river namelist file was produced along with a netcdf file for each of the rivers named in it. In simulations with the Shelf model, NOC-L found that reading in over 500 river files impacted upon model performance (input/output overhead). The SMB 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

Calibration was carried out for October 2012. The data available in October 2012 was collected by MS using the MRV Scotia. This is the best available data for SMB that covers the area offshore and the mouth of SMB. The offshore ADCP location covered one tidal cycle, as did the transects and the CTD measurements which were all recorded within a couple of days of each other. In addition, data recorded at fish farms throughout the Scottish Waters was provided by Alan Hills (SEPA). This provided 5 locations within the inner part of SMB which proved to be essential, especially as they are located at fish farm sites.

The hydrodynamic model was initially run with 3 vertical layers whilst getting the model to run and to carry out initial sensitivity tests, and then further refined with 5 vertical layers. Subsequently the model was run with 10 layers which is the current form presented in this report.

It was found that the external timestep needed to be 0.25 seconds and Isplit was set as 3.0. Various simulations were undertaken changing the timestep, but due to the constrictions with higher flow speeds and smaller elements in the channel to the north of Muckle Roe it was found it had to be reduced to these values. Horizontal mixing was prescribed with a spatially constant Smagorinsky coefficient of 0.2. Vertical mixing used a constant coefficient of 1E-5, with a Prandtl number of 1.0. Bed roughness lengthscale was set at 0.04m, the same as for the PFOW model. Sensitivity tests were undertaken with varying the bed roughness but current speeds were found to be relatively insensitive to the bed roughness in the deeper water where the MS survey data had been collected, this is likely due to the deep depths and low current speeds.

### 3.3.2 Offshore water level and current calibration

The data collected by MS included an offshore ADCP deployment for a period of one tide located outside of SMB and a vessel mounted ADCP (VMADCP) transecting across the mouth of SMB and various vertical profiles using a CTD in and around SMB. Initial comparisons were made against the offshore ADCP measurements which are presented in this section.

Figure 3-3a presents the comparisons of current speed, current direction, water levels and the location of the measurements within the SMB area. The results presented are from the SMB model simulation SMB_33. A number of simulations preceded this one (simulation

SMB_33) which entailed sensitivity tests to bed roughness, horizontal mixing, sponge nodes and boundary configurations. However these results are the ones with the preferred model configuration.

The bed roughness length scale used was a spatially constant 0.04m. No sponge nodes were used as a nesting boundary approach was being used which proved to be stable at the boundaries; earlier versions with water level boundary only did have stability issues which were partially controlled with the sponge nodes.

The top left frame of Figure 3-3a shows comparisons between the observed current speeds (that have been depth-averaged) and the model current speeds at the same location. The location can be seen in the top right frame.

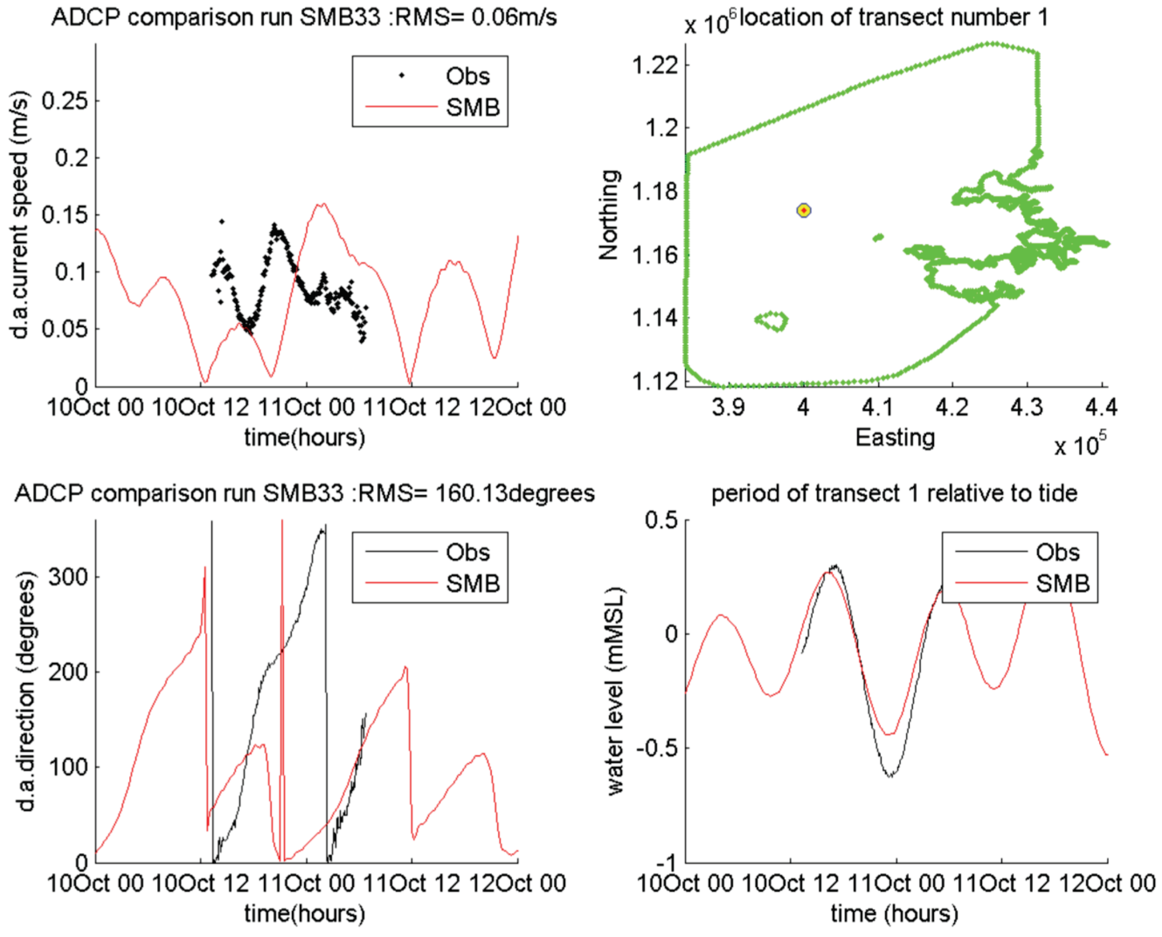
For this simulation, the wind was derived from an interpolation of the wind available from the Met Office wave model, however a sensitivity test (by turning off the wind) showed the model not to be very sensitive to the applied wind at this location and for the period of the simulation. This may in part be due to the comparison being made with depth-averaged currents in deep water. The roughness was the same as that used for the PFOW model.

It can be seen that current speeds are very low for the observed data (black), varying between 0.05 and 0.15m/s. The model (red) produces speeds of a similar magnitude. There also appears to be a phase shift of a couple of hours when examining the peak in the current speeds. This phase shift is also evident in the comparison of current directions. Although the model rotates in a similar manner and in the same direction, the phase shift is apparent. However examining the water levels in the bottom right hand frame the phase shift is not as apparent.

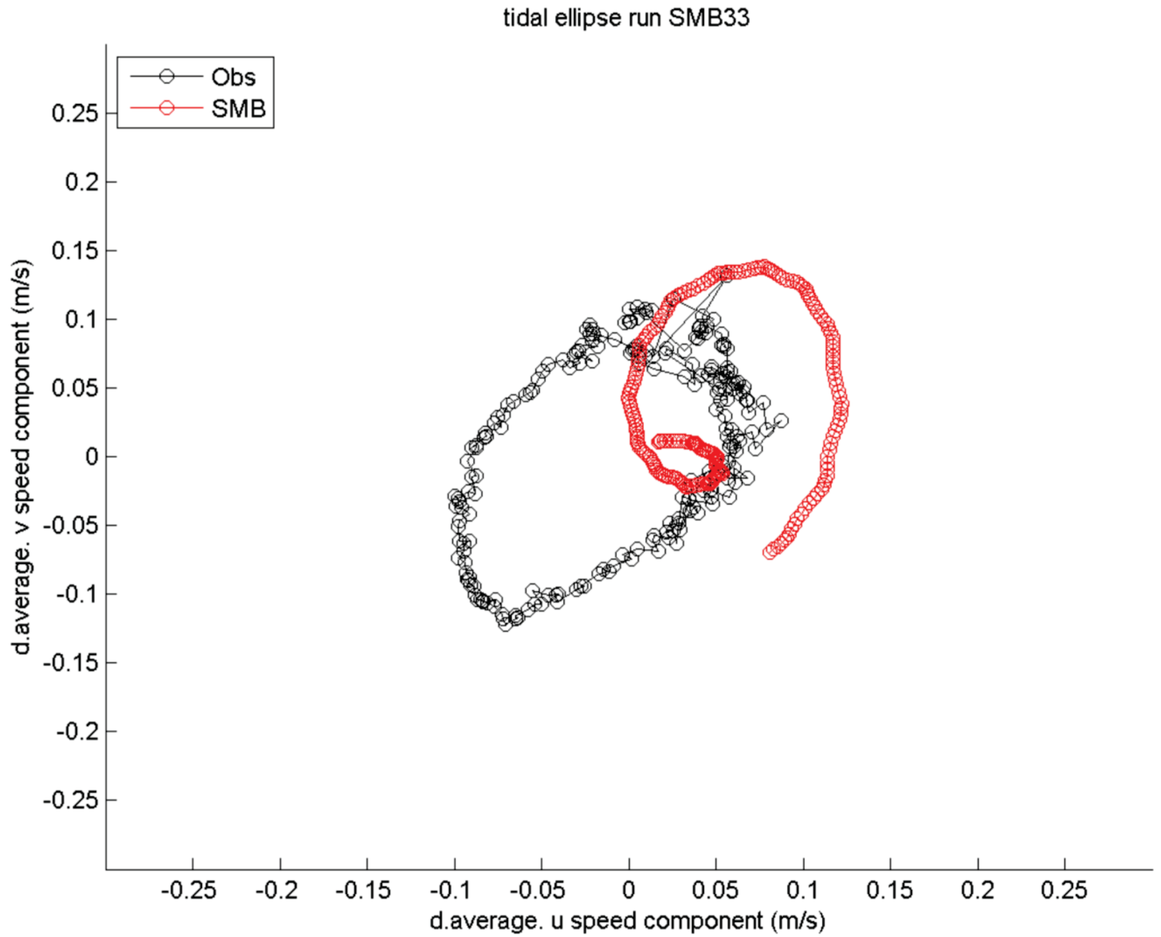
The water level comparisons are reasonable although the tidal range is smaller by 0.25m. No other water level data is available within SMB.

The location of the ADCP is in an area where the flow diverges around Shetland when flowing eastward and converges when flowing westward. Due to the low flow conditions and the location and nature of the divergence/convergence it has proven difficult to get the comparisons closer than those presented. This model takes its boundary conditions from the PFOW model which in turn shows very similar results to the SMB model at this location.

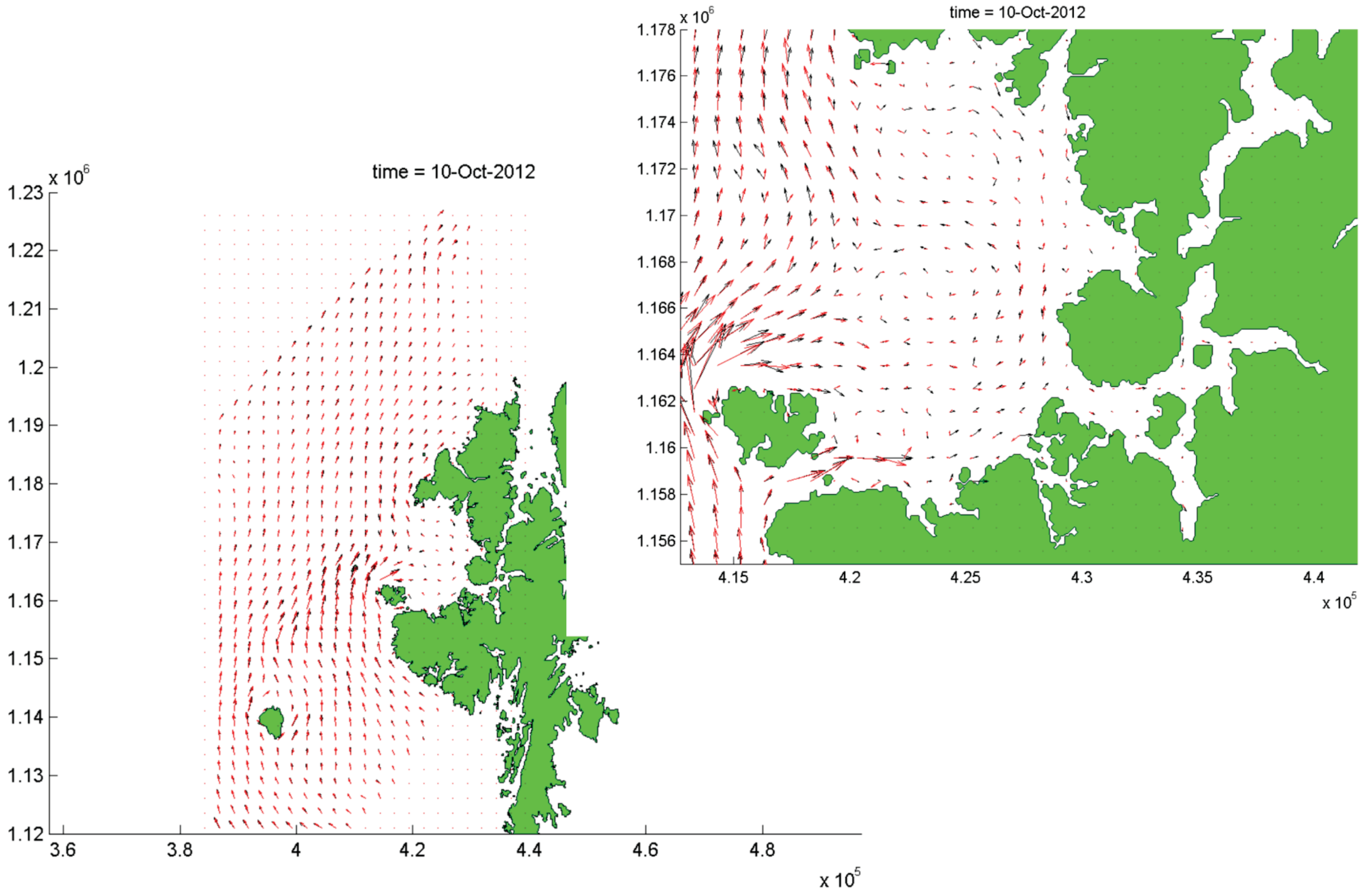
Another way of visualizing the flow conditions and providing a comparison between the model and observed data is to plot the tidal ellipse. This is presented in Figure 3-3b. The general direction of the major and minor axes are comparable however the issue with the phase shift means a better match is not possible for the same period of time. Figures 3-3 c-o show hourly depth-averaged current vectors for the whole model area (left panel) and a close-up of the St Magnus Bay (SMB) area (right panel). Additionally two sets of coloured vectors are included, the black vectors represent the simulation including the wind (shown in Figure 3-4i) and the red vectors the case without wind. These are provided to help show the nature of the circulation both outside and inside the Bay and how the wind in this case can affect the flow patterns. Outside of the Bay the direction of the current rotates clockwise with the peak ebb and flood flows being orientated west to east. The flow at times is directed across the mouth of SMB, which in turn appears to set up an anticlockwise circulation in the southern part of the bay and a clockwise circulation in the northern part. Whilst this appears to be the case with/without wind it can be seen that flows within the bay are sensitive to wind conditions and therefore wind is an important mechanism in the movement of the water within SMB.



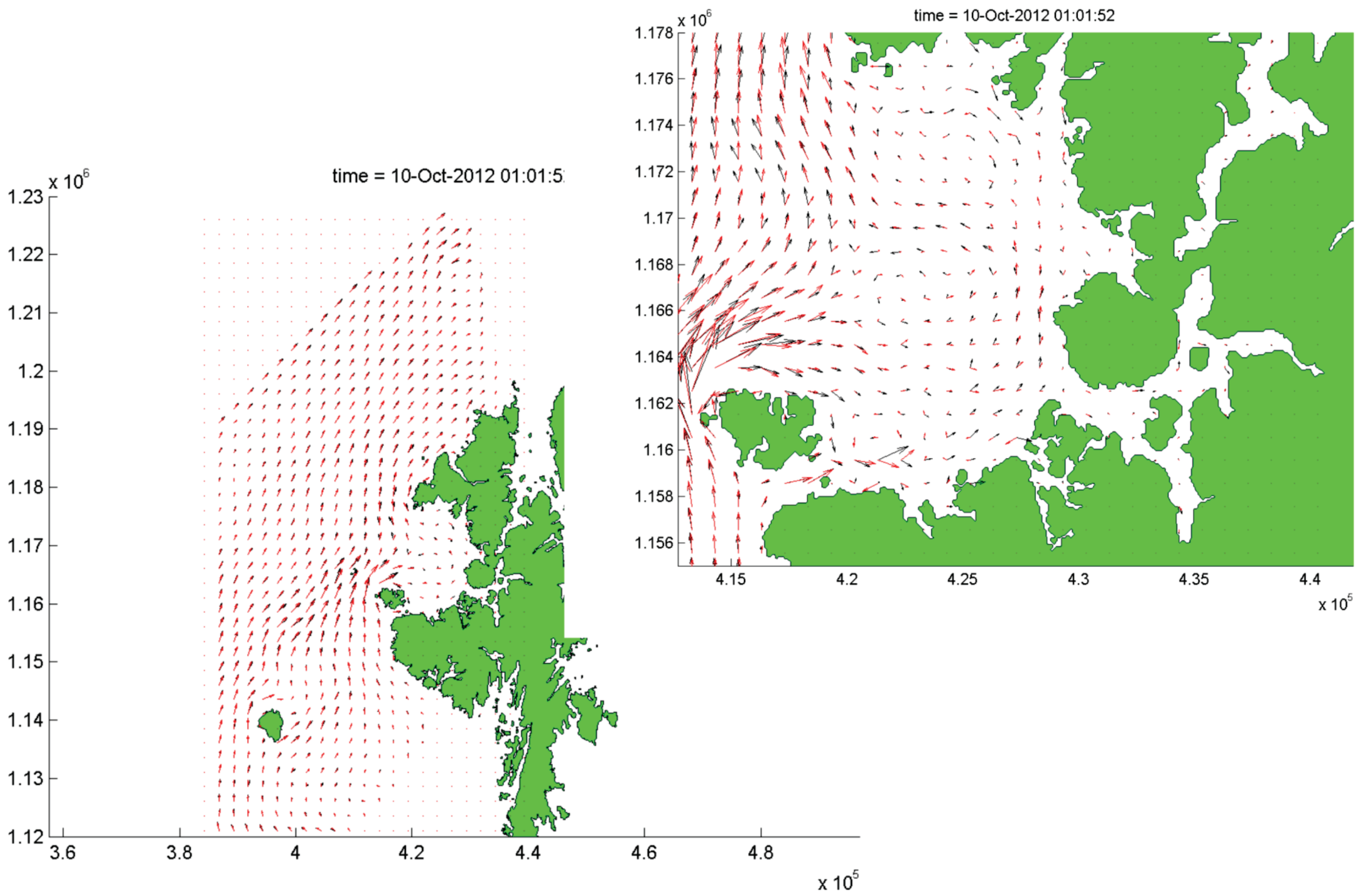

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | ADCP measurements versus model timeseries comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



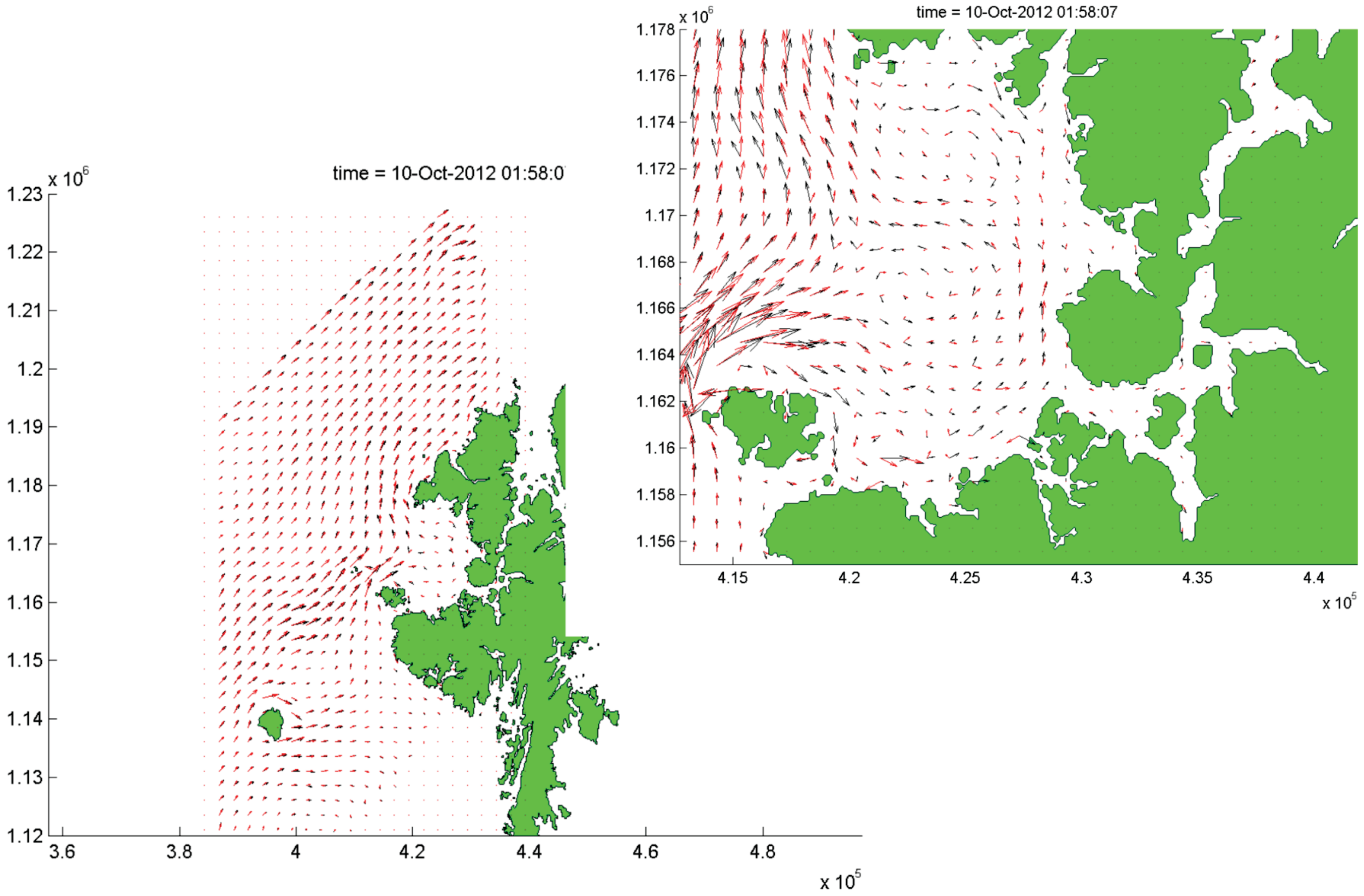

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | ADCP measurements versus model tidal ellipse comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3e | | |
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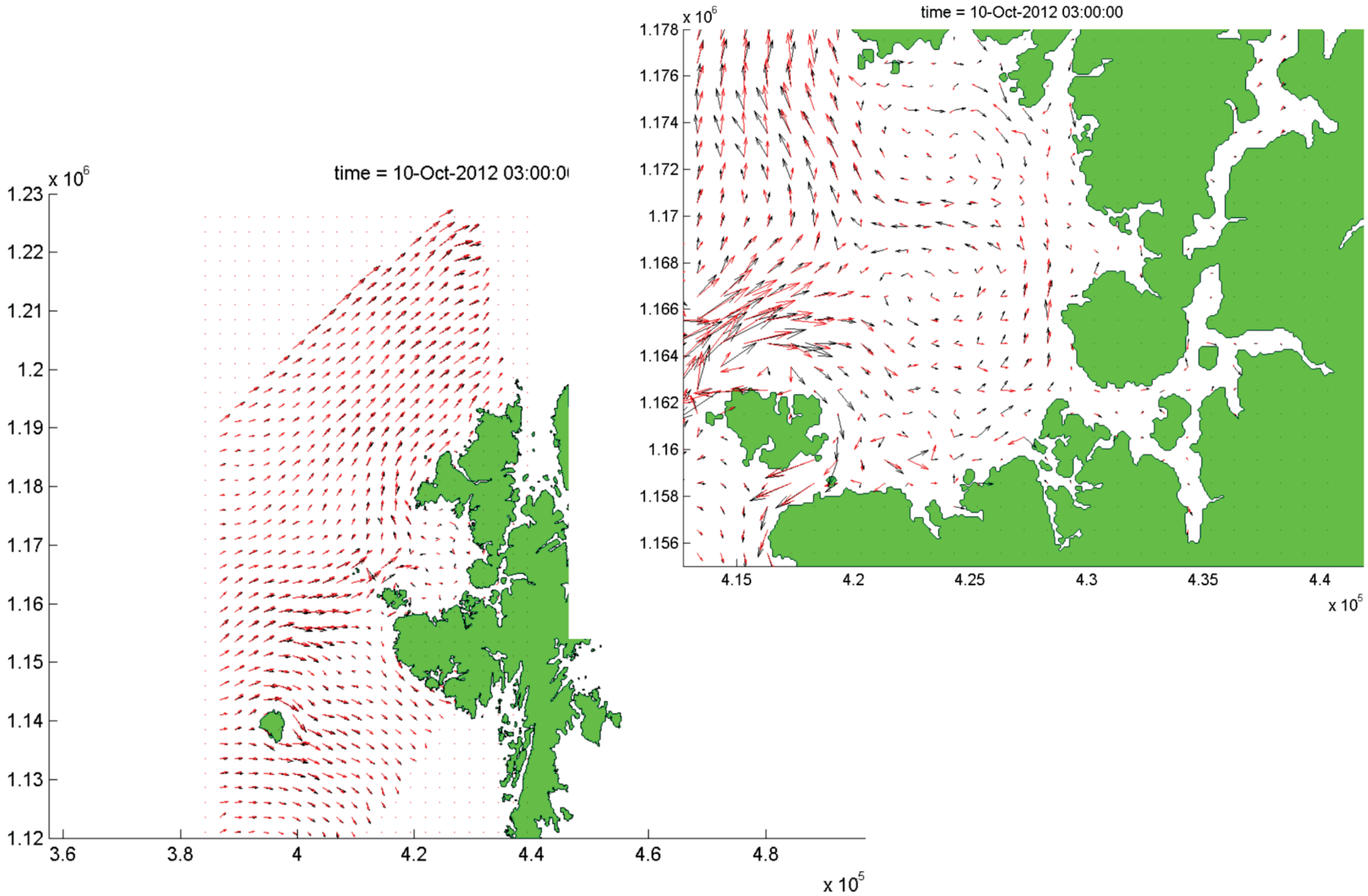
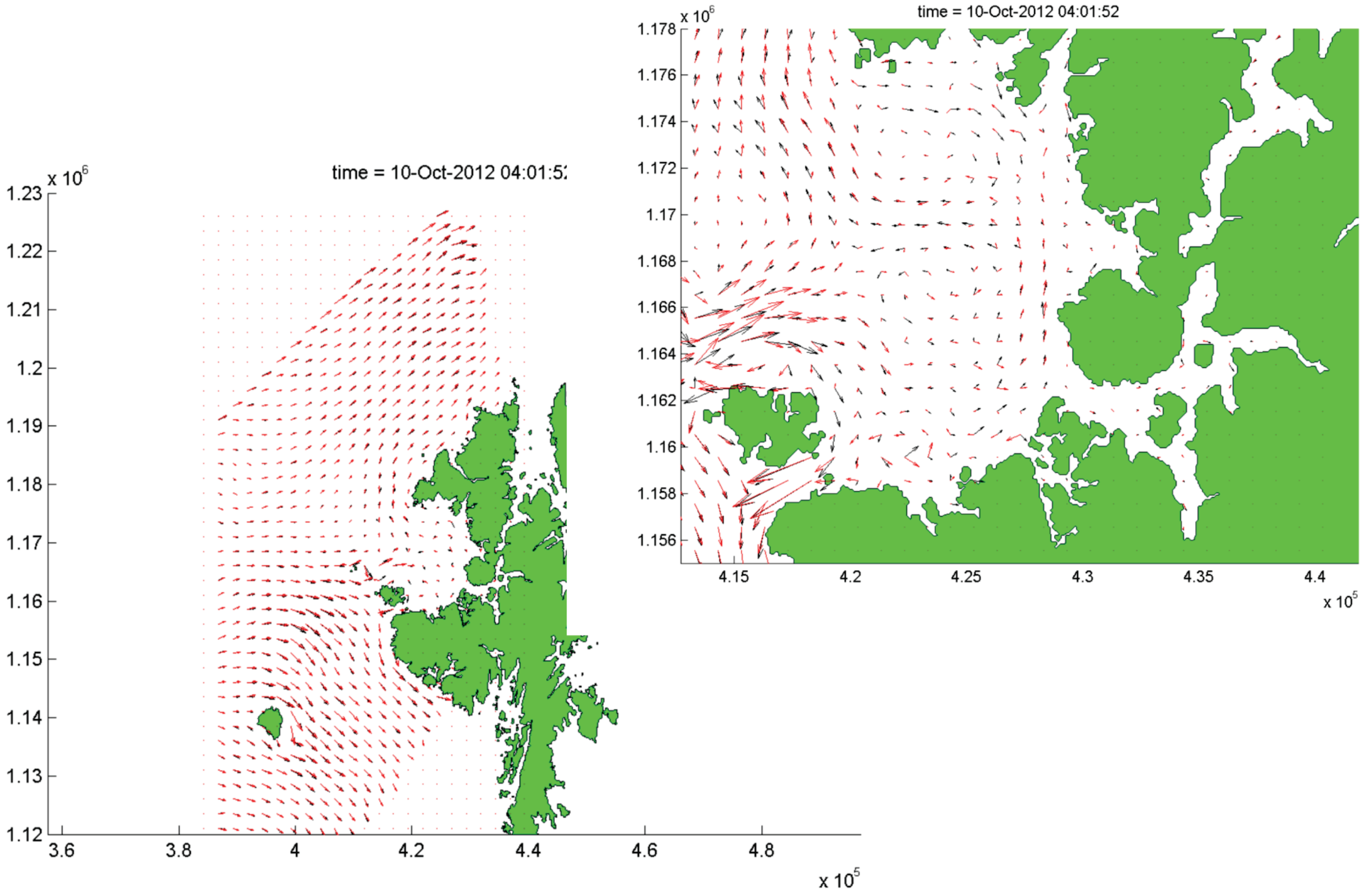
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3g | | |
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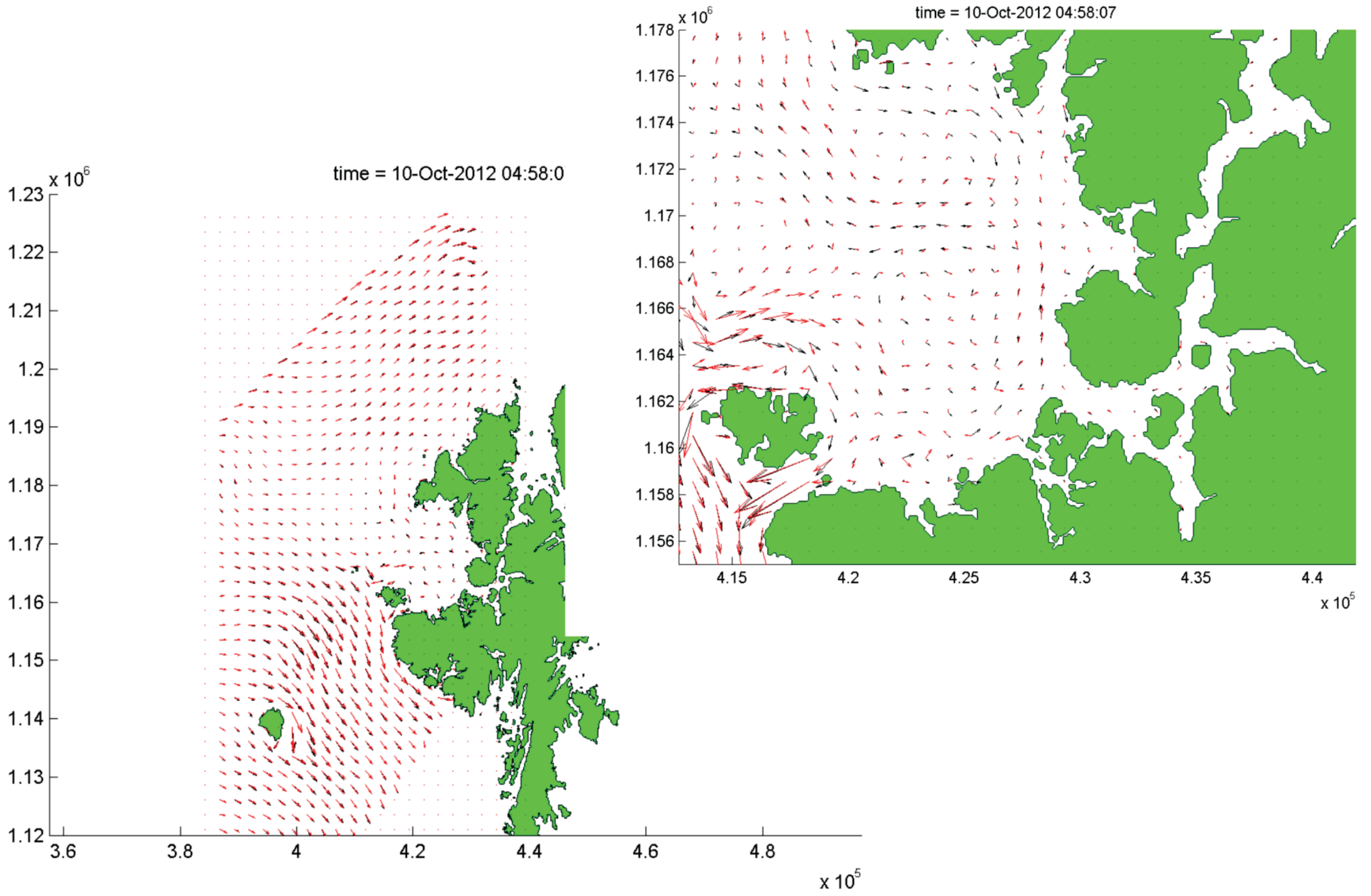
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3h | | |
|---|---|---|---|---|---|---|
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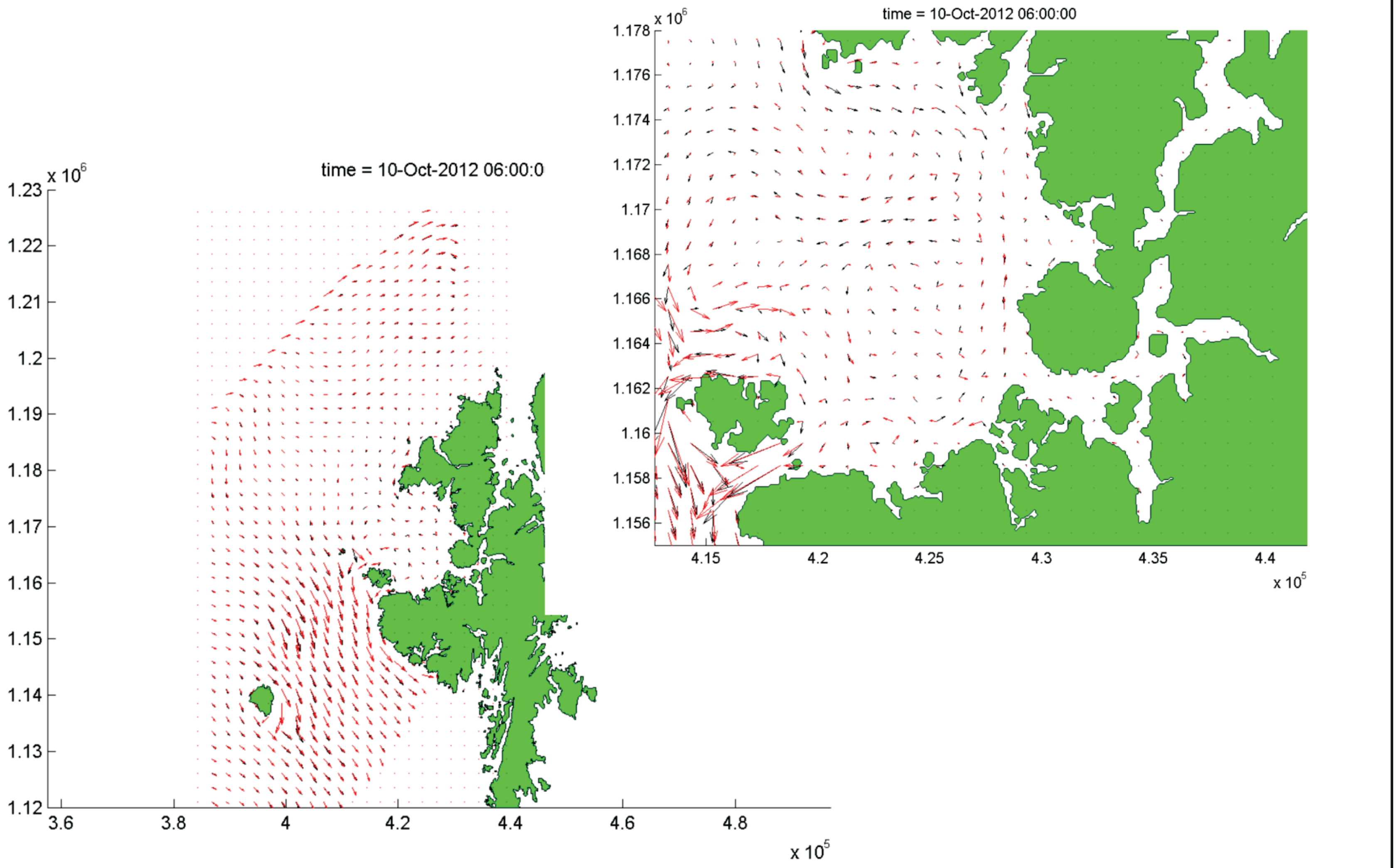
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3i | | |
|---|---|---|---|---|---|---|
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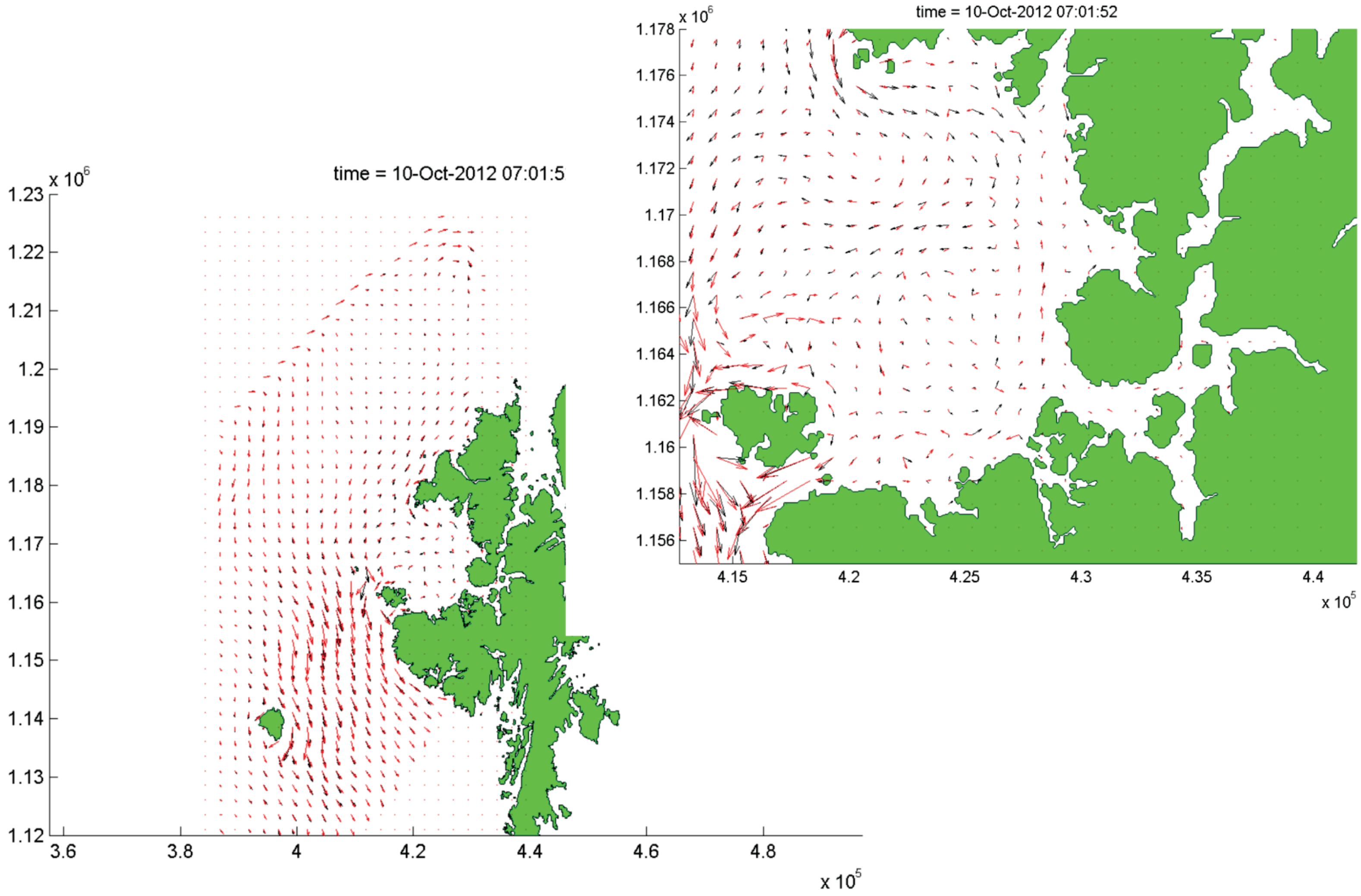
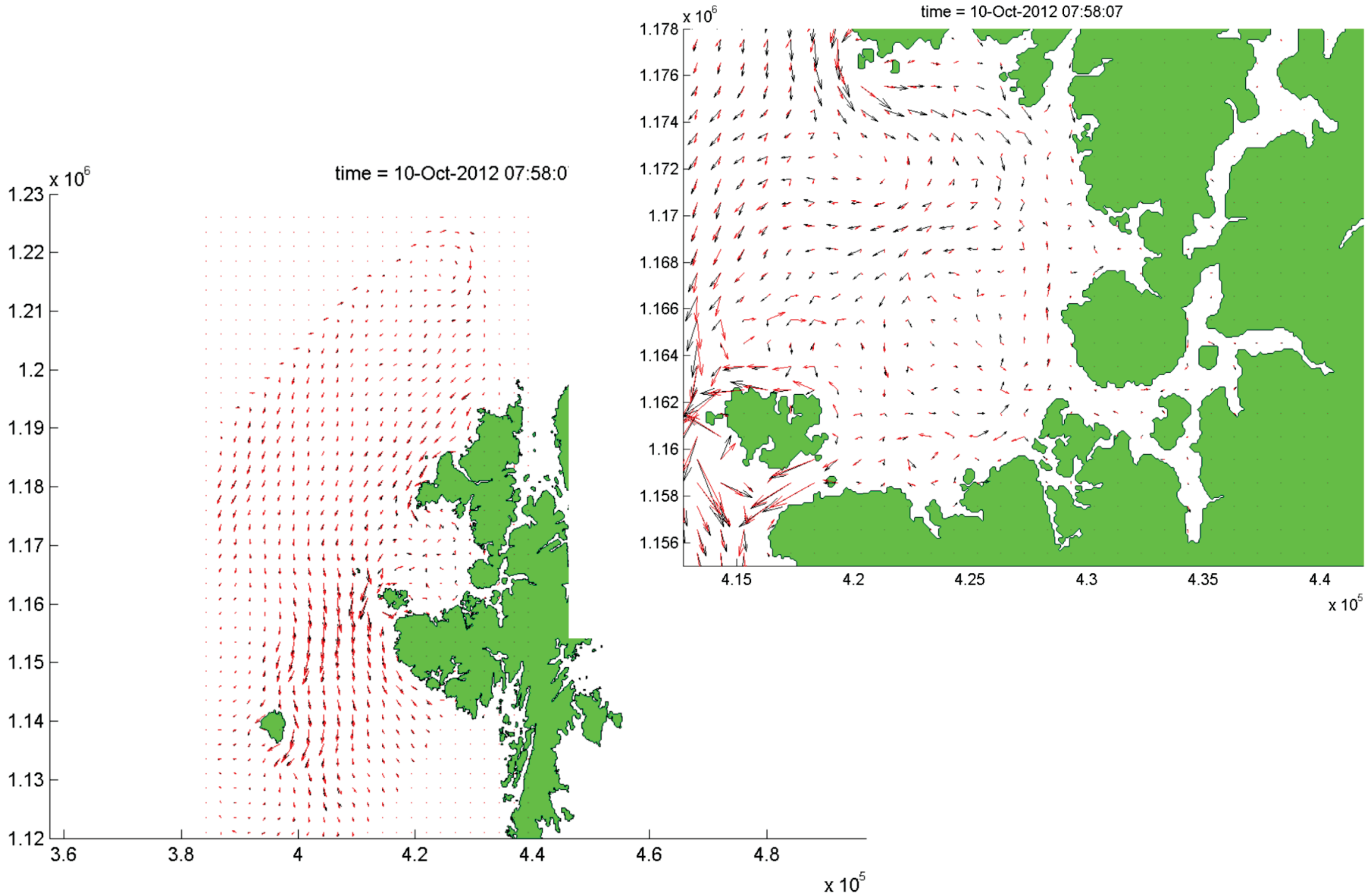
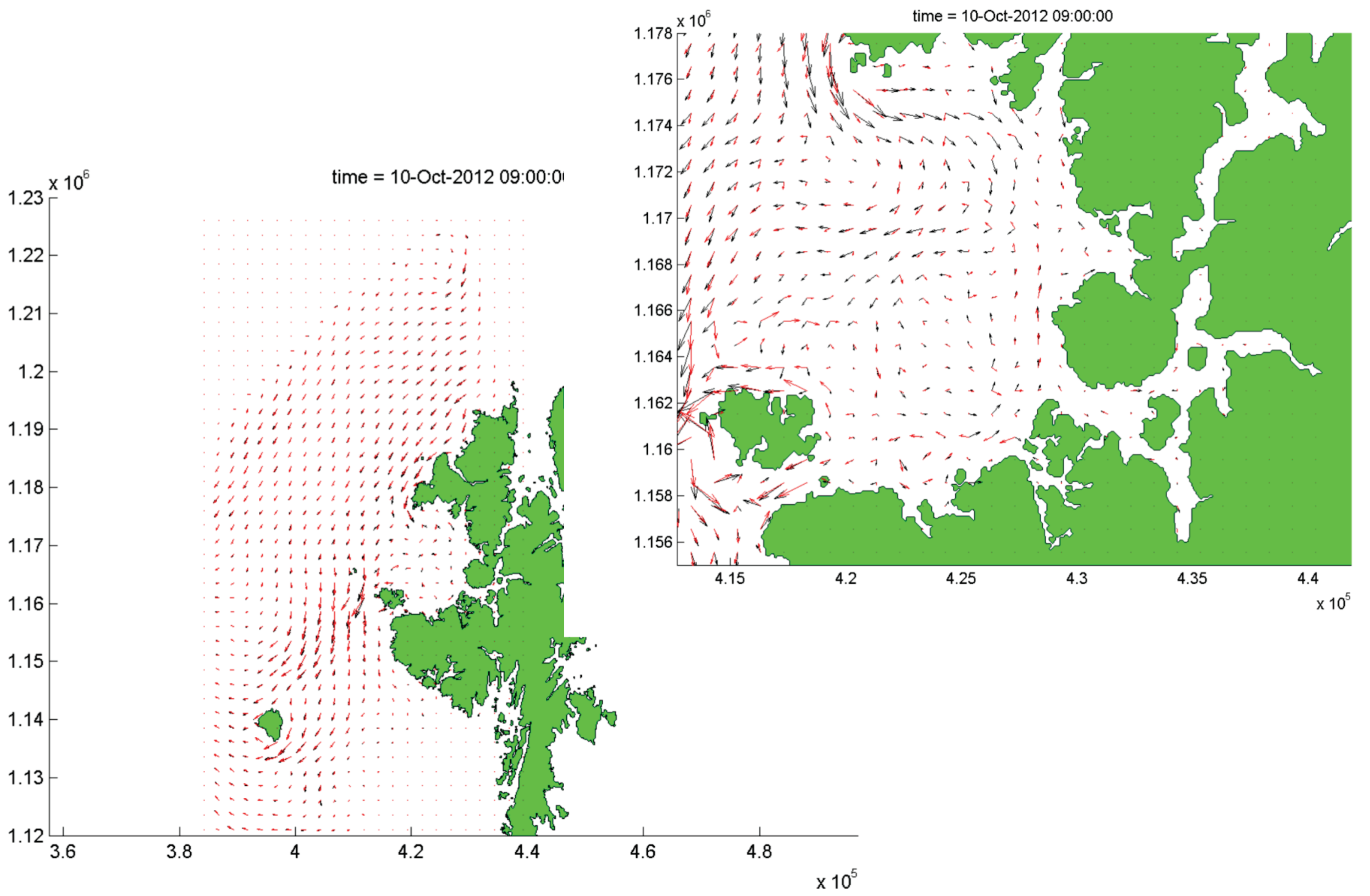
| | | | | Designed DMP | Drawn | Date 14/112012 |



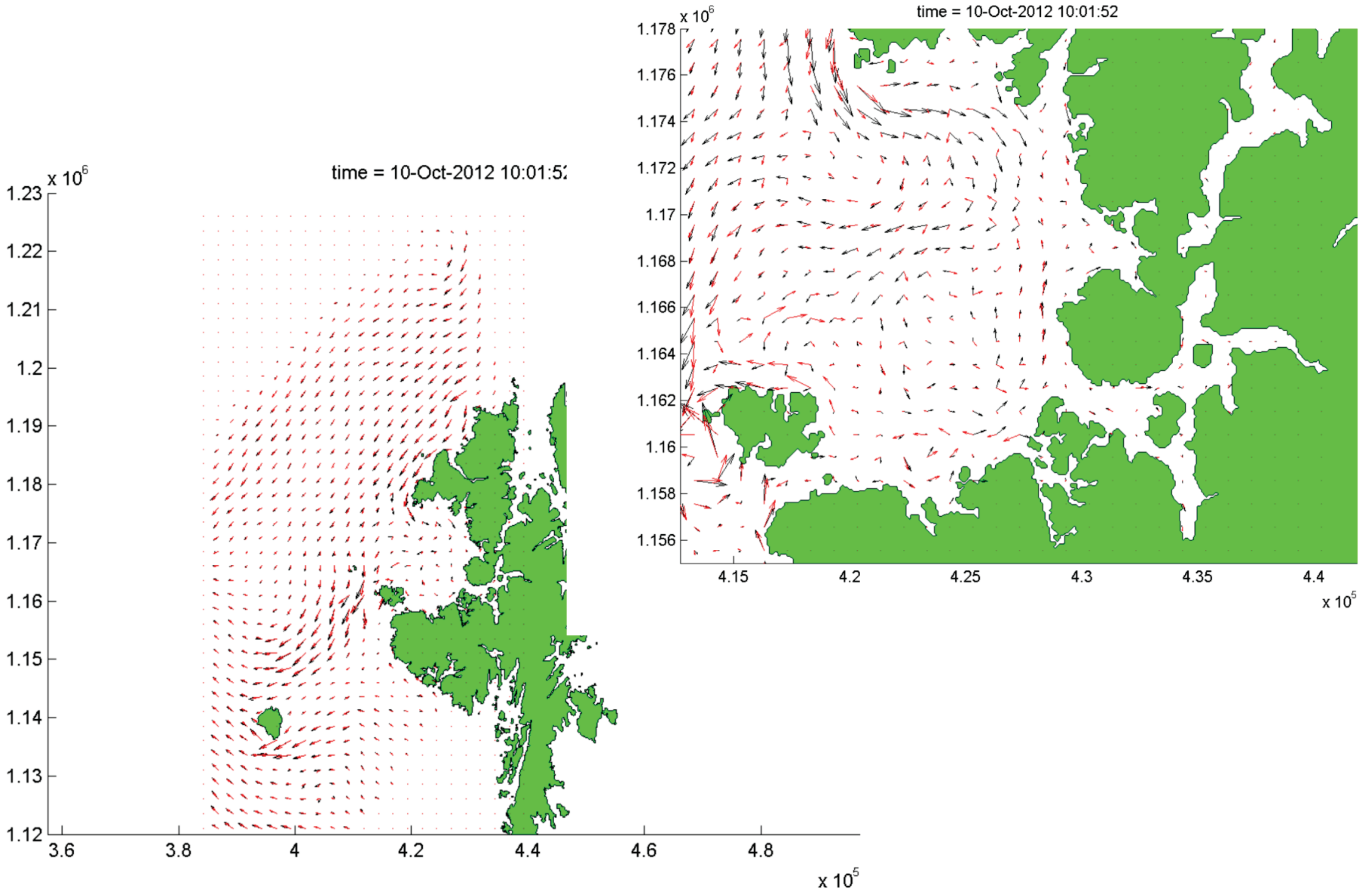

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3j | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



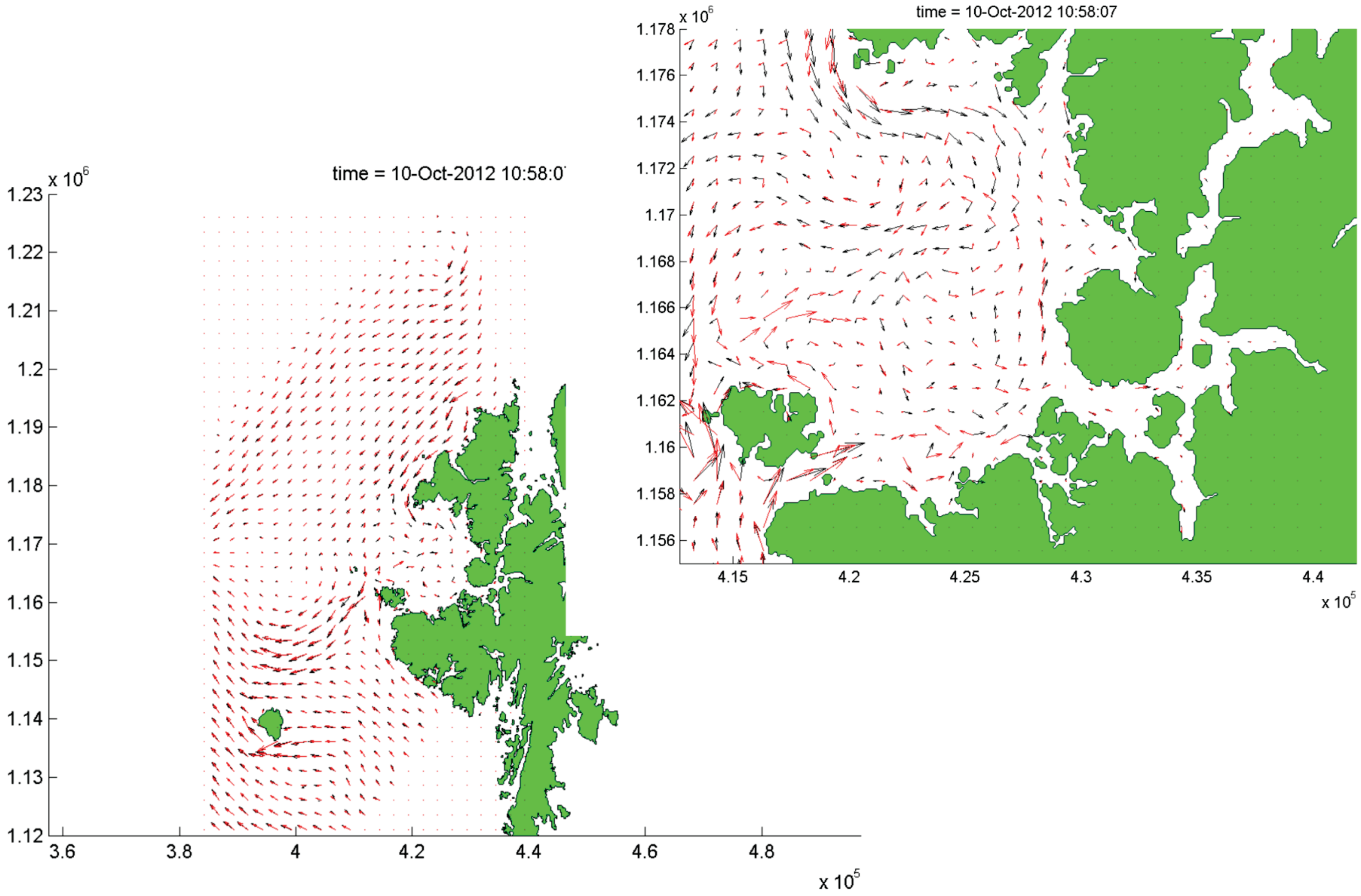

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3k | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



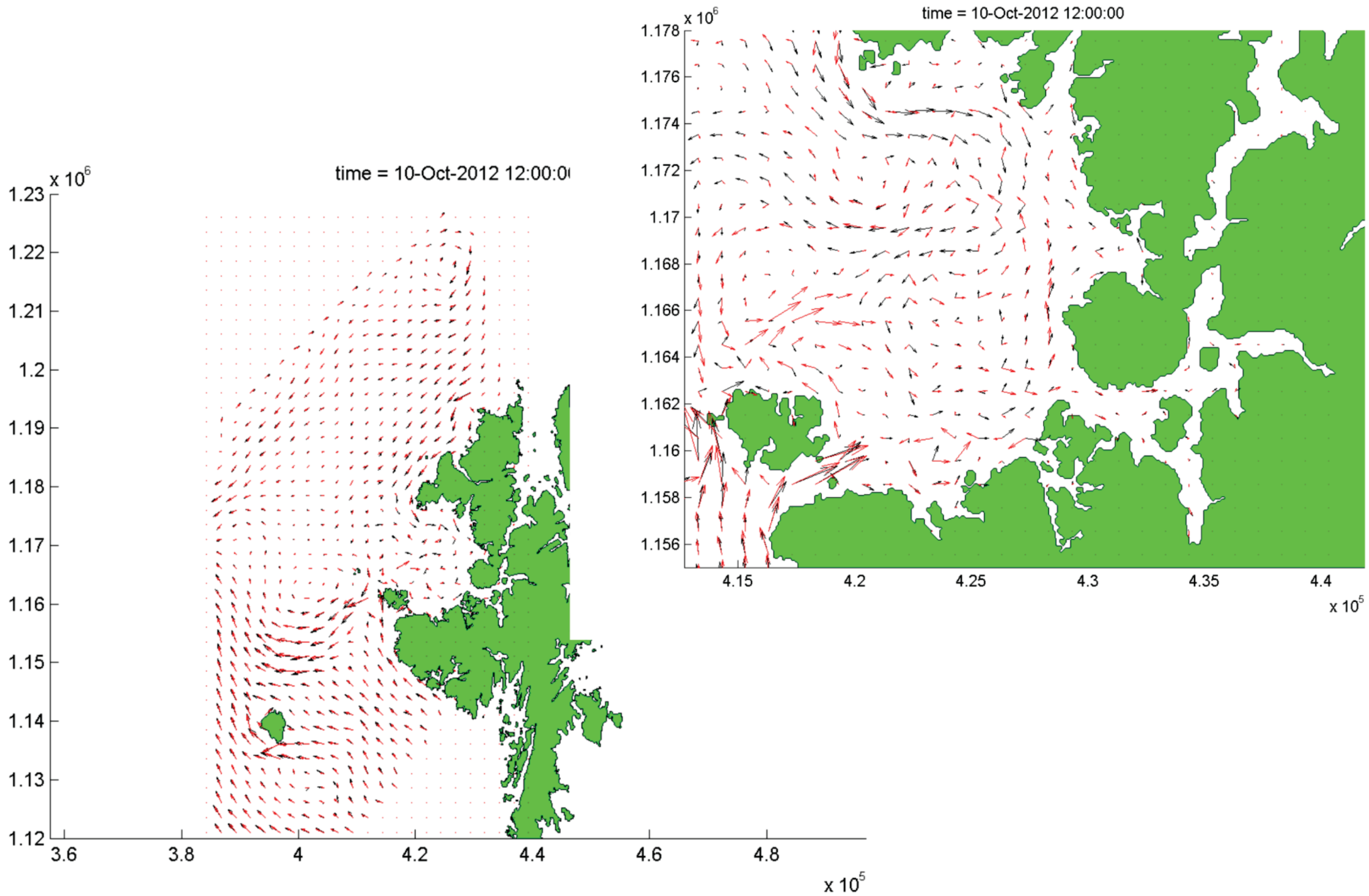

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3l | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3m | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3n | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3o | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Flow vectors at time shown for whole model area and within St Magnus Bay. Black vecotrs simulation with wind Red vectors simulation without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

### 3.3.1 Comparison against VMADCP transects

In addition to the offshore ADCP, the MRV Scotia also undertook vessel mounted ADCP (VMADCP) transects across the mouth of SMB for a complete tidal cycle, this was part of the same survey as the fixed station ADCP measurements used above. A Matlab script was written which reads in the records for each transect, depth-averages them, and then finds the model results for the corresponding location and time. A selection of these transects are presented in Figure 3-4a-h, whilst the remaining ones can be found in Appendix A.

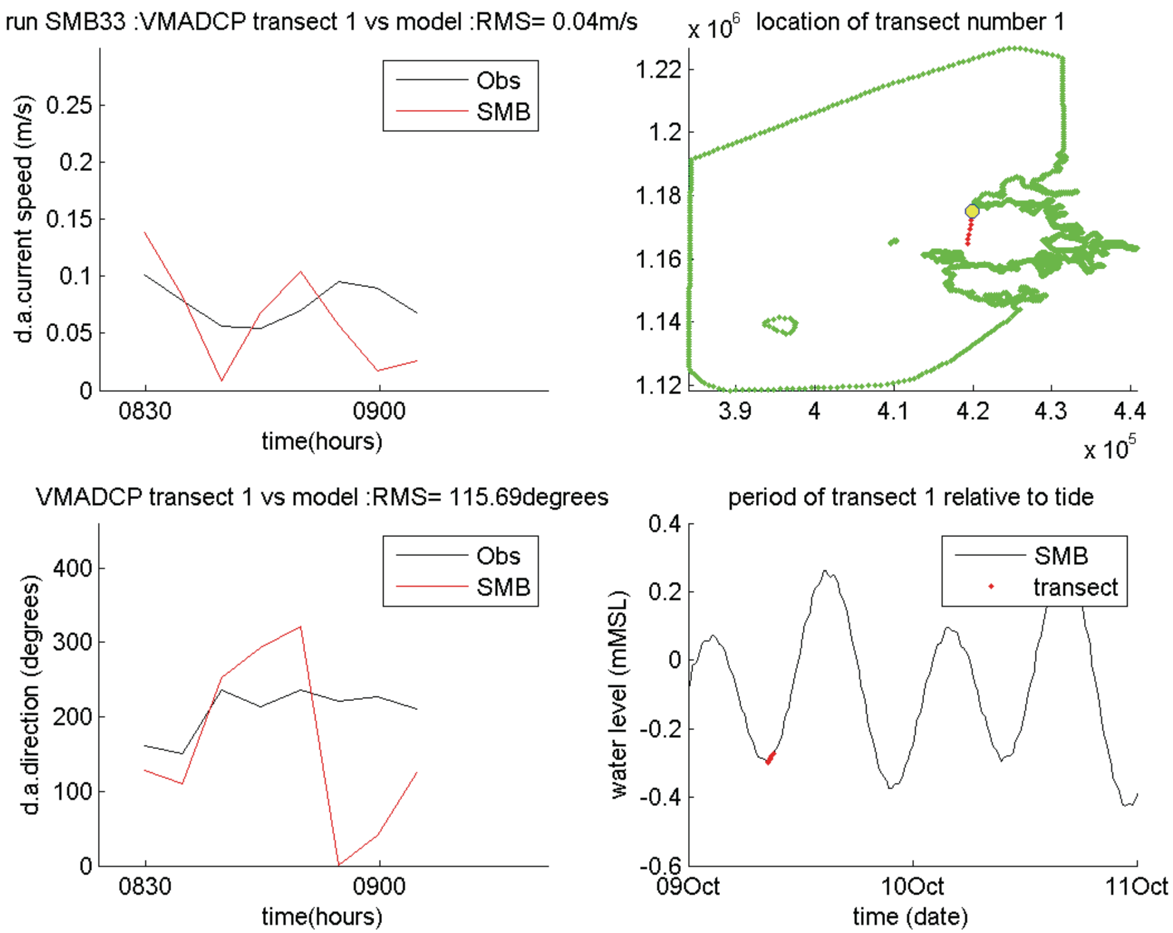
These have been plotted as comparisons of depth-averaged current speed versus time (top left), depth-averaged direction versus time (bottom left), the location and starting point of each transect (top right), as well as the period in the tidal cycle that the measurements were made (bottom right). The simulation (SMB_33) used to compare against the measurements was the same one used for comparisons against the offshore ADCP data, it therefore includes the effect of wind. The observed transects are indicated by “Obs” in the legend, and the model results by “SMB”.

Figure 3-4a shows the current and direction transect compared against the measurements at a time of low water (shown in the bottom right hand frame). Observed current speeds are generally low throughout the transect measurements, rarely going above 0.1m/s (depth-averaged).

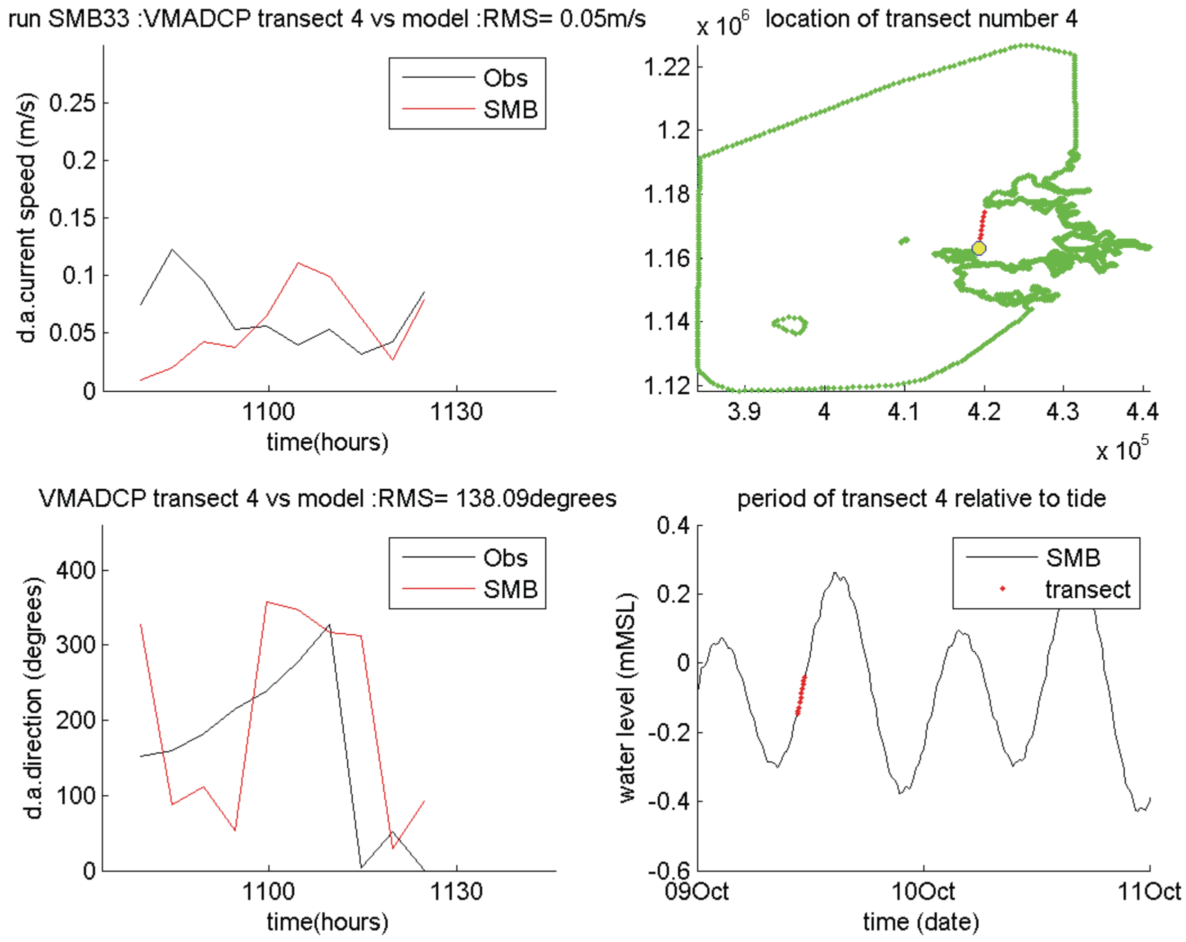
The comparisons between model and observed speeds show the model to produce speeds with similar magnitude, and in some cases similar features within the profile. However the phase difference observed offshore at the ADCP location means that a better comparison is unlikely, especially with current speeds that are less than 0.1m/s.

The RMS error is also shown in the title for each frame. It can be seen in Figures 3-4a-h that the RMS error for depth-averaged current speed is in the order of 0.02- 0.06m/s.

Figure 3-4i presents the wind speed and direction (at the offshore ADCP location) applied to the model during the simulation.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 1 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 4 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
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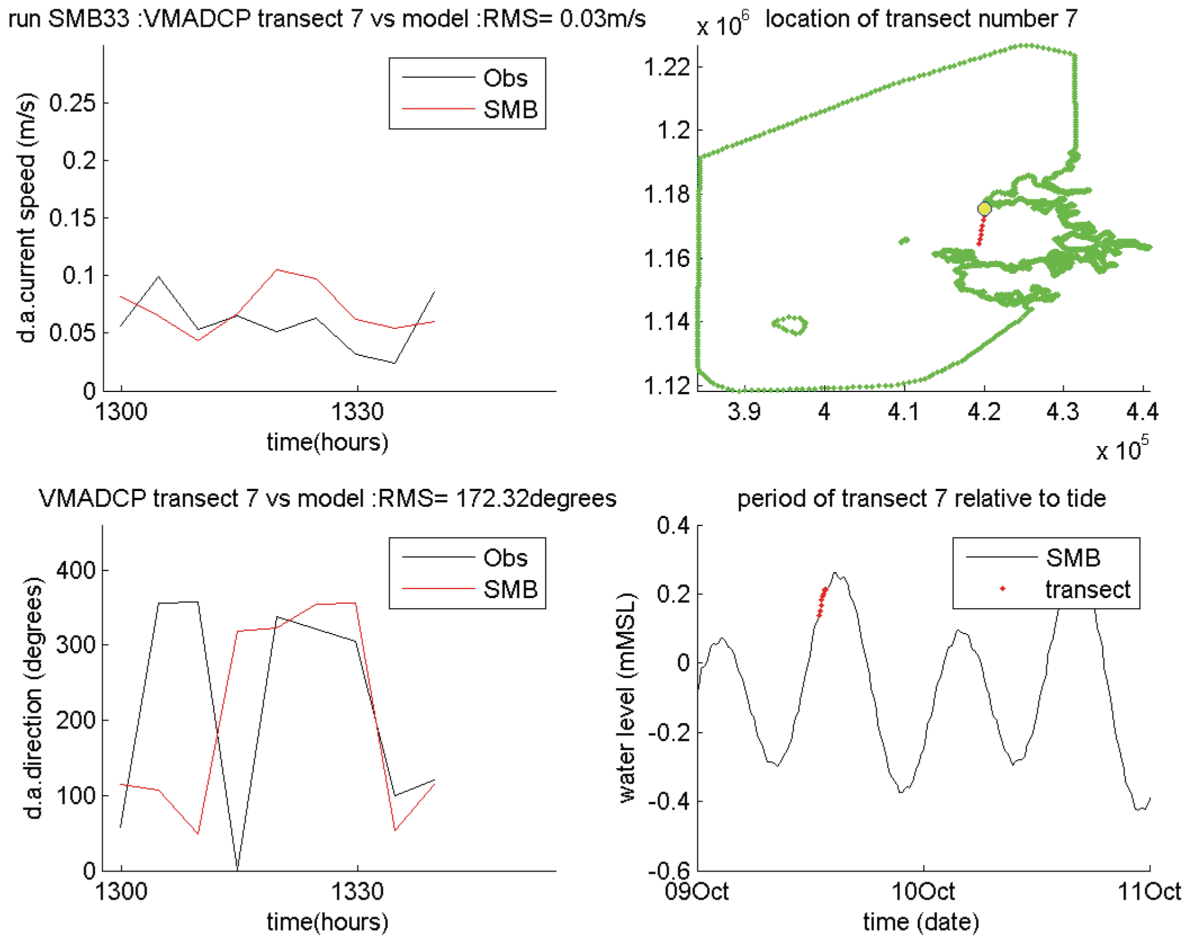


| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 7 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
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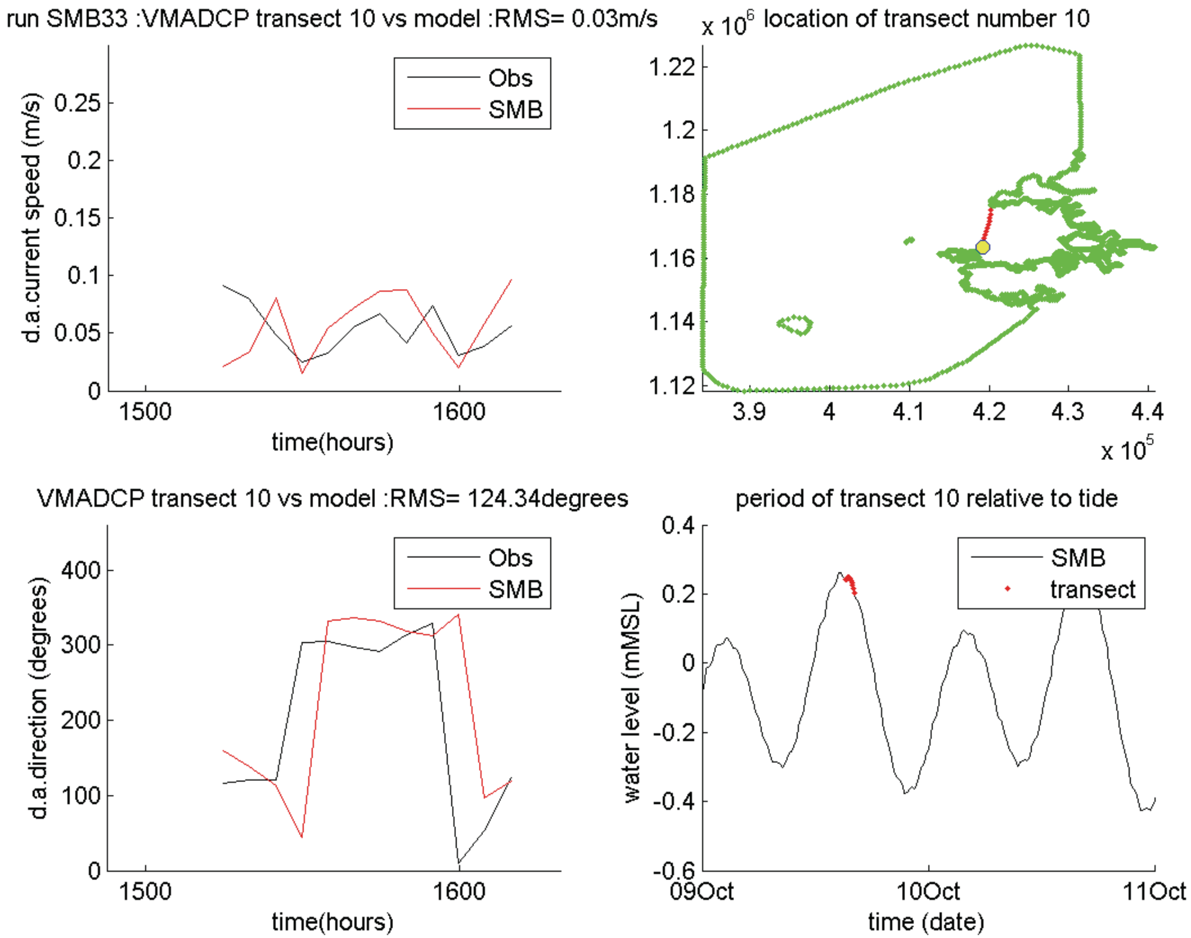


| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 10 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
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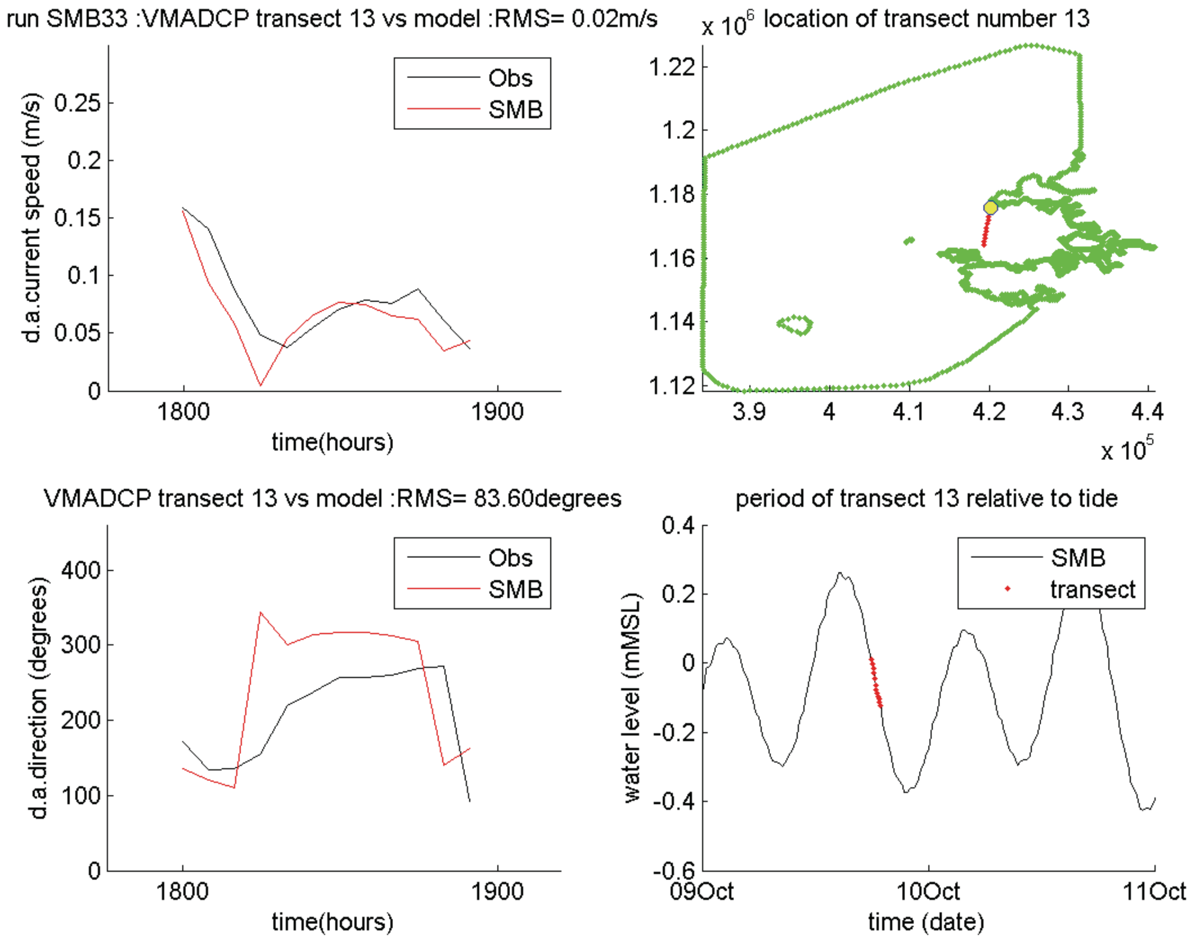
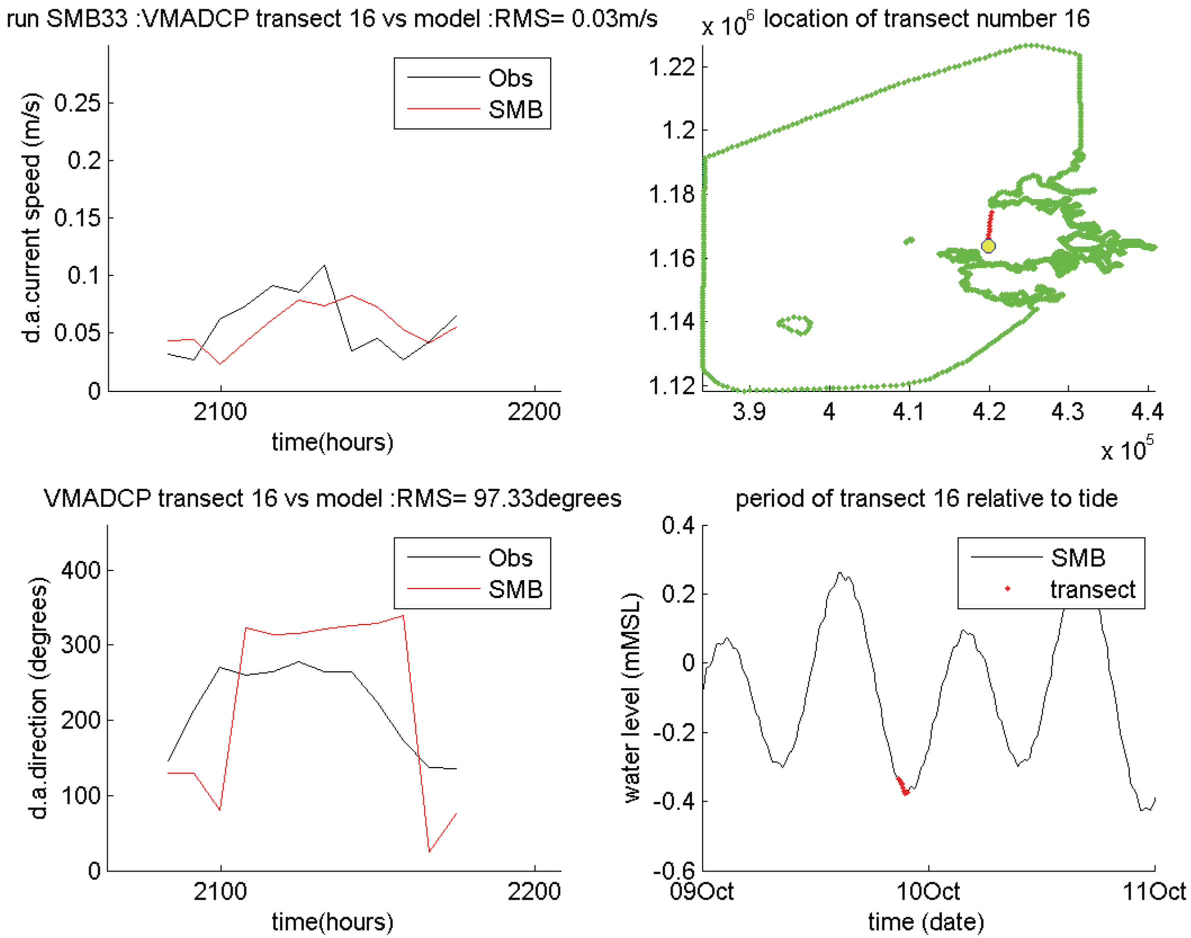
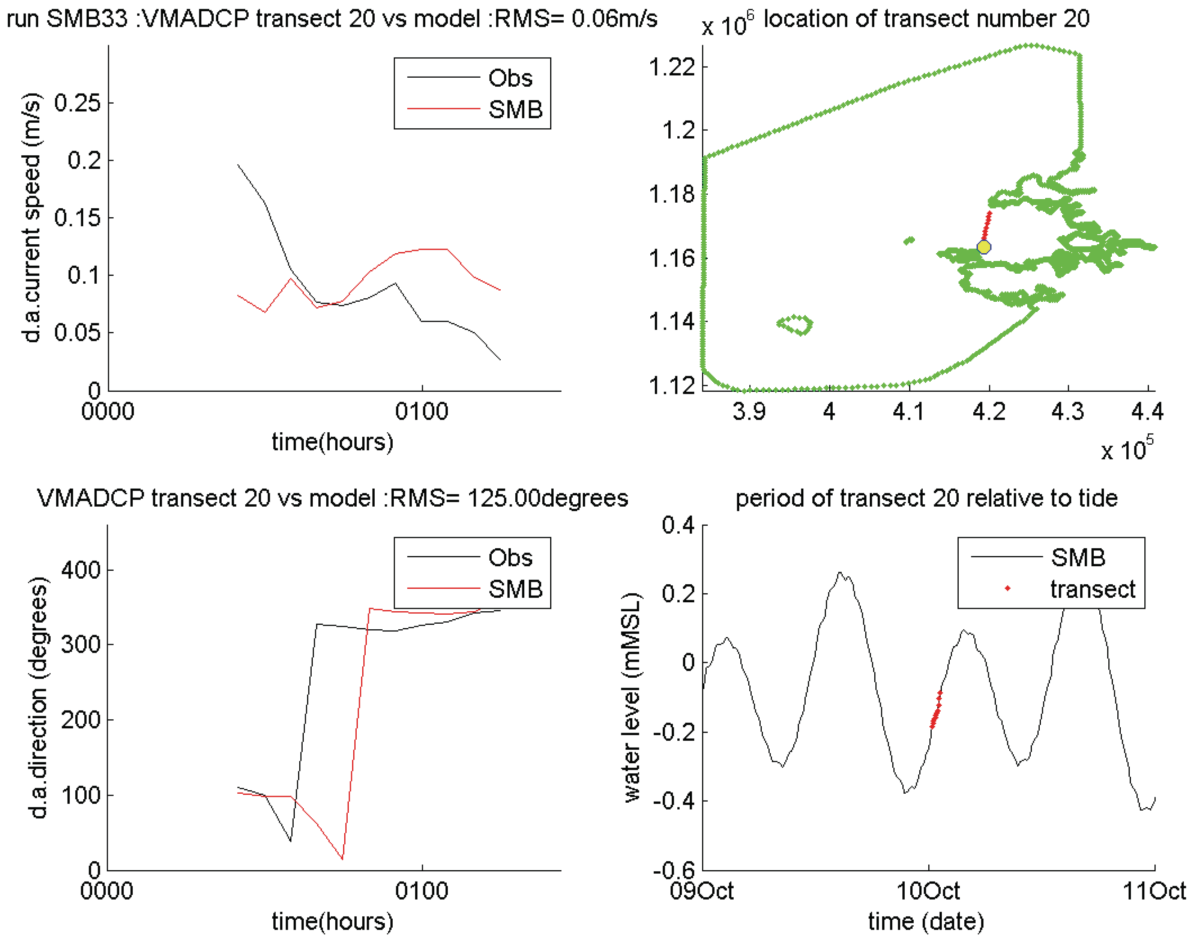


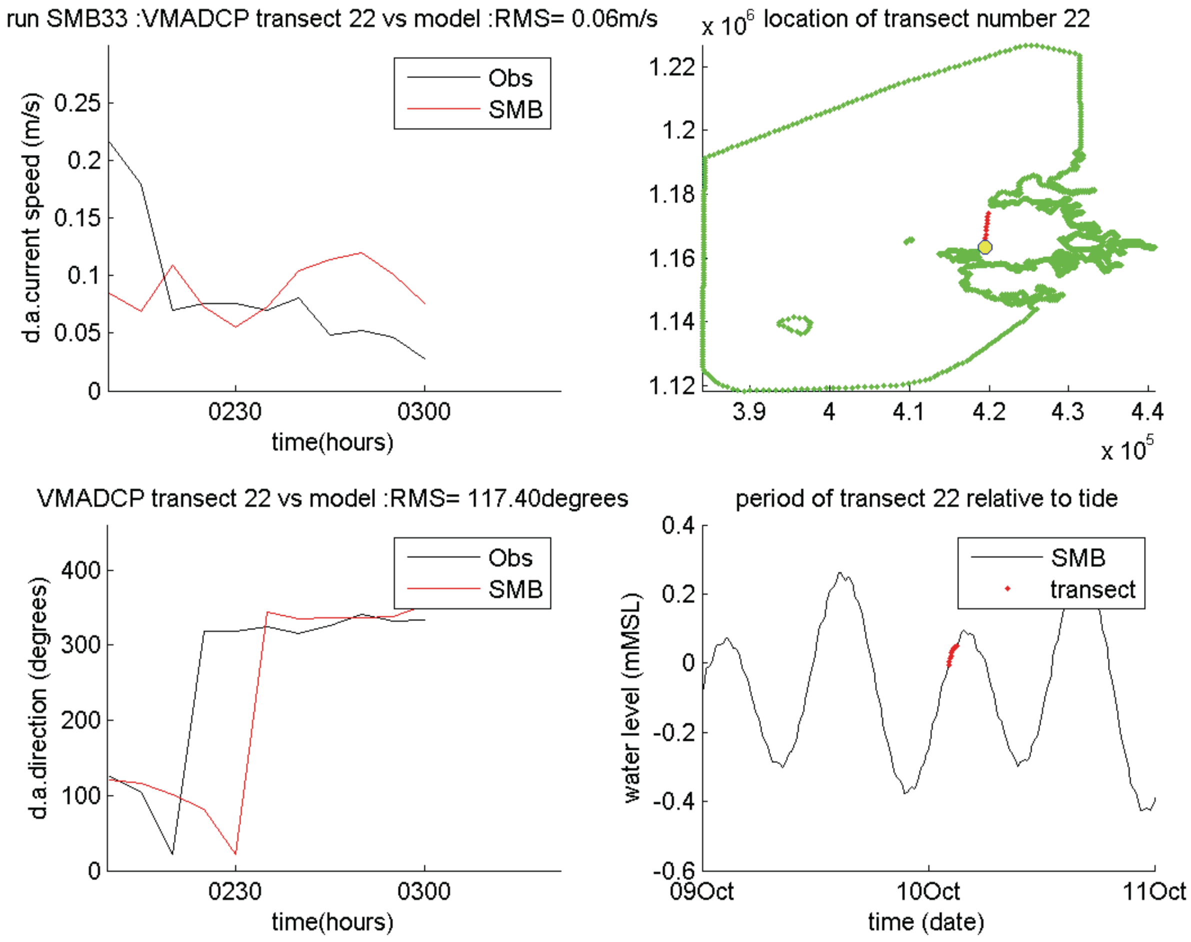

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 13 comparison | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: DMP | Drawn: | Date: 14/112012 |



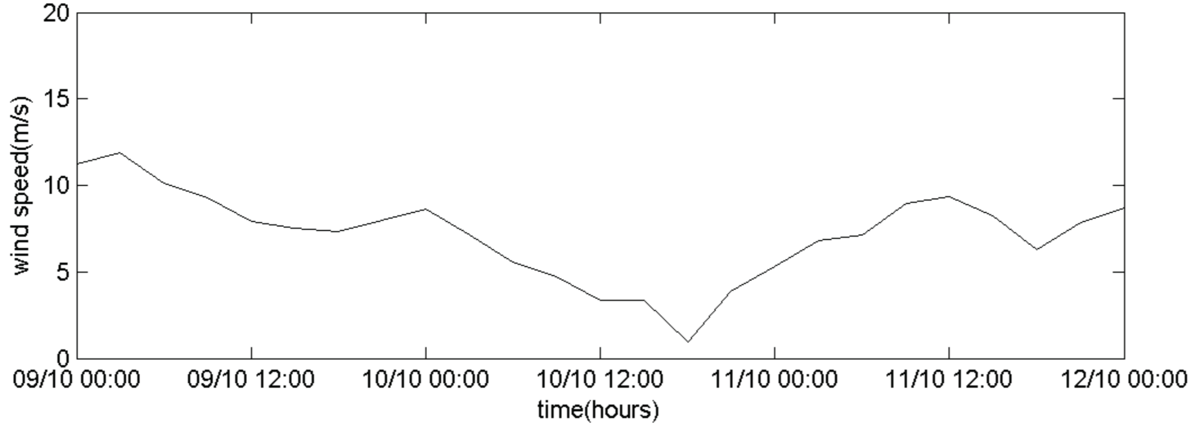

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 16 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

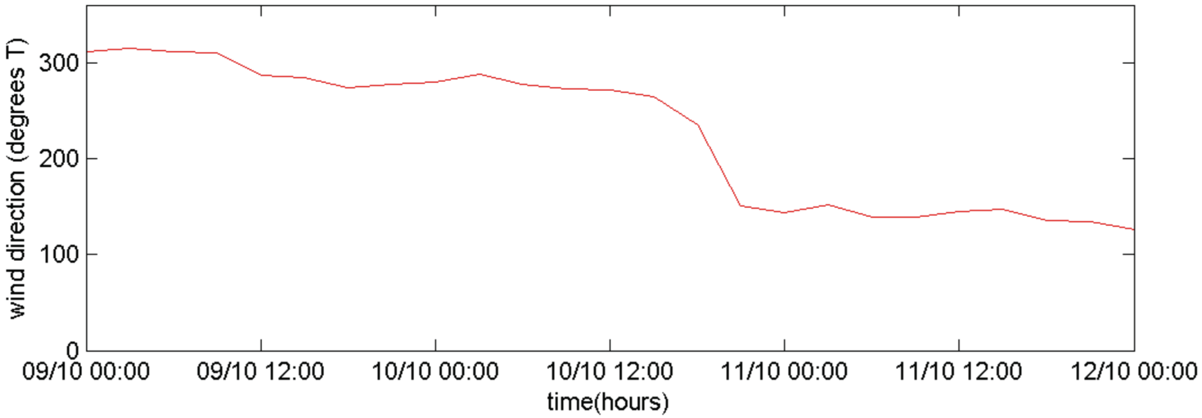



| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 20 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | VMADCP transect 22 comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4i | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Wind speed and direction during simulation period | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

### 3.3.2 Comparison against Fish Farm data

SEPA collated and made available current speed data obtained as part of licensing for fish farms. This data consisted of a minimum of 15 days of recorded current speed at a range of locations in Scotland, including within SMB. Five of these locations were selected because they were distributed throughout the inner parts of SMB.

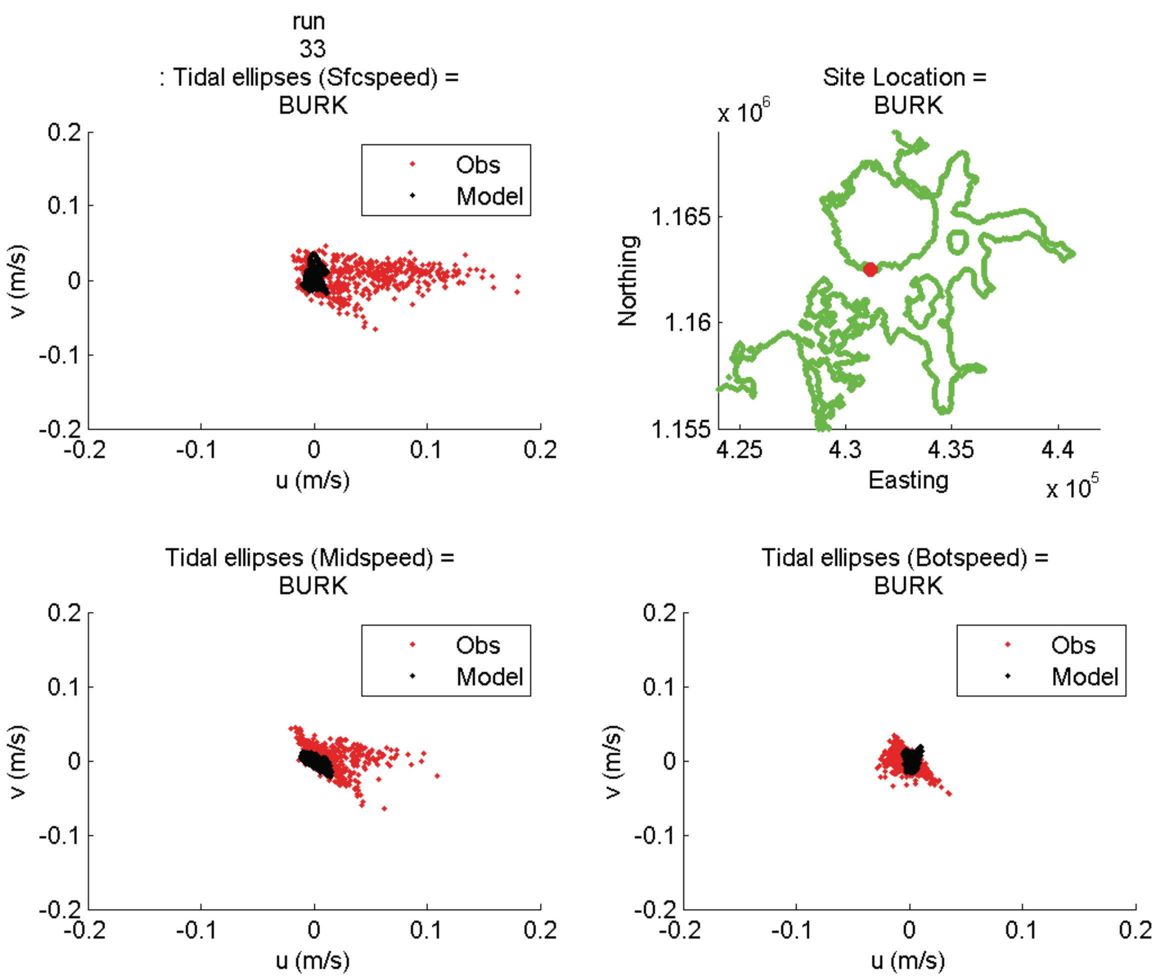
*Table 3-1 Dates from which the selected fish farm data was collected*

| Fish farm name | Start time of 15 day observations |
|---|---|
| BURK | 12:00 28th April 2001 |
| WPL | 12:00 28th February 2001 |
| OLNA | 15:30 9th April 2007 |
| BUD | 15:00 20th February 2002 |
| MUCE | 17:00 12th April 2001 |

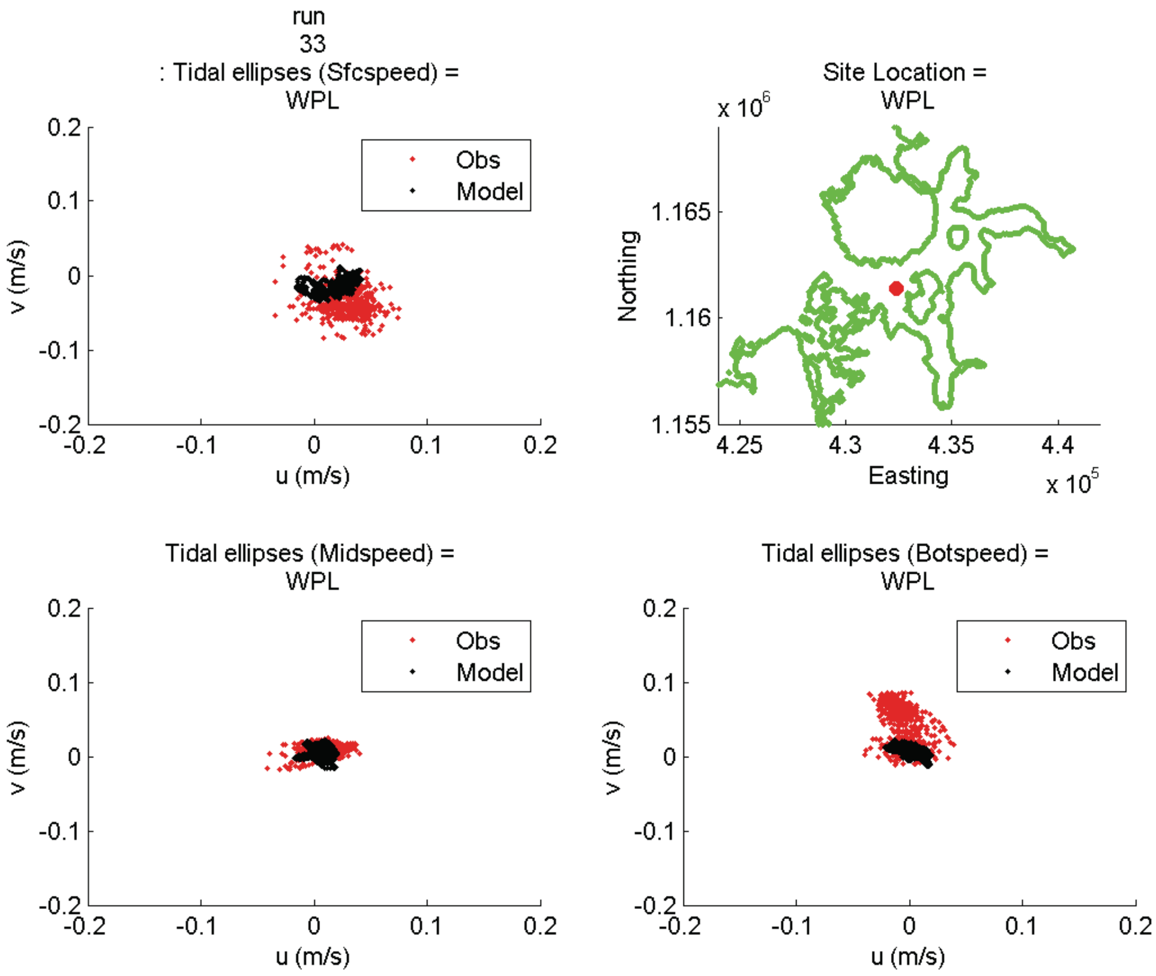
These measurements were made during a range of periods of time and not within the period (or year) of the model simulation. At each location, measurements were made at near-surface, mid and near-bed depths; the model results at the top (layer 1), middle (layer 5) and bottom (layer 10) were used for comparison. Additionally flow speeds were low which meant that the effect of wind proved to have a significant influence upon the current speeds.

A harmonic analysis of the observed fish farm datasets (15 days) was then undertaken at each of the five locations, and the speed components reconstructed from the constituents at the same times as the model results. Figures 3-5a-e present the near surface (top left), mid (bottom left) and bottom (bottom right) current speed ellipse (velocity components plotted against one another) for the observed speeds in black; the location of the measurement site is shown in the top right frame. The data points plotted in red are the model results from a simulation without wind included.

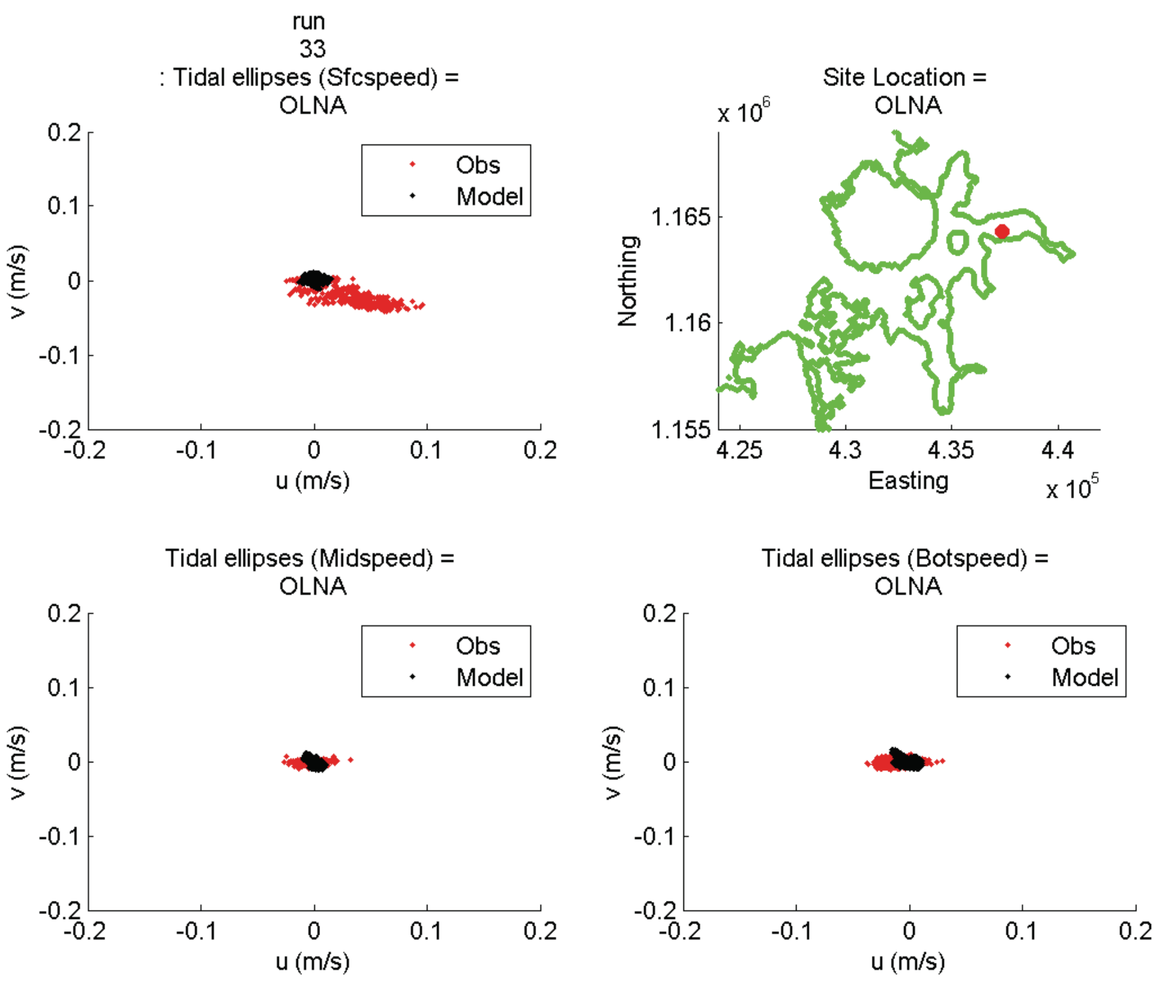
It can be seen that the model speeds are in general of a similar order to those re-constructed from current observations, with magnitudes of only a few centimetres per second.



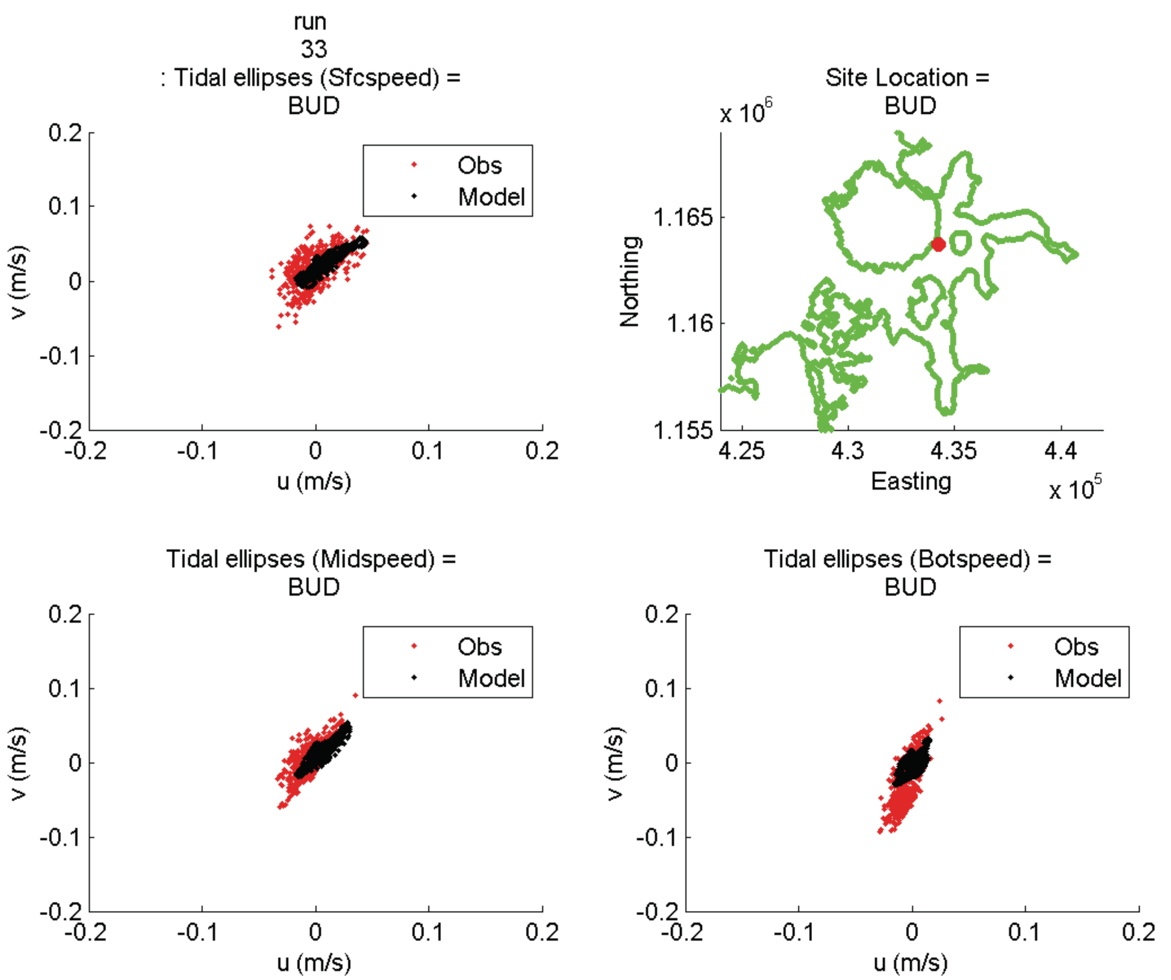

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm tidal harmonically reanalysed current speeds (therefore without wind) and model results without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



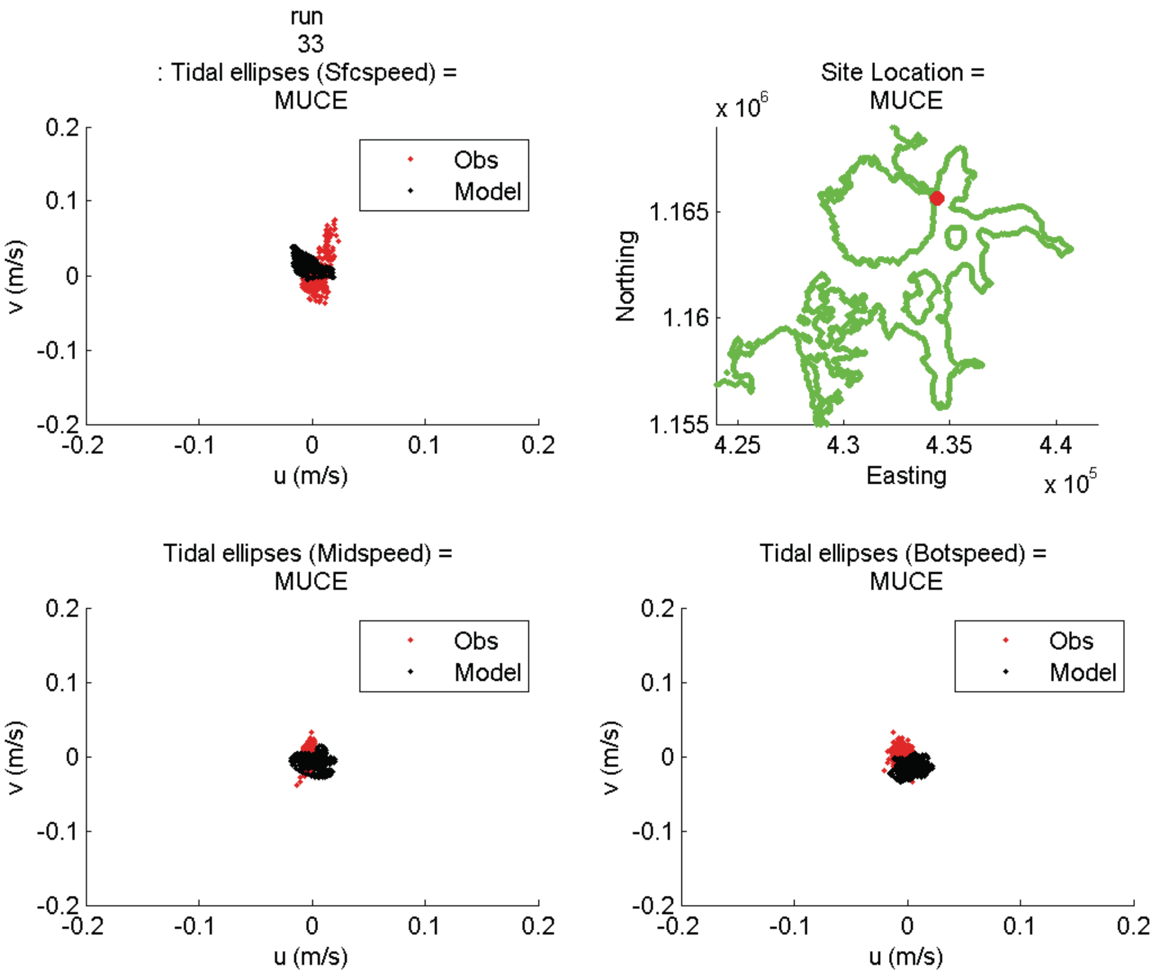

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm tidal harmonically reanalysed current speeds (therefore without wind) and model results without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm tidal harmonically reanalysed current speeds (therefore without wind) and model results without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm tidal harmonically reanalysed current speeds (therefore without wind) and model results without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

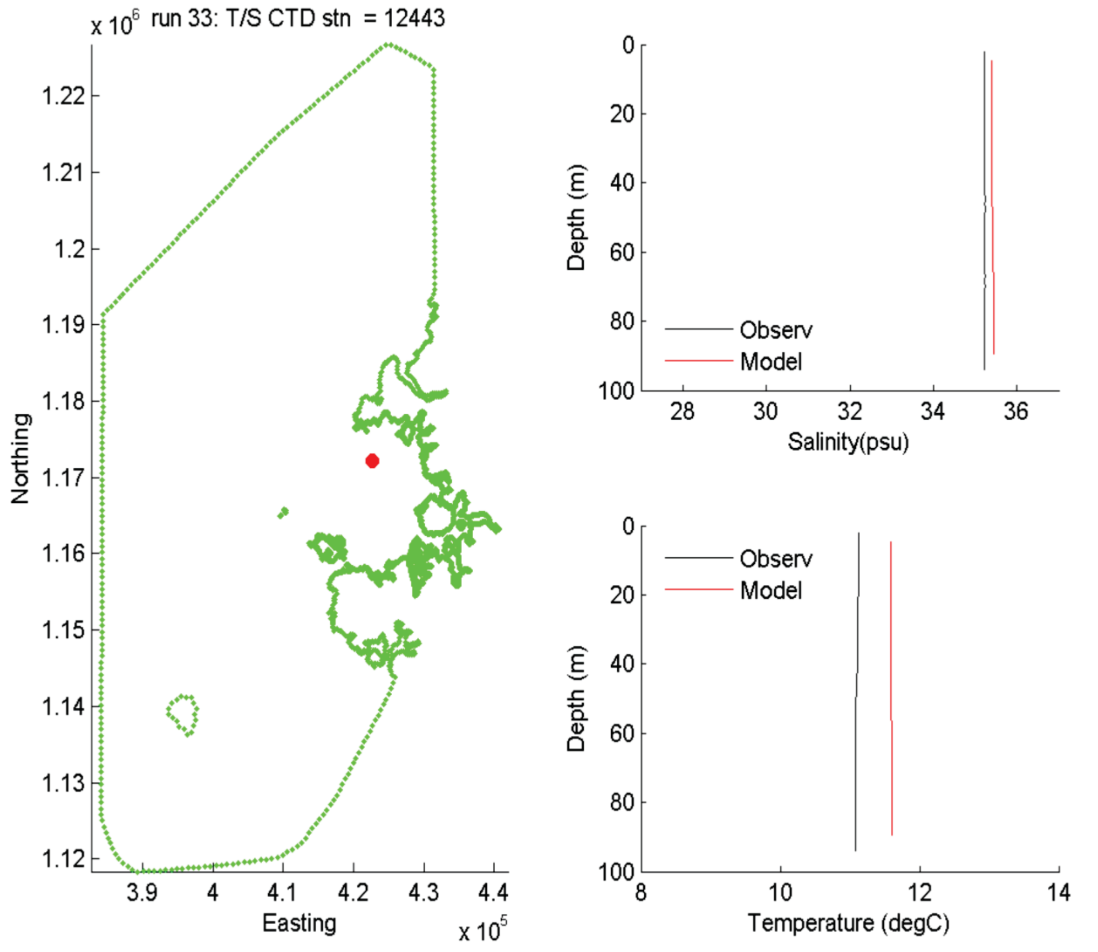



| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm tidal harmonically reanalysed current speeds (therefore without wind) and model results without wind | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

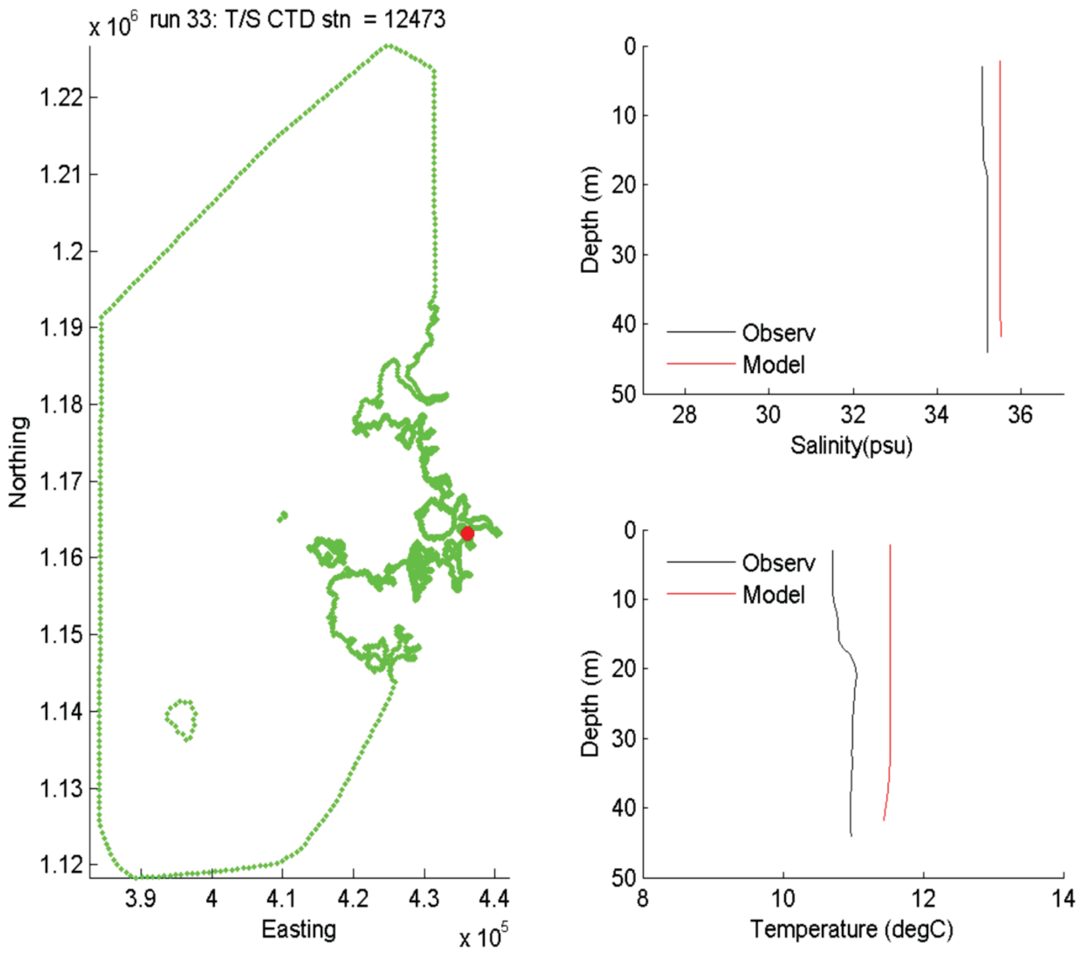
### 3.3.3 Comparisons against observed temperature and salinity vertical profiles – October 2012

As part of the October 2012 survey, MS undertook profile measurements of salinity, temperature and depth using a CTD instrument. These were made throughout the bay and provided a means to compare with the model measurements. Therefore for a simulation of the 10 layer model with wind, was undertaken for the same four day period but with the addition of temperature and salinity boundaries derived from the AMM model. In addition initial conditions of temperature and salinity were also taken from the AMM model. No river flow data or long and shortwave radiation was available for the period of the simulation and therefore the effects of these were not included. This is not an ideal comparison as the simulation is short, however, in the absence of the full met forcing it at least provided a means to test that the general temperature and salinity fields were of the right magnitude and that the data could be used for comparison. A full baroclinic simulation was undertaken for the month of May 2009 (including river inputs) which is reported in Section 3.4.3 below.

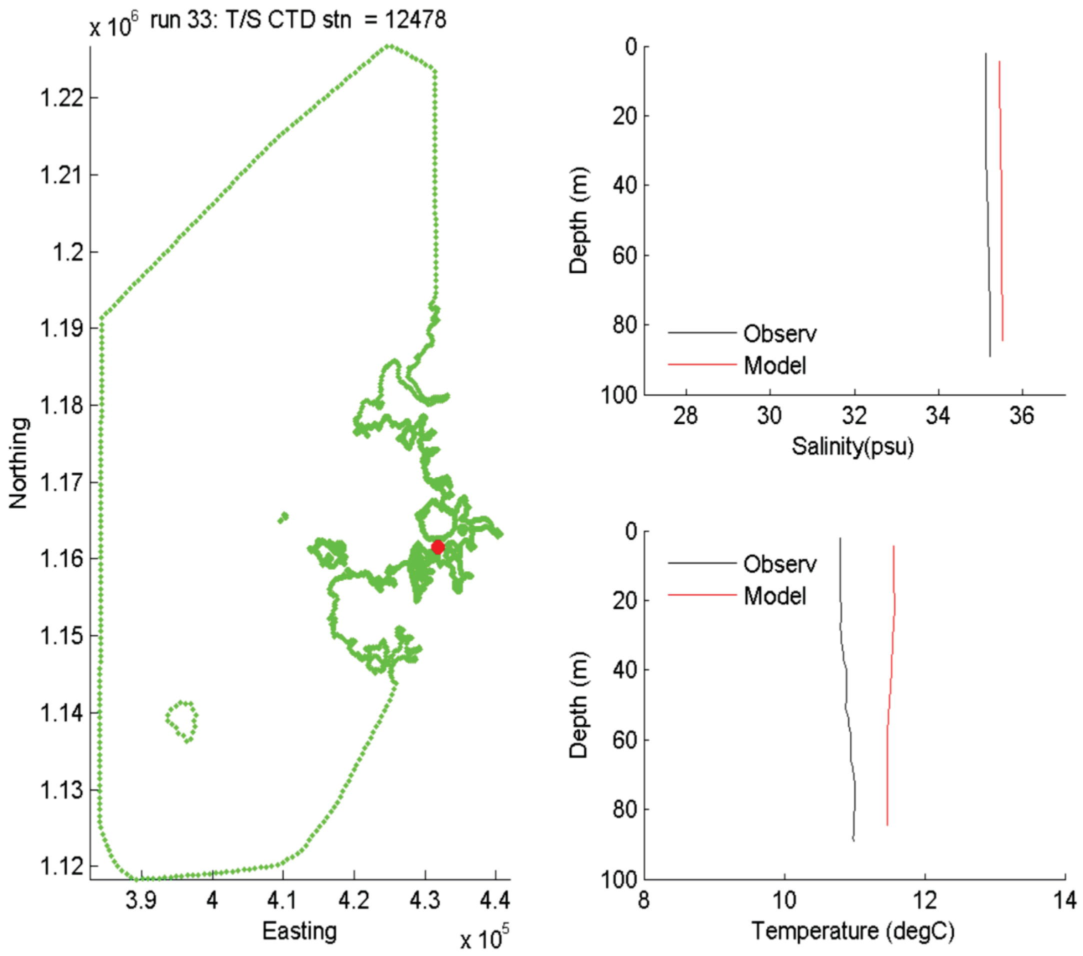
There were 55 vertical profiles within the SMB model domain at which comparisons were made. A small selection of these has been presented to provide a good spatial coverage in SMB; these can be seen in Figures 3-6a-g. In general most of the vertical profiles show the water to be vertically well-mixed, although some evidence of variation with depth can be seen in the observations in Figure 3-6b, with slightly cooler water above 20m depth. Comparisons of salinity between the model and the measured values are close with the model being less than 0.5psu greater than the observed. For temperatures, the model predicts temperatures which are approximately 0.5-0.75 degrees Celsius greater than the observed values. Both are within the tolerance ideally expected from the model. As the model did not include full met forcing, the temperature within the model does not undergo any exchange of heat between the atmosphere and the sea water.



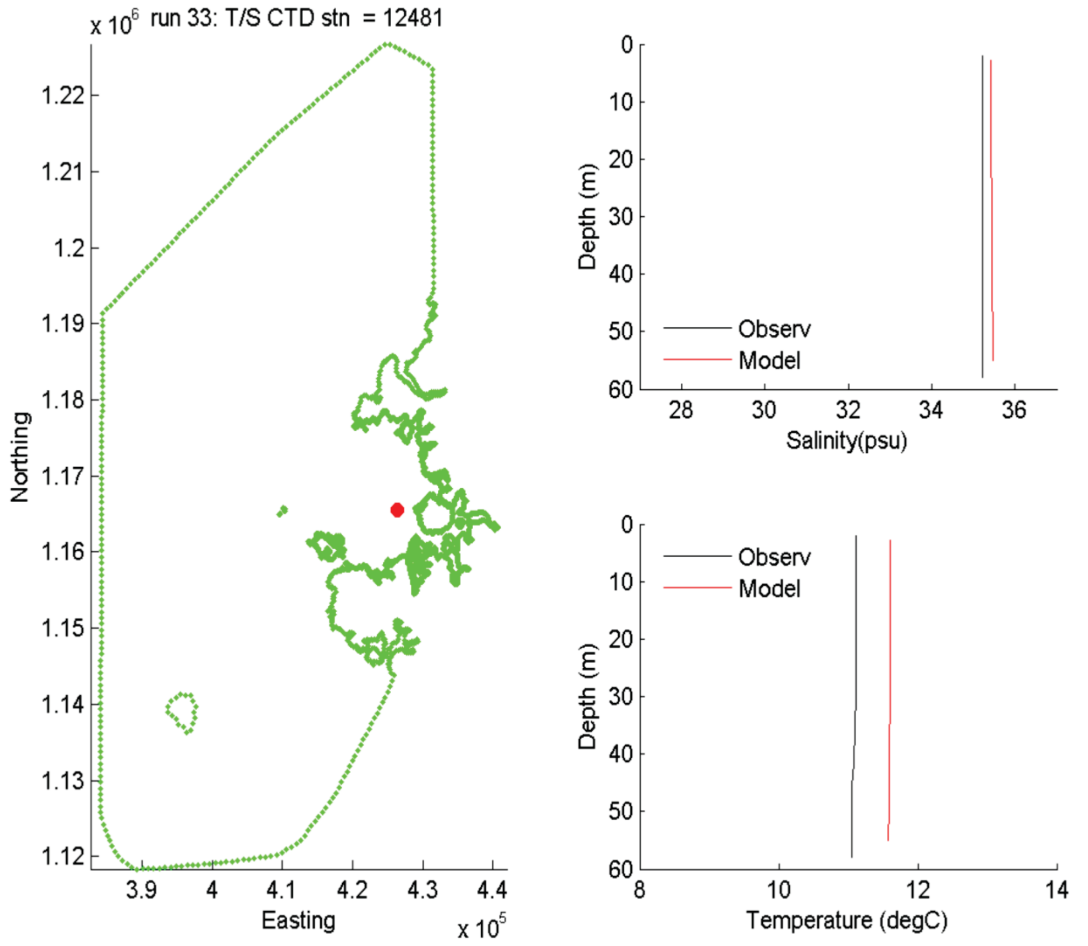

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



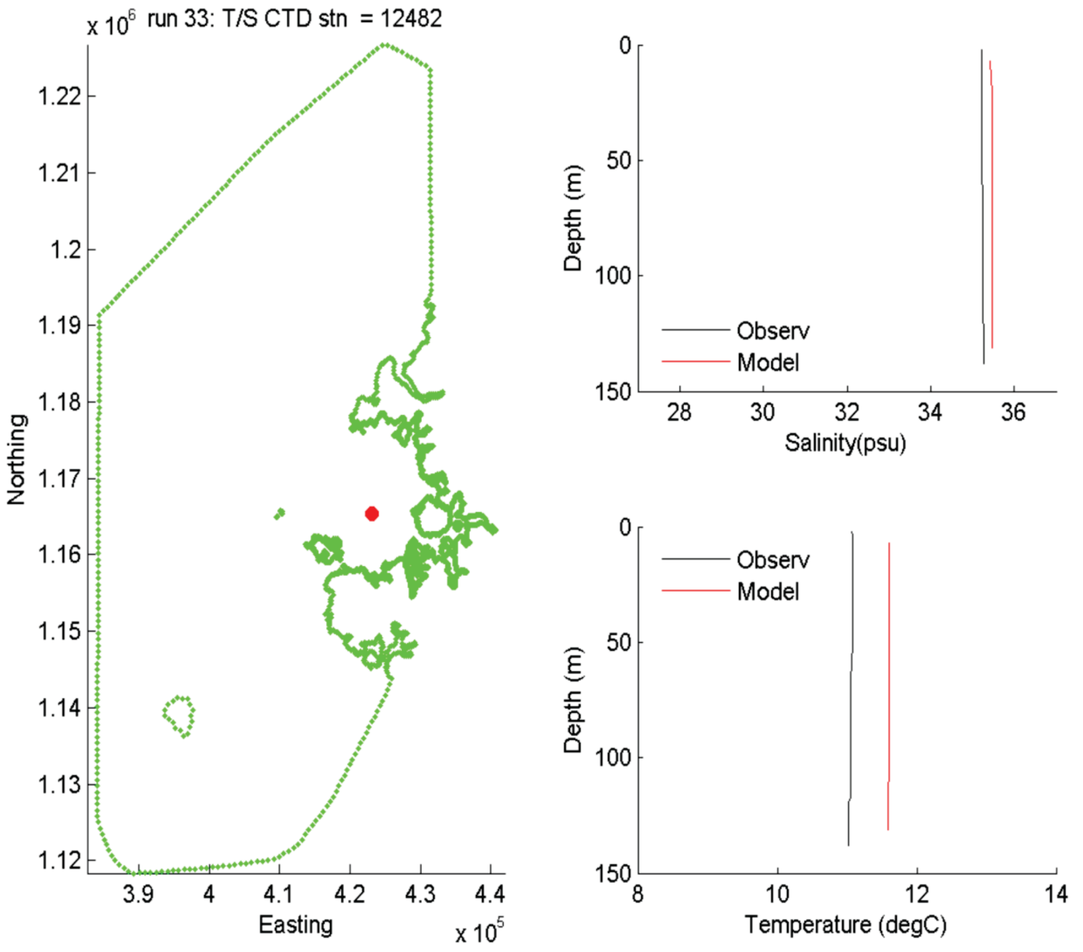

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



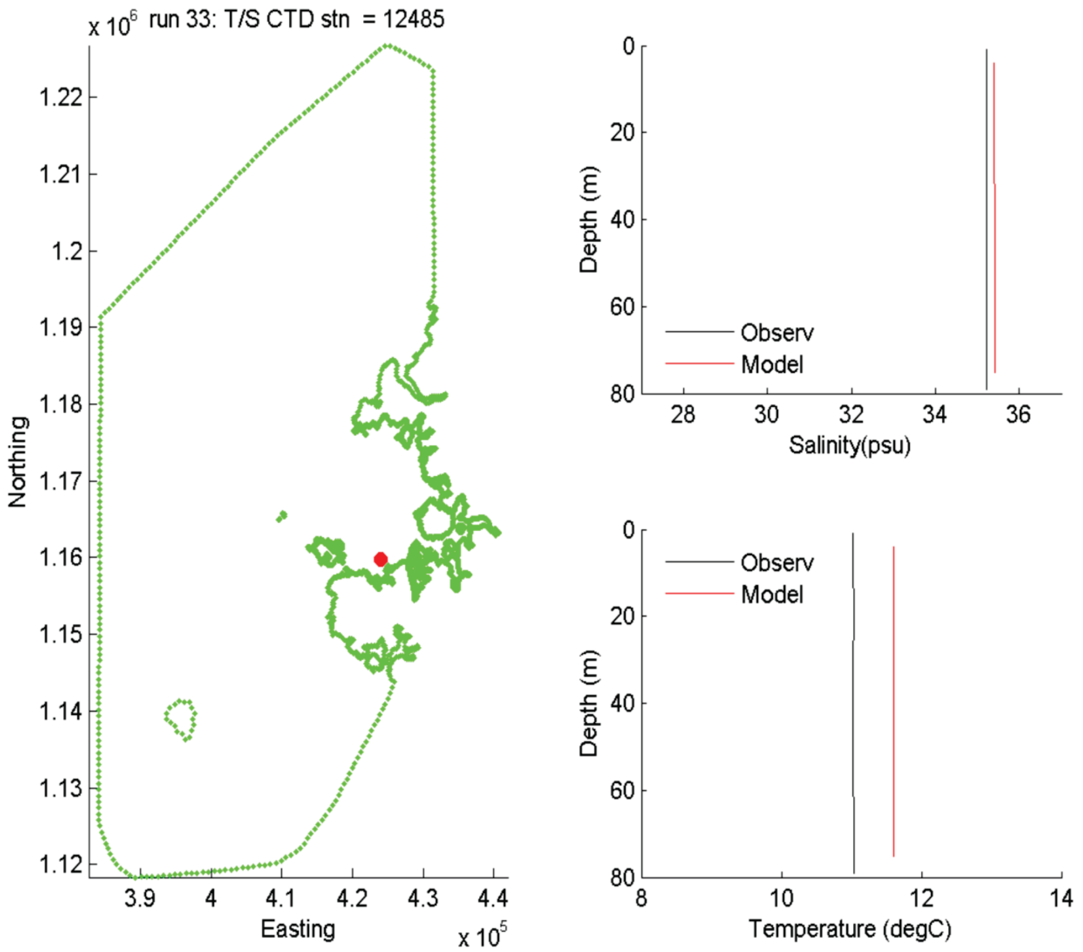

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



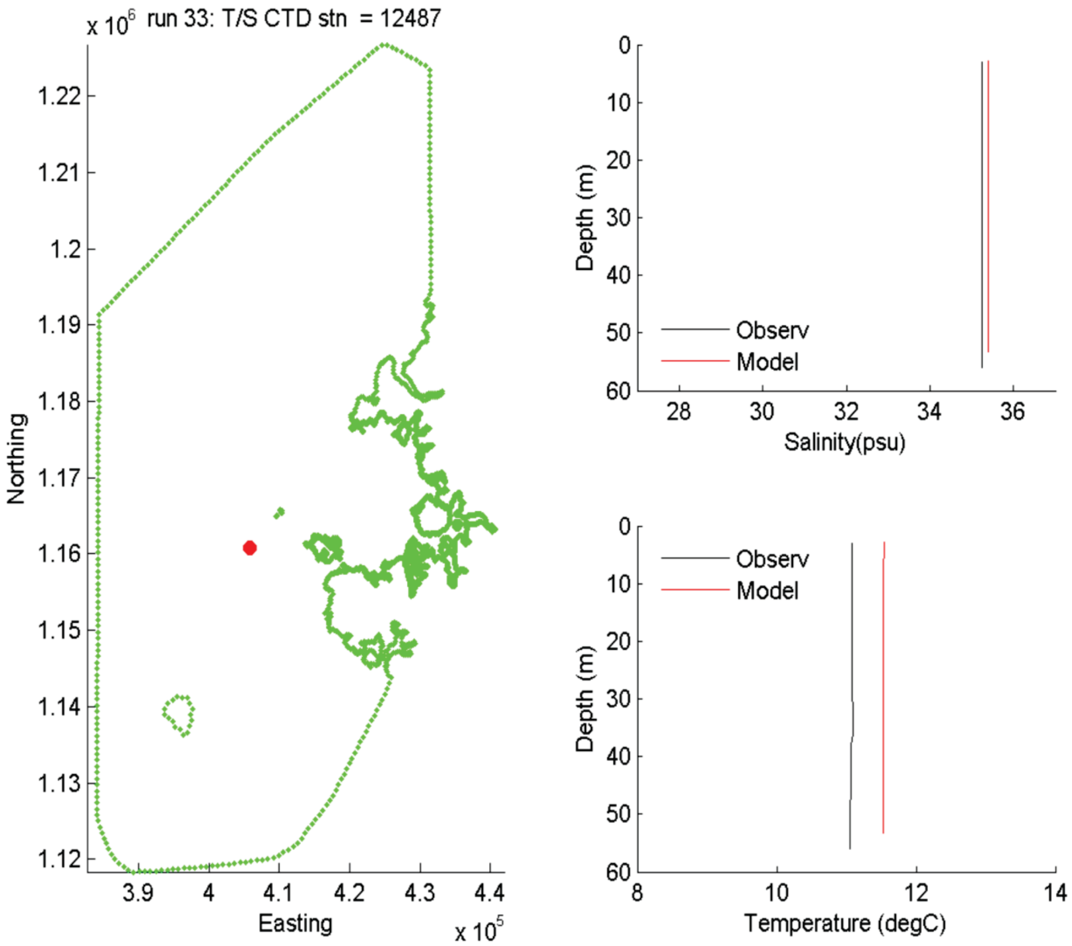

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: DMP | Drawn: | Date: 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

## 3.4 Flow Model Validation

### 3.4.1 Introduction

Validation runs were carried out for May 2009 and October 2001. Data was available for May 2009 to validate against temperature and salinity profiles, and October 2001 for validation of current speed against fish farm measurement.

### 3.4.2 Direct comparisons with Fish farm data at site COLE1

The fish farm data were each collected at different times and locations. However there was a site which coincided with a simulation that had been run for the PFOW model namely October 2001. During this period local wind speed/direction information had also been recorded alongside the currents and was applied throughout the whole model domain as a timeseries. This is an oversimplification but in the absence of other more detailed data was felt to be appropriate.

Figures 3-7a and b present the comparisons between the model results and the data, with Figure 3-7b being the same comparison as Figure 3-7a but zoomed in on a shorter timeframe. The top two frames show the surface current speed and direction, the middle two the mid-depth and the bottom two the near bed current speed and direction. Observed current speeds are generally in the region of 0.1m/s although there are isolated periods when speeds at the surface attain speeds of 0.2m/s. Given the low current flows it is very difficult to get an exact match. Examining Figure 3-7b it can be seen that many of the peaks in current speed have been reproduced by the model although not all of them. There are a number of reasons for differences including but not limited to boundary conditions, spatially constant wind from local site (may not be applicable over entire area) and errors in measurements of such low current speeds. Therefore, given some of the possible errors and the low current speed we believe that the model represents the current speeds reasonably well. The current direction comparisons do not appear to be as good although the eye is attracted to all measurements whether current speed is very low or not and so some of the directions may be misleading. The effect of wind appear to be stronger in the model than the observations (surface current sets in a constant direction for several days in the model, while the current appear to rotate in the observations).

### 3.4.3 Comparisons against observed temperature and salinity vertical profiles – May 2009

In order to validate the temperature and salinity predicted by the model, a longer simulation was required coincident with available data. Such data was found in the BODC archive for four locations outside of SMB but within the model domain. The SMB model was therefore run in baroclinic mode for the period of May 2009 as results from the PFOW model were available towards the end of this time period, thus allowing a good length of time for the model to become warmed up.

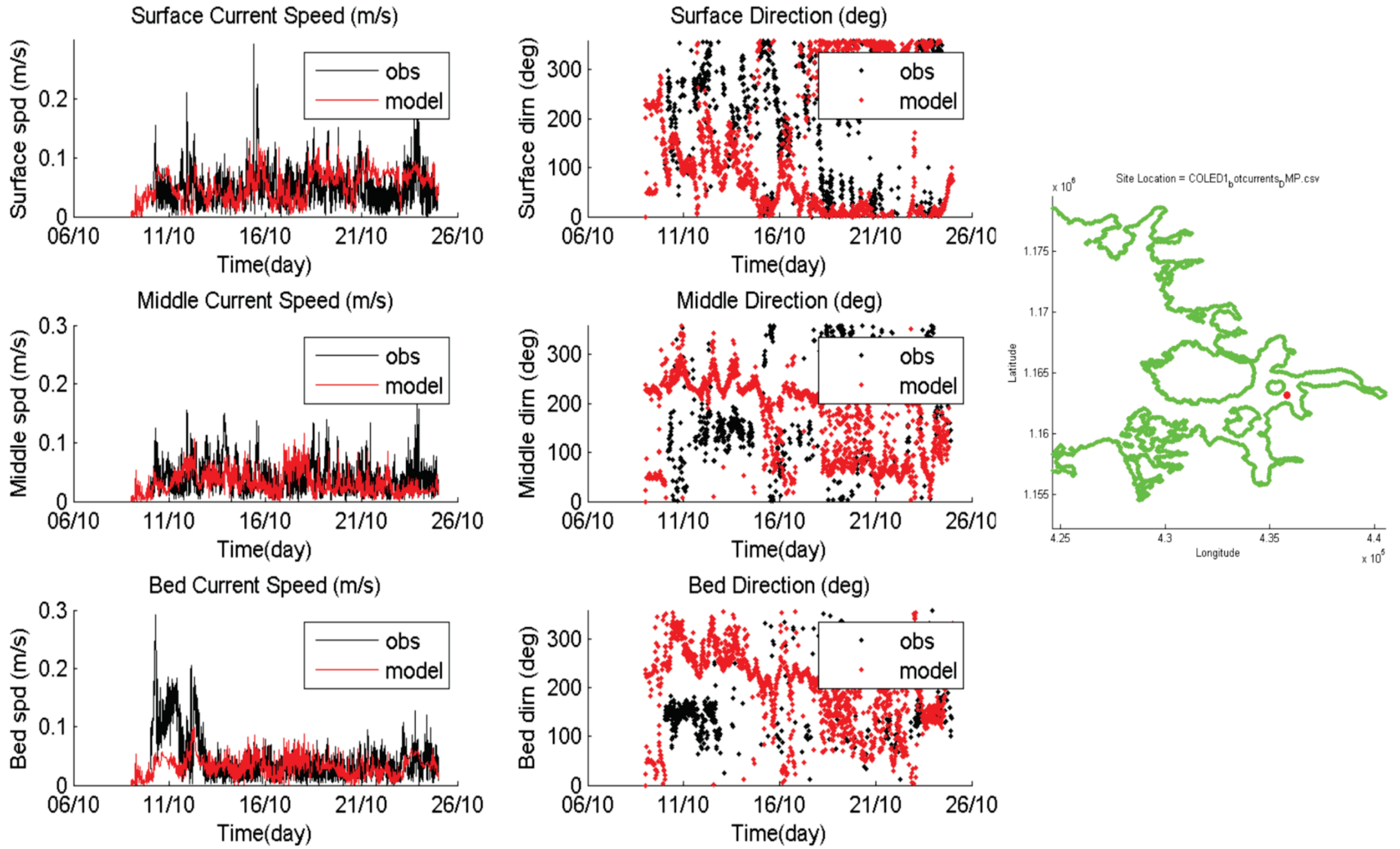
Boundary conditions, river flows and meteorological forcing (from the Met Office mesoscale model) were created for the SMB mesh and the simulation undertaken. Some smoothing of the initial few hours of the nesting boundary was required so as not to create a shock within the model when the current speeds were introduced as these are not affected by the *iramp* smoothing parameter in FVCOM.

Results from the model in the form of temperature and salinity comparisons with vertical profiles of temperature and salinity are presented in Figures 3-8a-d for locations from west to east towards SMB.

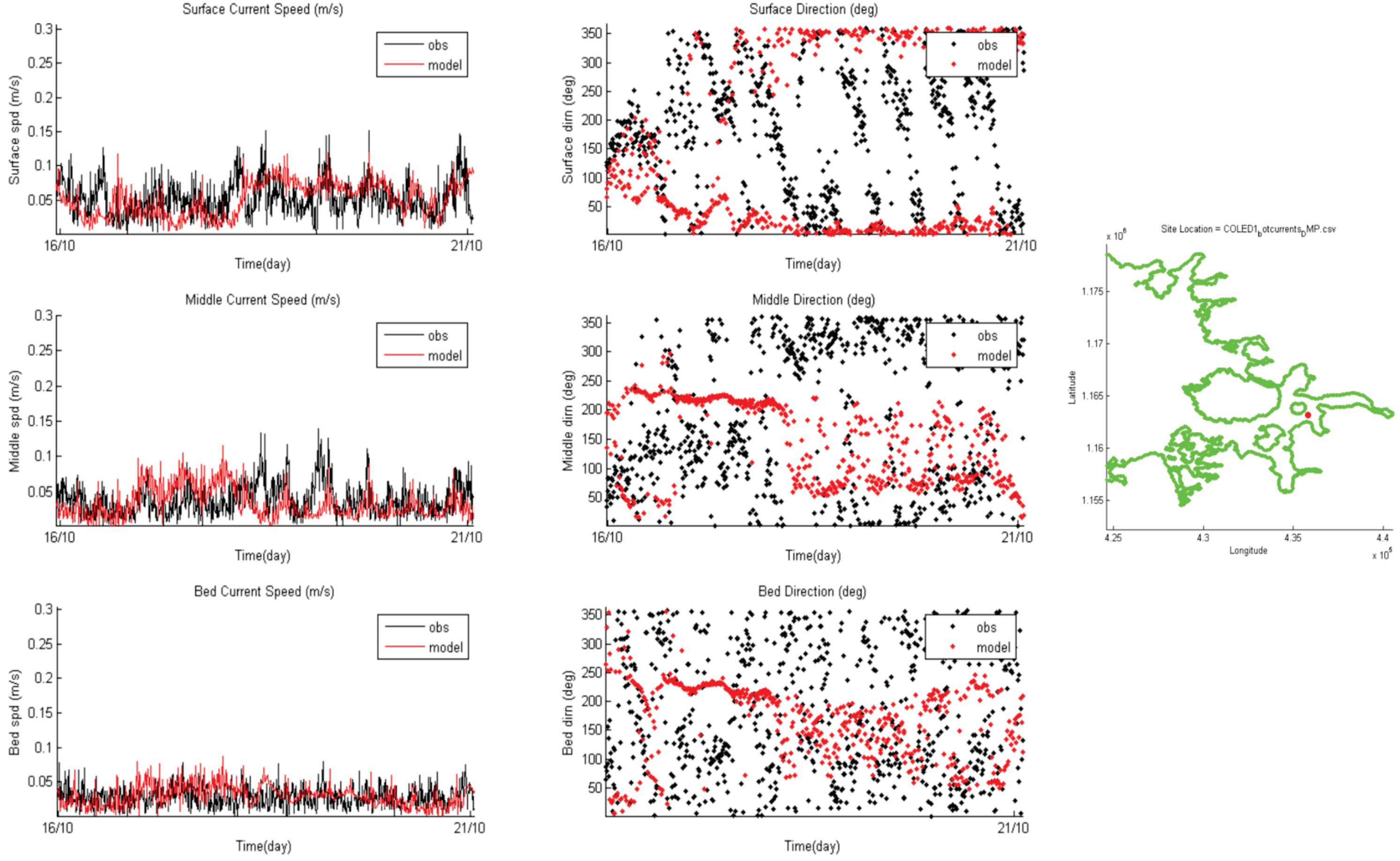
The offshore location (Figure 3-8a) is close to the model boundary and shows a good reproduction of the data and the AMM results. The temperature for the AMM and the SMB model are slightly higher than the observed data in the top half of the water column by almost 1 degree although the SMB model results are closer to those observed. This is also the case for Figure 3-8b, although the salinity can be seen to be very slightly lower than that observed for mid depths although well within the required accuracy. The temperature at the surface and the bed reproduces the observed values closely. Between about 75m and 20m water depth however the SMB model is over-predicting temperatures by just over 0.5 degrees. However the AMM model does this to a greater extent which appears to have translated into the SMB model via the boundary conditions derived from the AMM model.

Figure 3-8c shows that the SMB model is predicting slightly lower salinities than those observed or in the AMM model. This is less than 0.5 degrees however and therefore within the accepted limits. However this may suggest that the freshwater input may be too high. The temperature profile predicted by the model is also shown in this Figure, magnitudes are similar to the observations throughout most of the depth although the higher temperatures in the top 15m of the water column shown in the data is not reproduced. And shows a more mixed water column.

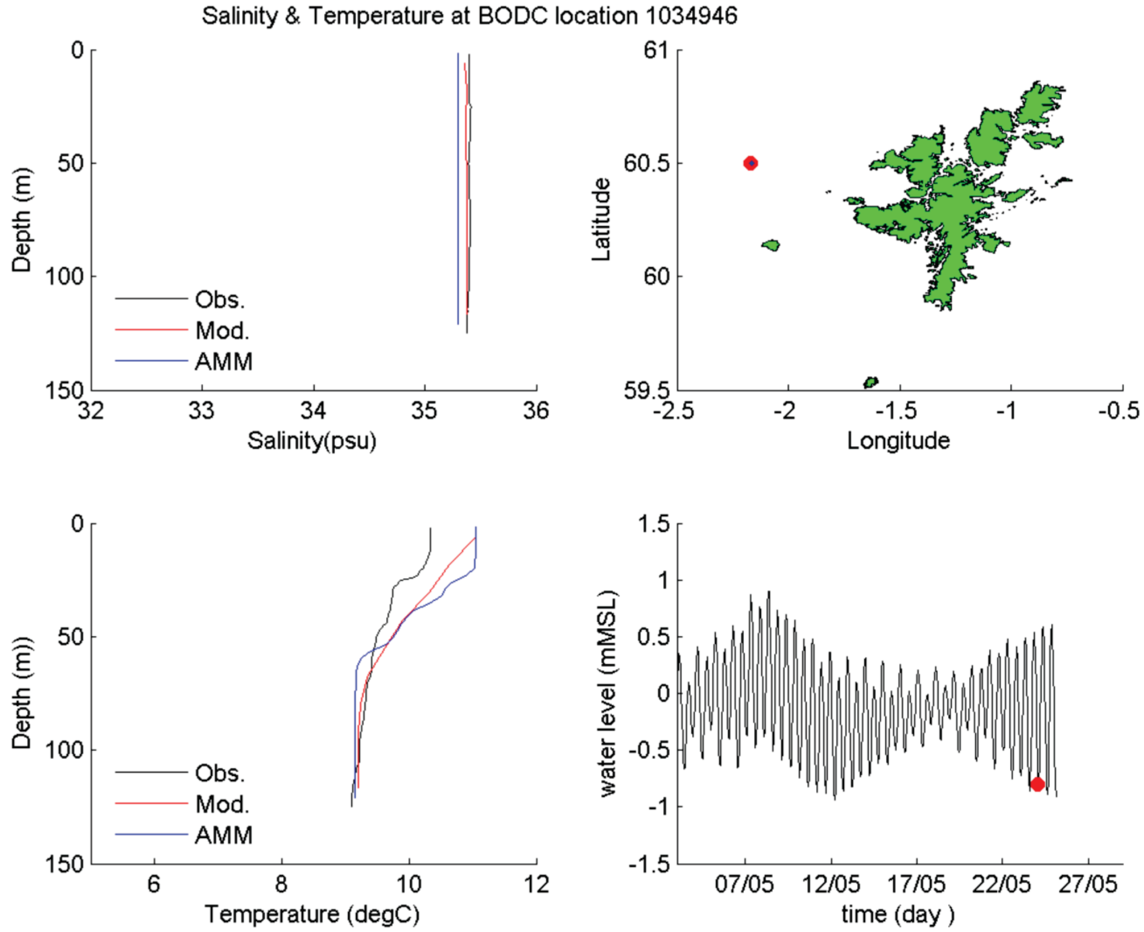
Figure 3-8d shows the same under-prediction of the salinity albeit quite small. The temperature profile however shows the same vertically mixed condition as in the previous Figure, however in this case the data also shows the same feature. This suggests that for this time period the water column is stratified offshore, but closer to SMB it is vertically well-mixed.



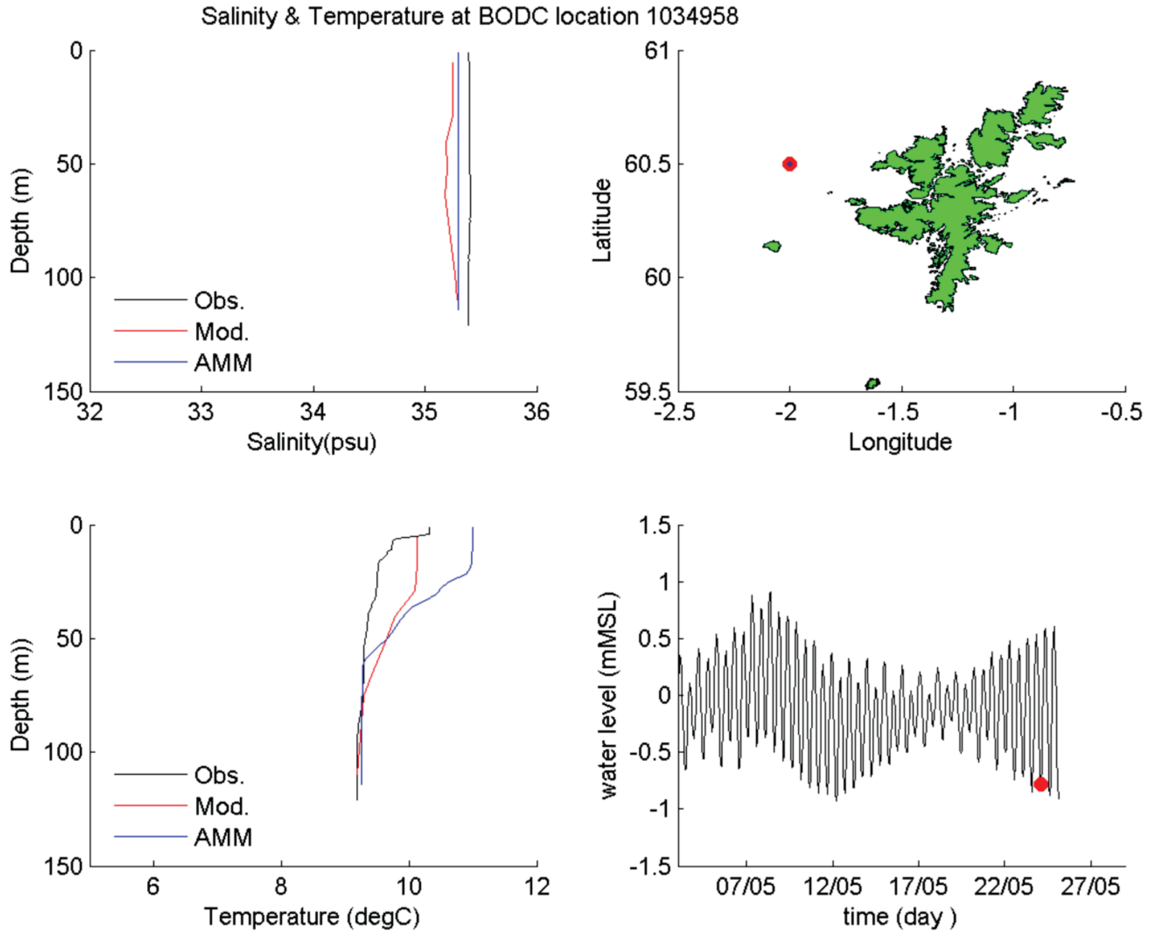

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-7a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | St Magnus Bay Model | Comparison between observed fish farm data at COLED1 and model results (with wind included) | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



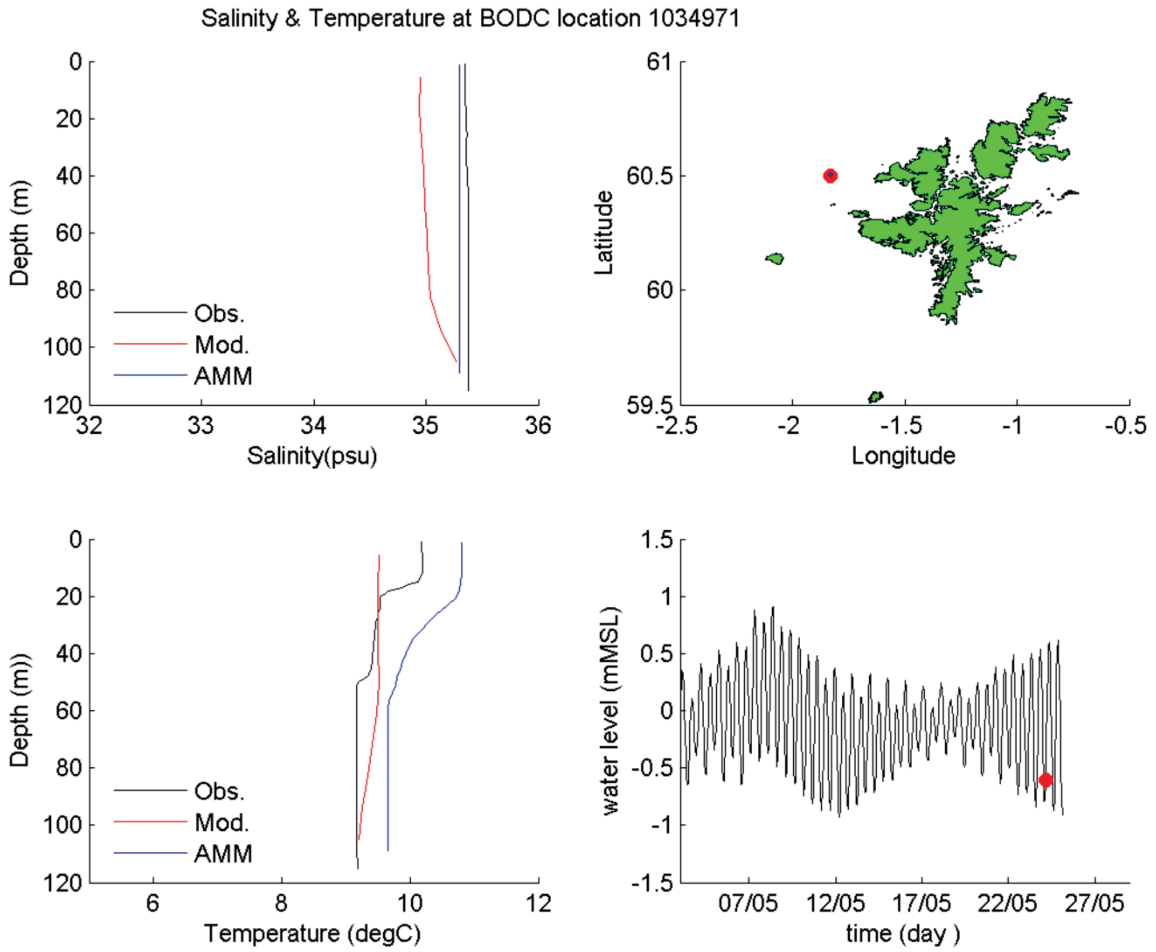

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-7b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed fish farm data at COLED1 and model results (with wind included) – shorter time frame | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



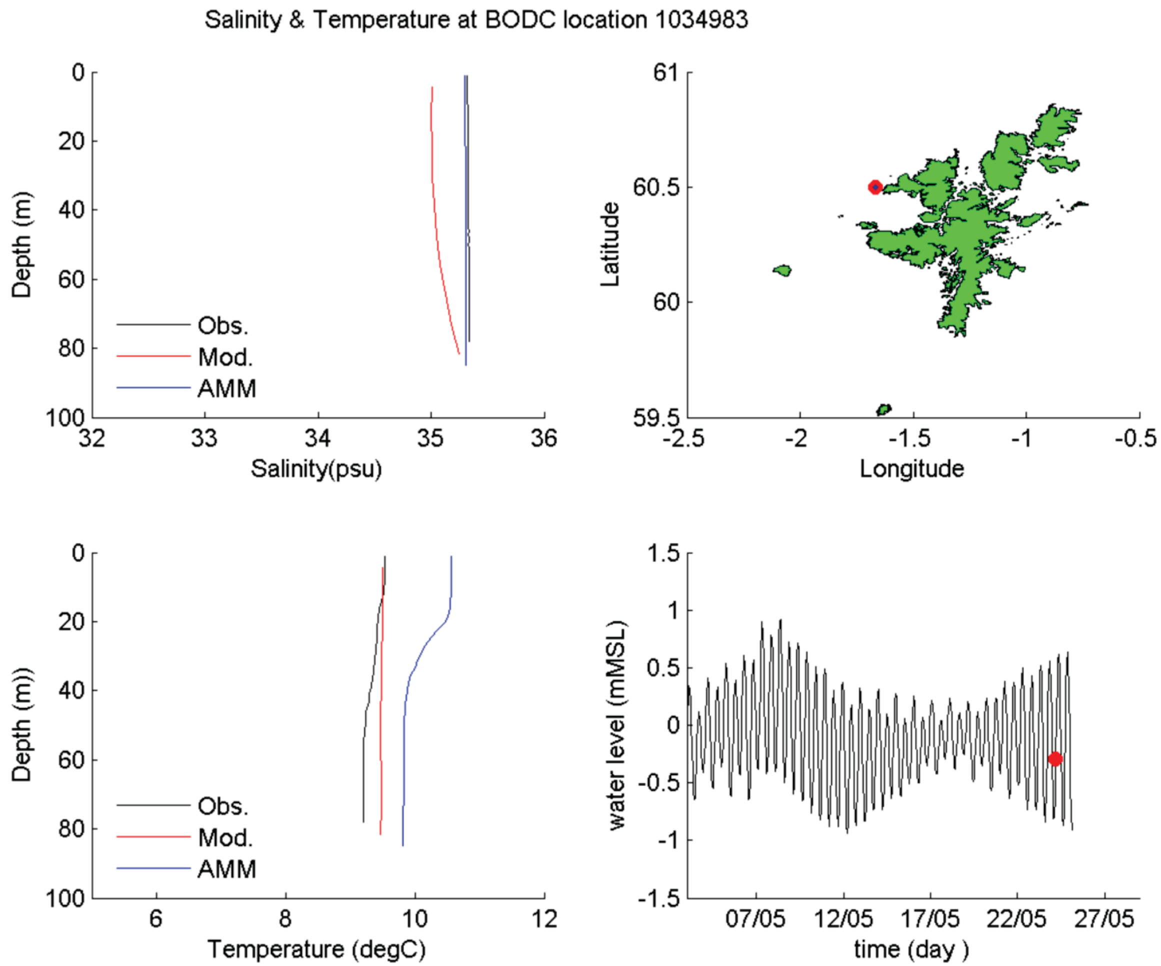

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-8a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model for the May 2009 baroclinic simulation | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-8b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model for the May 2009 baroclinic simulation | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-8c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model for the May 2009 baroclinic simulation | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-8d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model for the May 2009 baroclinic simulation | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

## 3.5 Summary of model calibration and validation

In general, current speeds within SMB are low and are influenced by wind as much as by tides. Comparisons with current measurements outside of SMB have shown the model to have similar magnitude current speeds but turns earlier than observations. Comparison of transects across the mouth of the Bay show the model able to reproduce the magnitude of current speed well, including the structure (especially for direction) along the length of transects; without the effects of wind however, the comparison was not as good suggesting that wind plays an important role. Comparisons of the model flow vector results with and without the wind applied showed differences in the flow patterns within SMB. The current speeds within SMB are therefore sensitive to the applied wind given that tidal current speeds can be low.

Measurements of currents at such low speeds could contain a relatively large error compared with measurements of higher flow speeds. Errors could be of a similar order to the observed current speeds, therefore it would be important to get the predicted current speeds to the same order of magnitude as the low observed current speeds, which has in general been achieved within SMB.

In addition to the tidal ellipse comparisons with the fish farm data, a simulation was undertaken at one of the Fish Farm locations within SMB. This observed data was concurrent with a PFOW model run which provides boundary conditions. In addition to the current measurements, wind measurements were also made at the site. Therefore the simulation also including this local wind which has been seen to be important in the inner SMB region. The results showed that the reproduction of the low speed conditions was achieved along with reproduction of some of the features within the observed speed record. At such low speeds it is likely that accurate wind speed data would prove beneficial and is likely to play an important part in improving upon the comparison with data.

Although limited data was available, the model has shown that it is able to reasonably reproduce the temperature and salinity measured within the model domain including some of the vertical features that are present.

## 3.6 Flow model simulations

### 3.6.1 Introduction

This section of the report describes the climatology runs of the flow model for the St Magnus Bay (SMB) area. The model set up used has been described in the calibration section. The requirement was to produce a six month climatic run, from May to October, based on climatological forcing, representing a typical annual climate. This was carried out using the Scottish Shelf model climatology results as initial conditions as well as for boundary conditions. The input data sets for climatological meteorological forcing and climatological river fluxes used in the shelf model were also used for the SMB 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 were used for particle tracking and to develop connectivity indices. The results 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.

### 3.6.2 Climatology Input Data

#### 3.6.2.1 Boundary conditions

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 SMB 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. The decision to use boundary conditions from the shelf model instead of PFOW as in the calibration runs was based on the relative resolution of each model in the vicinity of SMB. The shelf model resolution is higher, therefore the bathymetry in the Shelf model is more consistent with that of the SMB model than that of the PFOW model in this area.

#### 3.6.2.2 River input

River climatology data was processed by NOC-L from two sources: (i) a reconstructed river climatology derived by reference to the E-HYPE model (126 Scottish rivers, 1980-2012 provided by the Swedish

Meteorological and Hydrological Institute, SMHI), distributed across the 508 G2G river discharge locations for the Scottish mainland, as originally provided by CEH for March 2007 – Sep 2010 (see below) (ii) G2G river climatology (1962-2011, 577 rivers) provided by CEH in August 2014 and updated in October 2014. 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 2 of these rivers fall within the SMB model domain. The rivers were processed in the same way as those for the baroclinic calibration model runs. Figure 3-9 shows the location of the rivers and the location of the nodes the rivers were applied at and the average monthly discharge in cumecs is given in Table 3-2.

*Table 3-2: Average monthly river discharge into St Magnus Bay in cumecs.*

| Average monthly river discharge(cumecs) | | | | | |
|---|---|---|---|---|---|
| | River 5 | River 8 | | River 5 | River 8 |
| January | 0.58 | 0.58 | July | 0.09 | 0.06 |
| February | 0.45 | 0.44 | August | 0.15 | 0.11 |
| March | 0.38 | 0.37 | September | 0.31 | 0.28 |
| April | 0.21 | 0.17 | October | 0.46 | 0.45 |
| May | 0.10 | 0.07 | November | 0.59 | 0.60 |
| June | 0.08 | 0.05 | December | 0.58 | 0.58 |

#### 3.6.2.3 Meteorological forcing

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

The met forcing were derived as monthly means, which were specified at the middle of the month i.e. mean February data were applied at the middle of February; then mean March data were applied mid-March etc. The data are then linearly interpolated to 6-hourly smoothed forcing data for each grid-point in the FVCOM model. For full details see the Shelf Modelling report (Wolf et al. 2015).

### 3.6.3 Validation

#### 3.6.3.1 Temperature and Salinity Comparisons

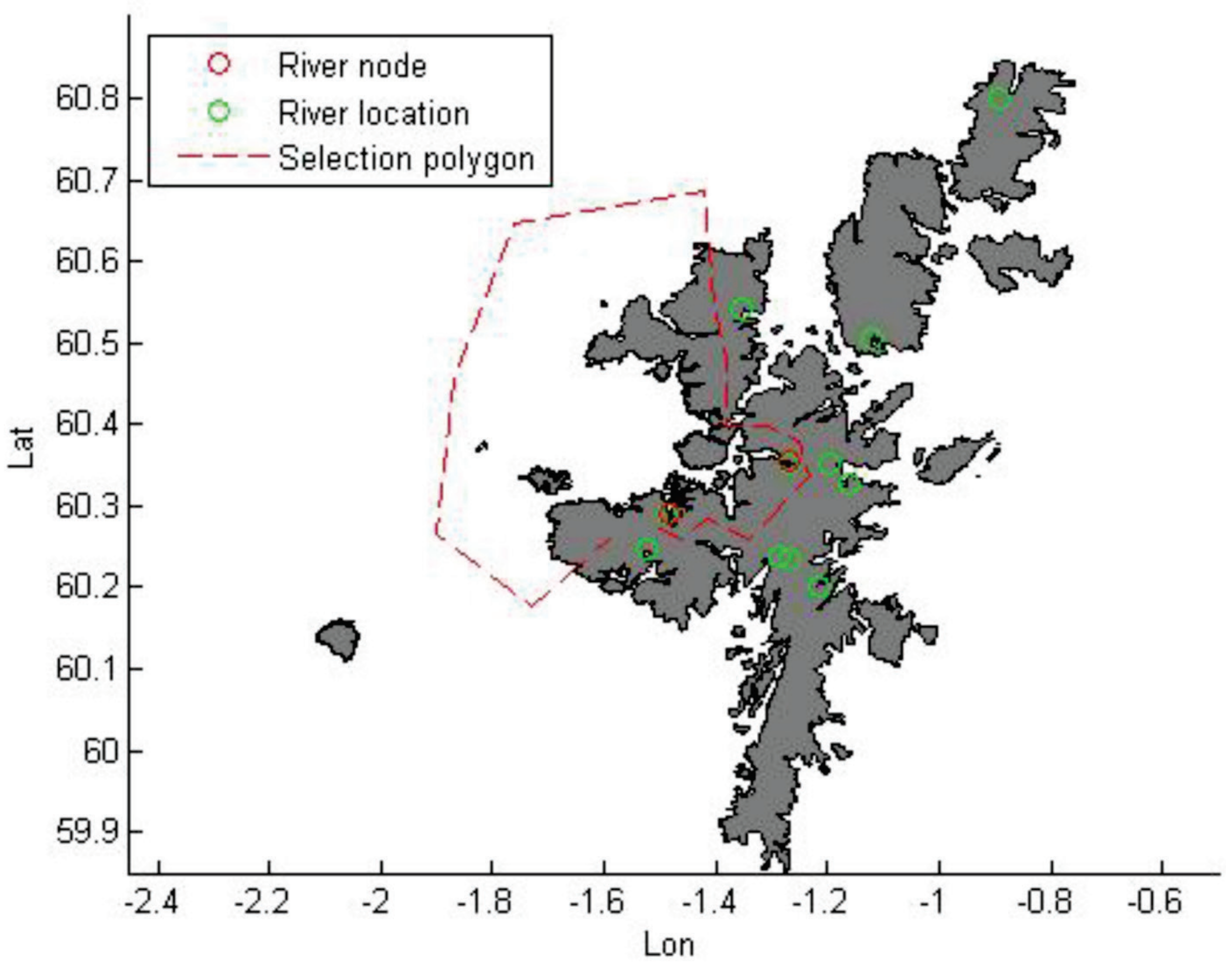
Average monthly sea surface temperature (SST) and sea surface salinity (SSS) observations are available from two sources:

1) The ICES (International Council of the Exploration of the Sea) dataset (http://ocean.ices.dk/HydChem) gridded and averaged for 1960-2004 (45 years) by Jason Holt (NOC-L). 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 SMB FVCOM results for May, August and October. The resolution of the WOA and ICES data is very low in relation to the model area. Unfortunately no other higher resolution data of SST and SSS are available, therefore the results from the shelf model are also presented.

Figures 3-10a-c shows the comparison of the data sets for SST. Comparison with the WOA and ICES data give good general agreement with the SMB SST. Comparison with the shelf model shows the SMB model gives slightly lower temperature in May and August.

Figure 3-11a-c shows the SSS comparisons. Results from both the shelf model and the SMB give lower sea surface salinities than the WOA and ICES data. The comparison between the Shelf and SMB models show some spatial variations in SSS. Around the boundary of the SMB model result match well however inside the model the salinity is lower than the shelf. This may be due to one of the river inputs not being included in the shelf model. This can be explained by the lower resolution of the Shelf model in the estuary in SMB and the method used to identify the river input locations. As the shelf model does not resolve the estuary the nearest node to the river discharge location in the shelf model was on the east coast of Shetland, not in SMB.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | | Checked DMP | Scale Not to scale | Rev. 0 |
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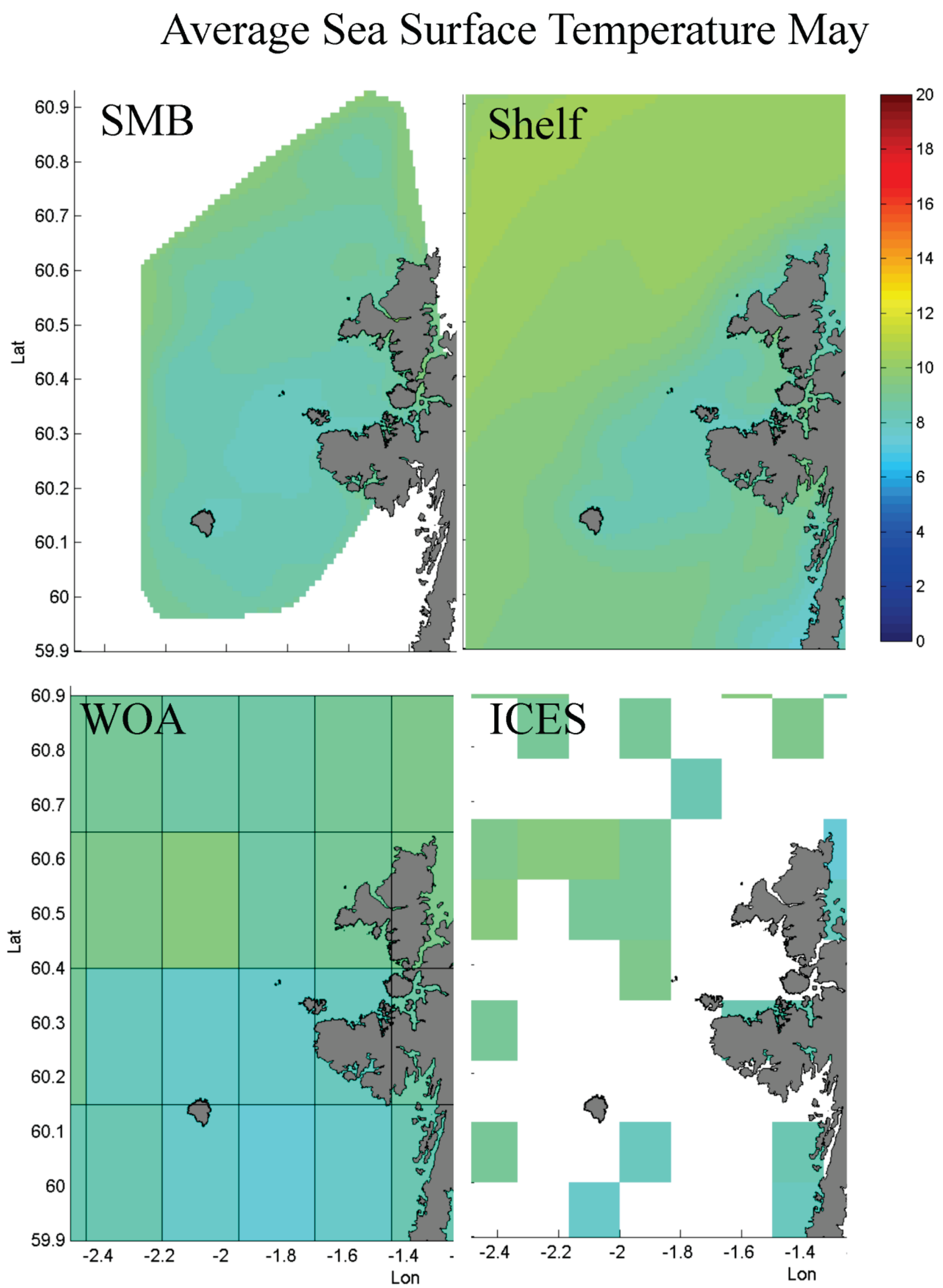
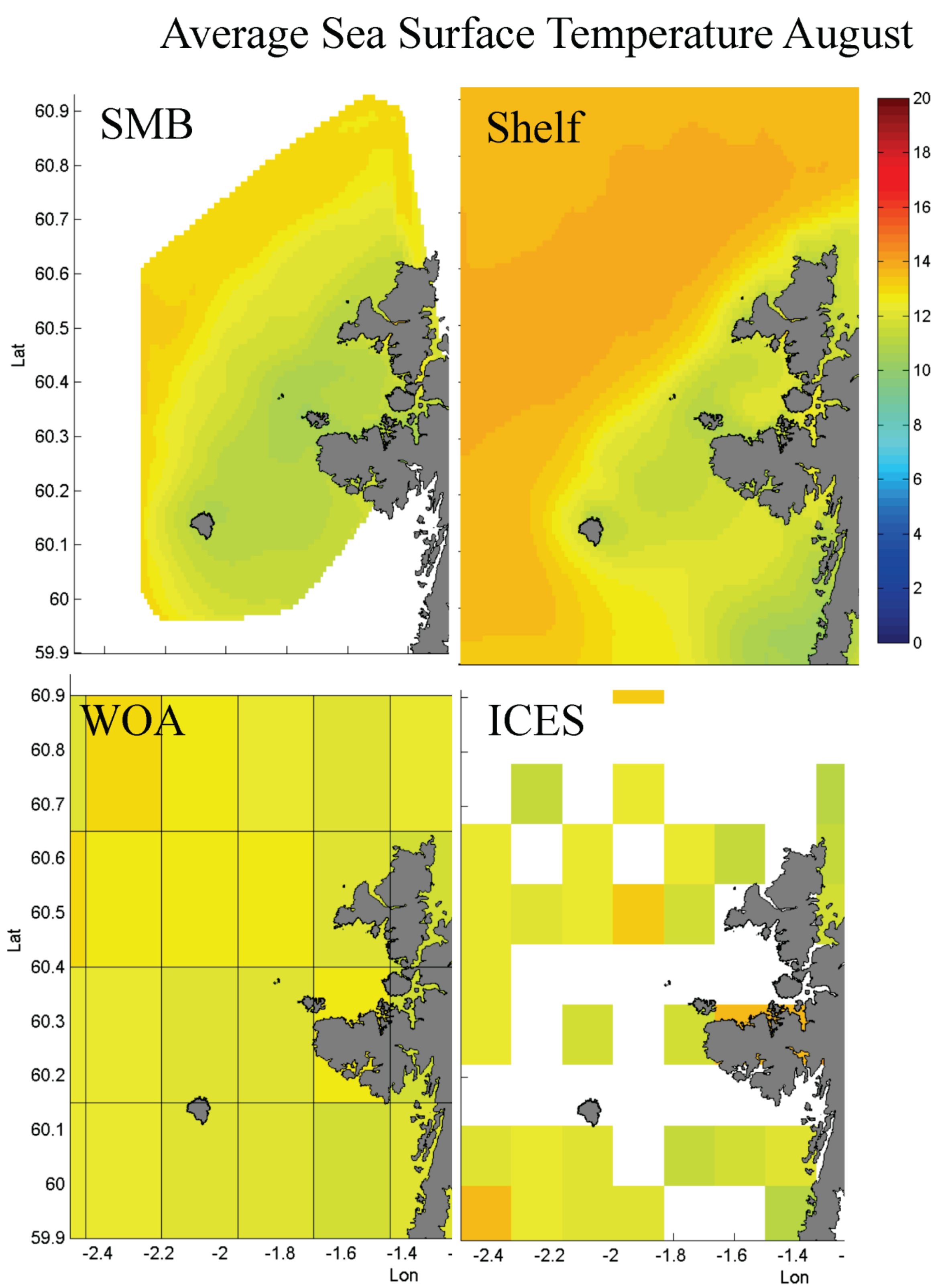
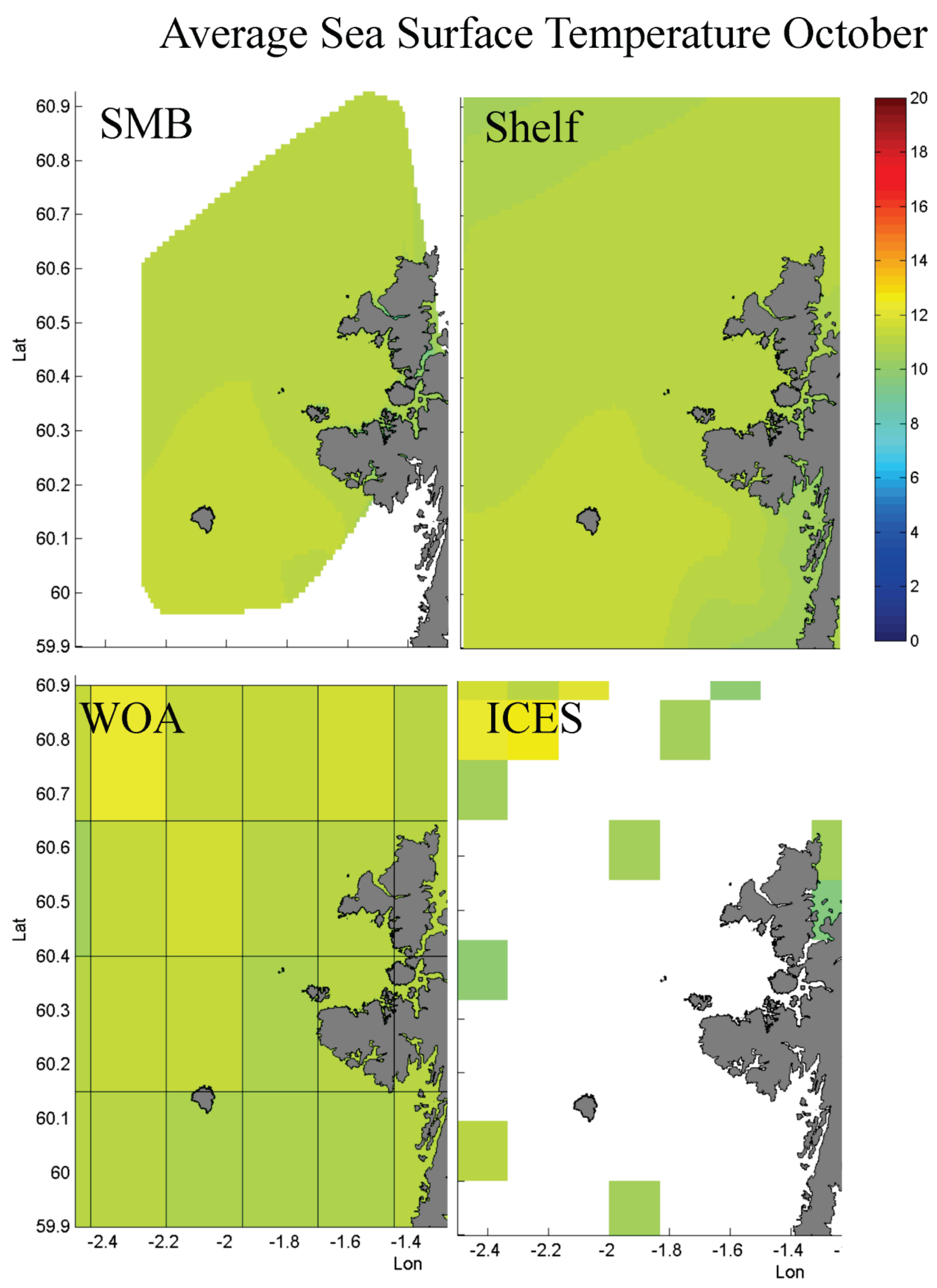


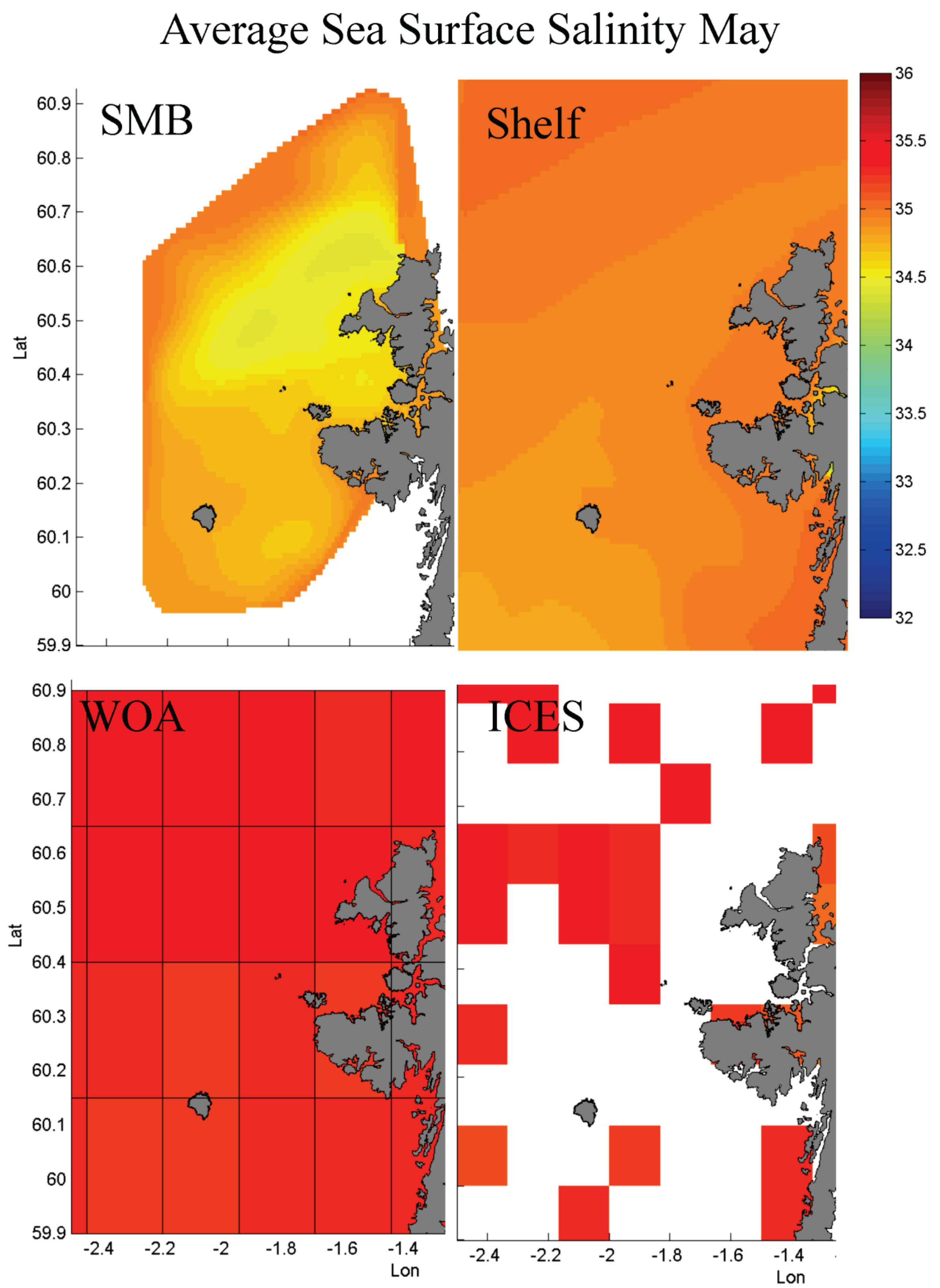

| Client | Consulting Engineer | Project: | **Figure 3-10a** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of sea surface temperatures averaged for May from the SMB climatology run, the shelf model, WOA and ICES data |



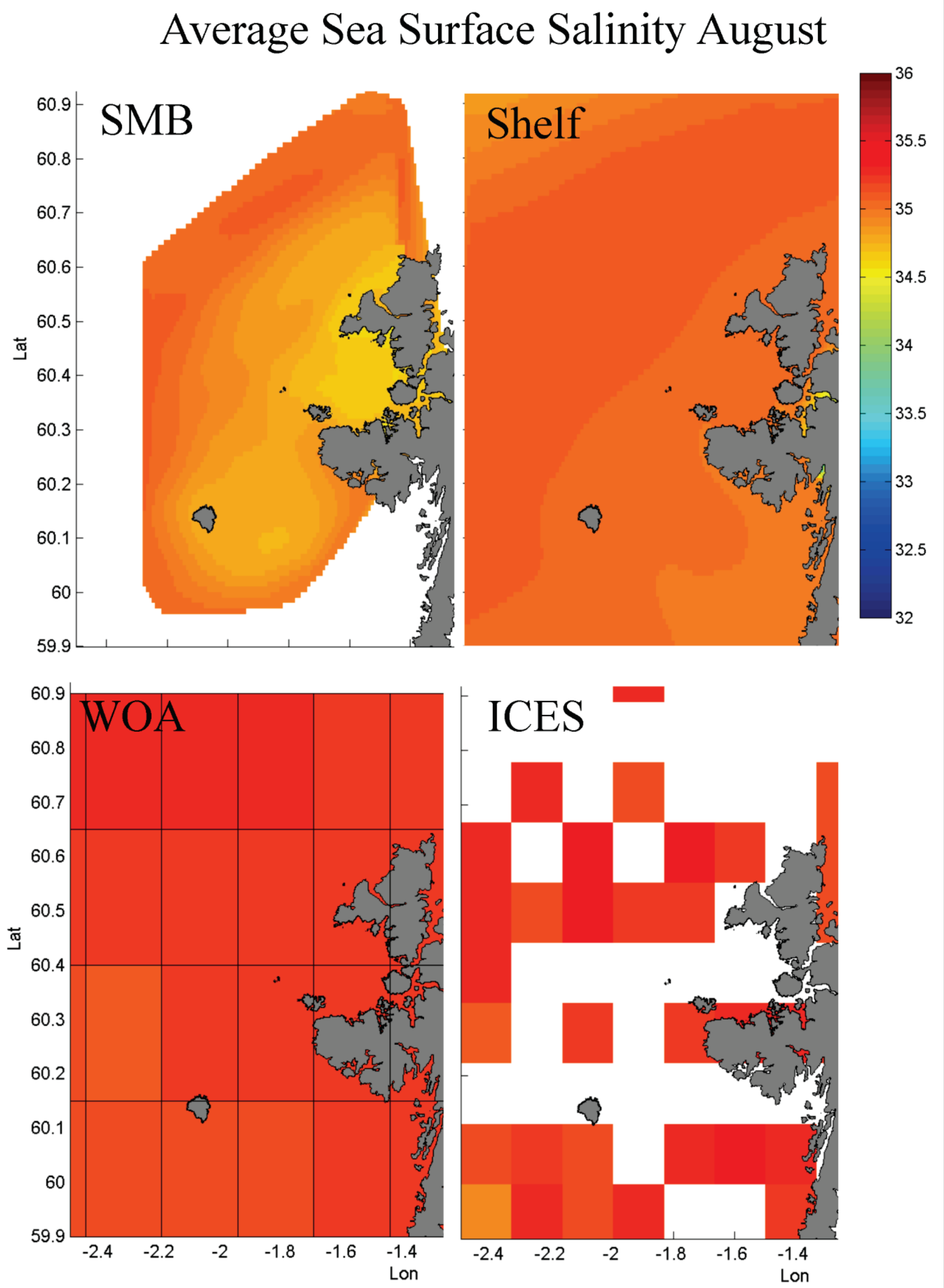

| Client | Consulting Engineer | Project: | Figure 3-10b |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of sea surface temperatures averaged for August from the SMB climatology run, the shelf model, WOA and ICES data |



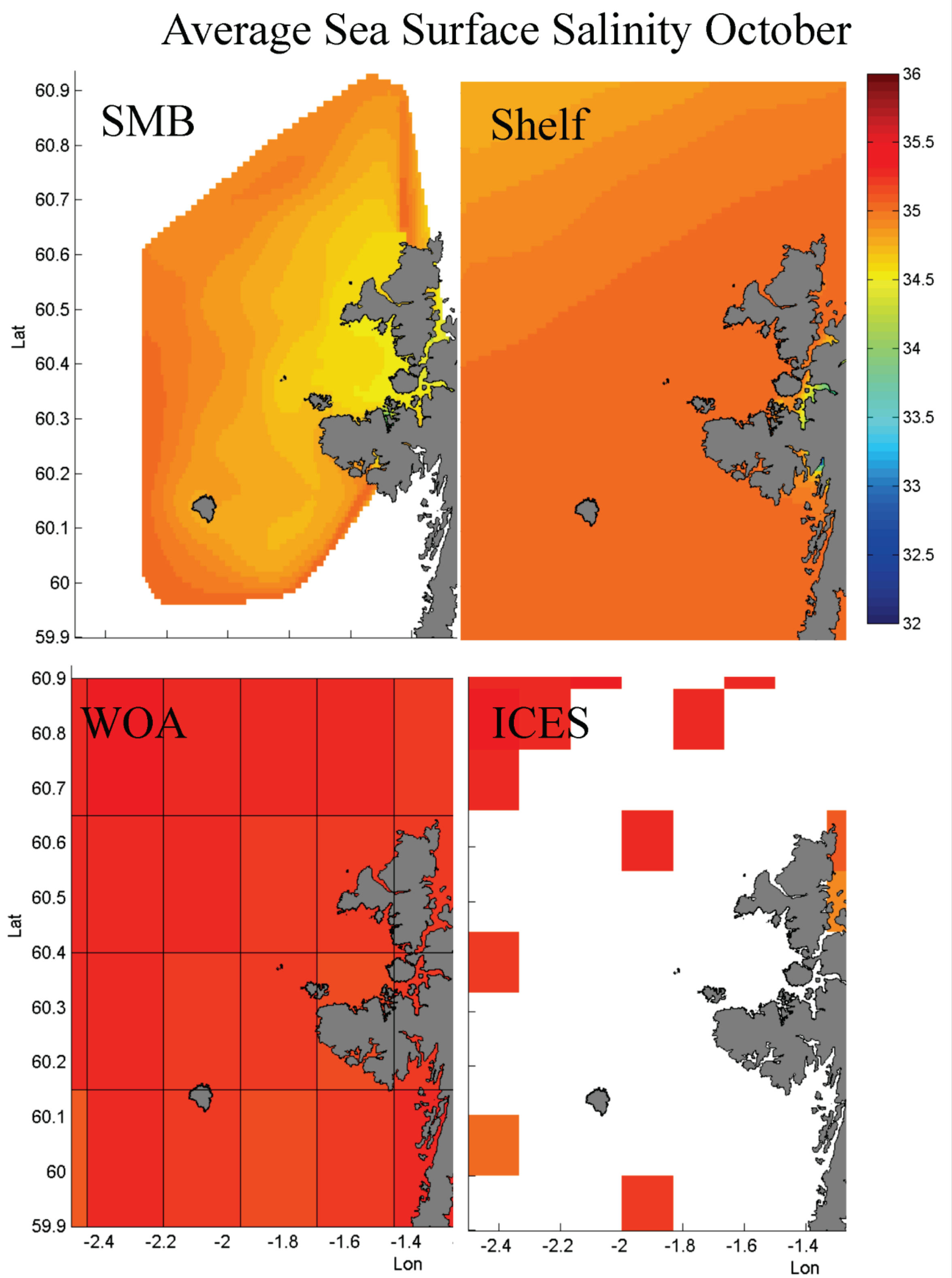

| Client | Consulting Engineer | Project: | **Figure 3-10c** |
|---|---|---|---|
| Marine Scotland | | St Magnus Bay Model | Comparison of sea surface temperatures averaged for October from the SMB climatology run, the shelf model, WOA & ICES data |




| Client | Consulting Engineer | Project: | **Figure 3-11a** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of sea surface salinity averaged for May from the SMB climatology run, the shelf model, WOA and ICES data |




| Client | Consulting Engineer | Project: | **Figure 3-11b** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of sea surface salinity averaged for August from the SMB climatology run, the shelf model, WOA and ICES data |




| Client | Consulting Engineer | Project: | **Figure 3-11c** |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of sea surface salinity averaged for October from the SMB climatology run, the shelf model, WOA and ICES data |

#### 3.6.3.2 Mean Spring/Neap Tidal Range

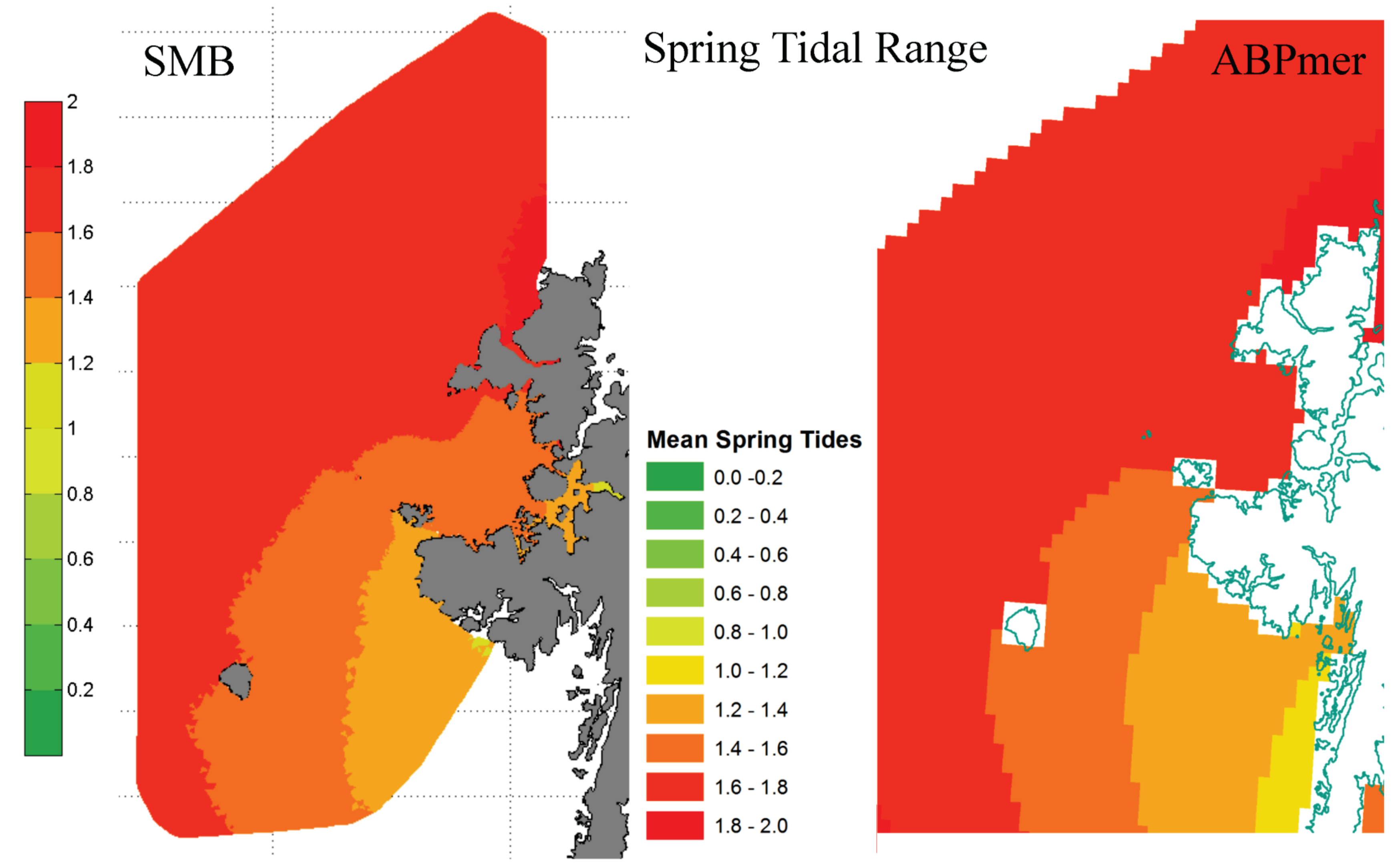
Mean spring tidal ranges have been computed directly from the two principal semi-diurnal components $M_2$ and $S_2$ based on the following equations from Pugh (1987):

*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*

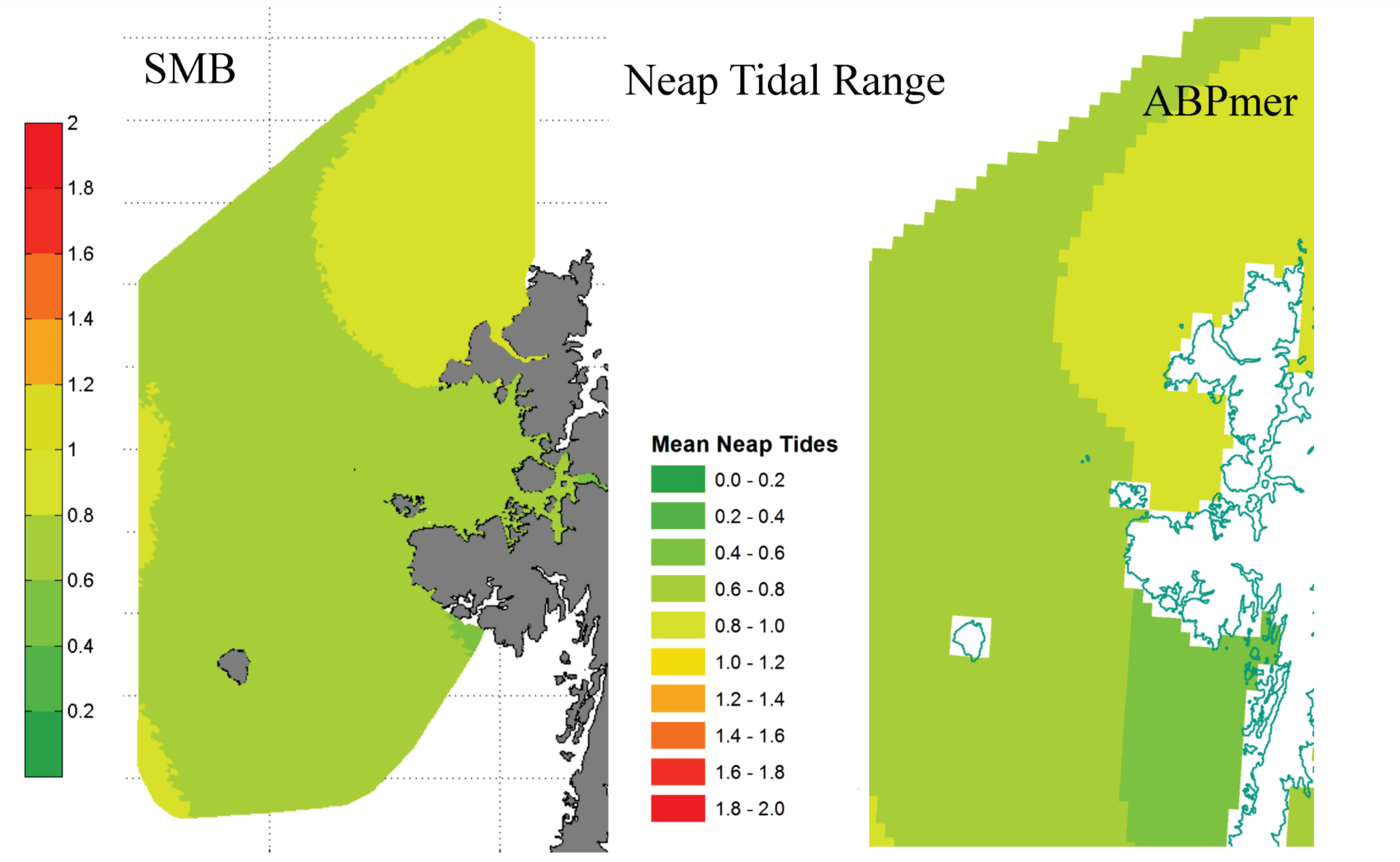
Values for these constituents were obtained from a harmonic analysis of 60 days' worth of data from the SMB climatology run (30/06 – 28/08). These harmonic components control the timing of the spring-neap cycle, and their combination is considered to give a good measure of average spring (and neap) tides. 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 3-12a. The corresponding plots for mean neap tidal range are shown in Figure 3-12b. The figures show good agreement between the SMB results and the ABPmer Atlas for both spring and neap tidal ranges.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-12a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay 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 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-12b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | St Magnus Bay 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 14/112012 |

#### 3.6.3.3 Mean Spring/Neap Currents

Mean peak current speeds have been calculated from a harmonic analysis of 60 days (30/06 – 28/08) of depth averaged tidal velocities, from the SBM climatology run. In line with the methodology used for the ABPmer / NOC Atlas, a mid-depth velocity was used for the calculations. The east and west components of velocity were analysed using T_TIDE to give the $M_2$ and $S_2$ amplitudes and phases. These were in turn analysed to give the semi-major axis amplitudes for each ellipse. The mean peak spring current was then computed as:

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

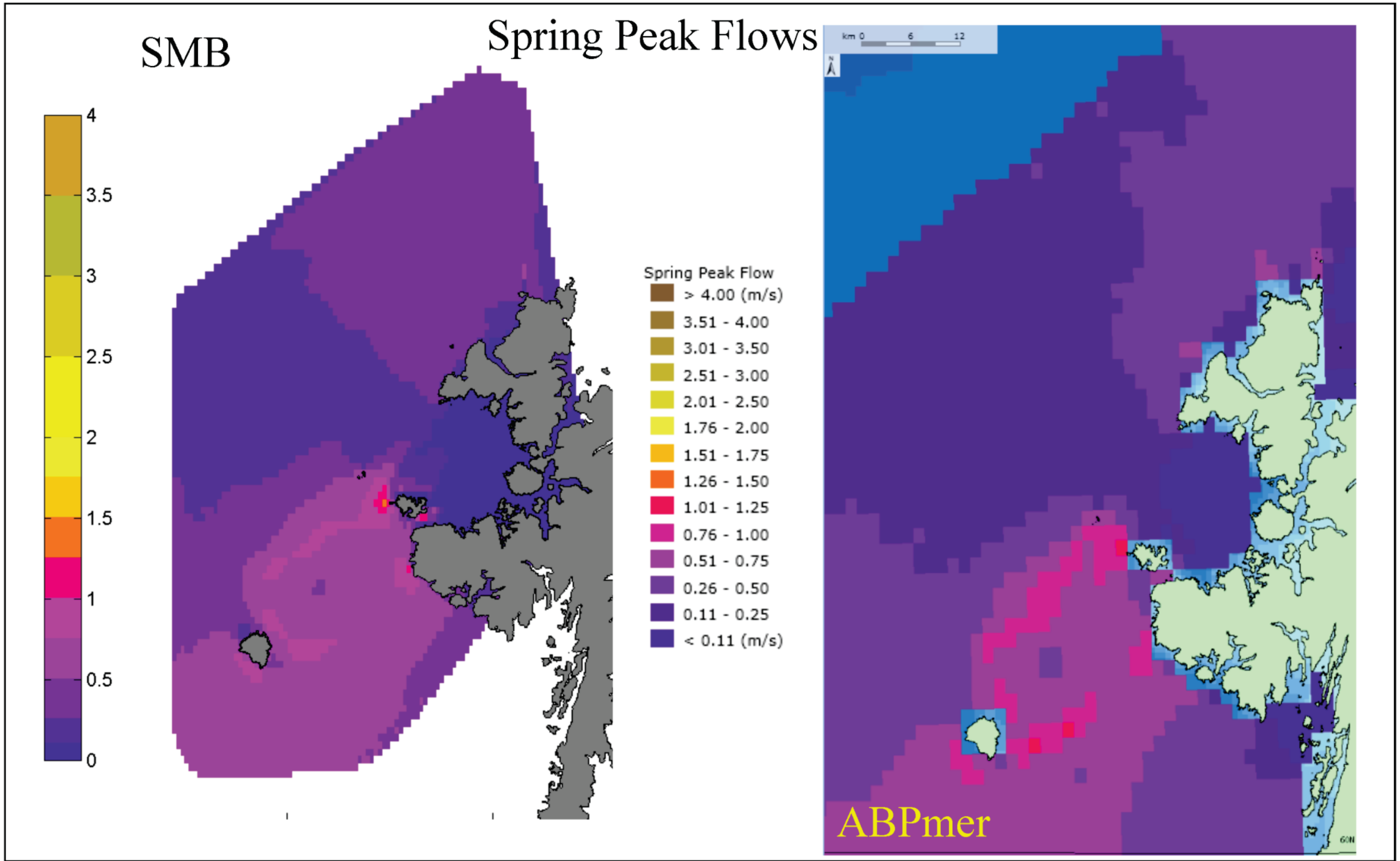
The mean neap spring current was computed as:

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

A map of the results for mean spring current is shown, along with the equivalent peak currents from the ABPmer / NOC Atlas of Marine Energy Resources, in Figure 3-13a. Corresponding plots for the mean neap current are shown in Figure 3-13b. Despite the difference in the resolution between the SMB model and ABPmer tidal atlas the results show good agreement in terms of magnitude and spatial patterns for both the spring and neap peak tidal currents.

#### 3.6.3.4 Residual Currents

Data regarding the residual currents around St Magnus Bay is not available at a suitable resolution to make comparisons with the SMB model results. Figure 3-14 shows the Canonical circulation on the NW European shelf from OSPAR (2000). It shows that the dominant feature in the vicinity of SMB is the northeast flow of Atlantic water to the west of Shetland. Comparison of the residual current from the shelf model with the SMB model for May, August and September are shown in Figure 3-15. The general pattern spatial and temporal variation in the residual current seen in the shelf model are replicated in the SMB model. Residual flows to the northeast, outside of the bay and clockwise circulation of residuals around Foula. However the residual speeds are consistently higher in the SMB model.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay 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 |
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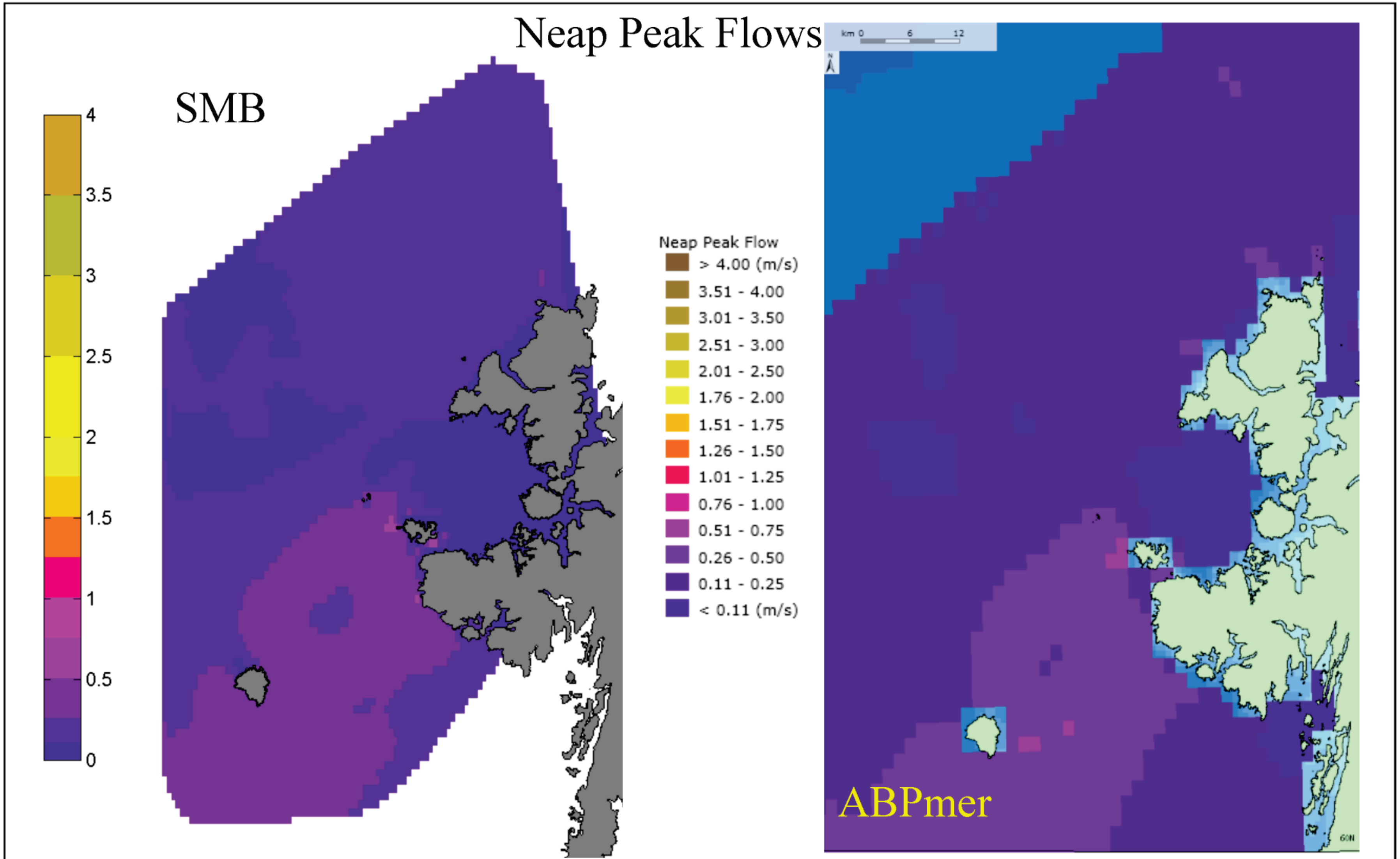
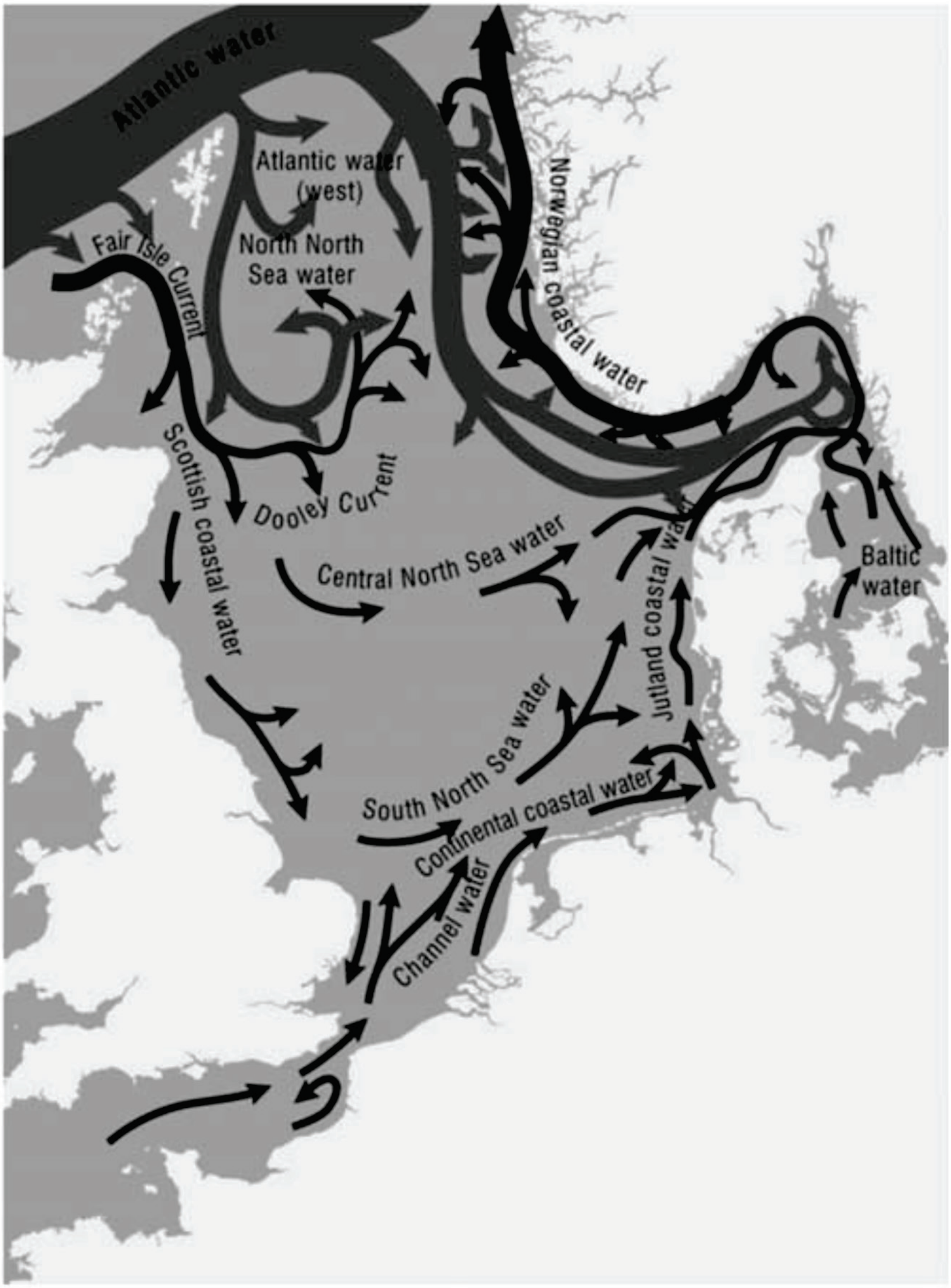
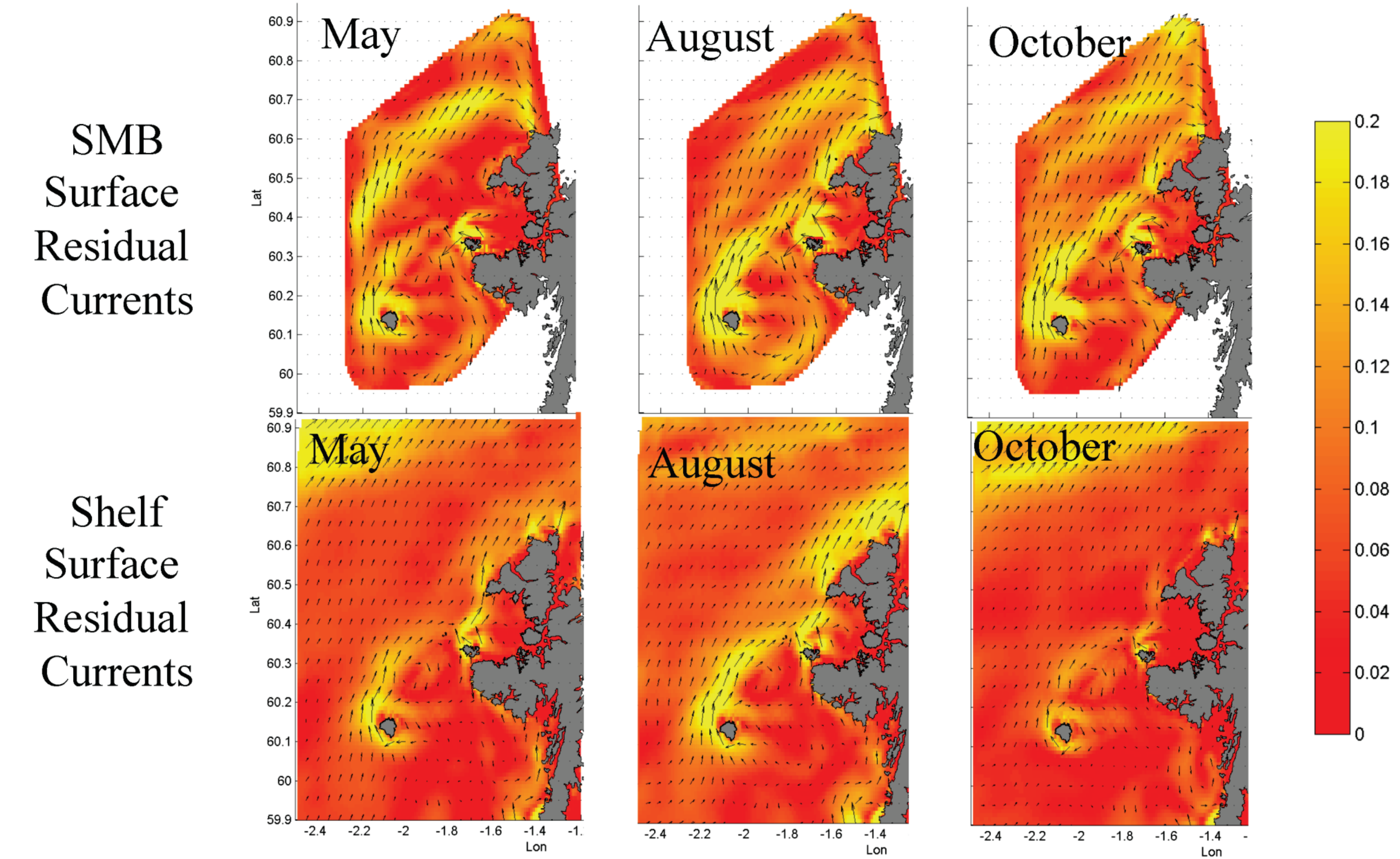



| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison of Mean Neap Peak Currents calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure 3-14 |
|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Canonical circulation on NW European shelf (from OSPAR 2000) |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Monthly average sea surface residual currents from May to October from the SMB model | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: | Drawn: | Date: 14/112012 |

### 3.6.1 Seasonal Variations

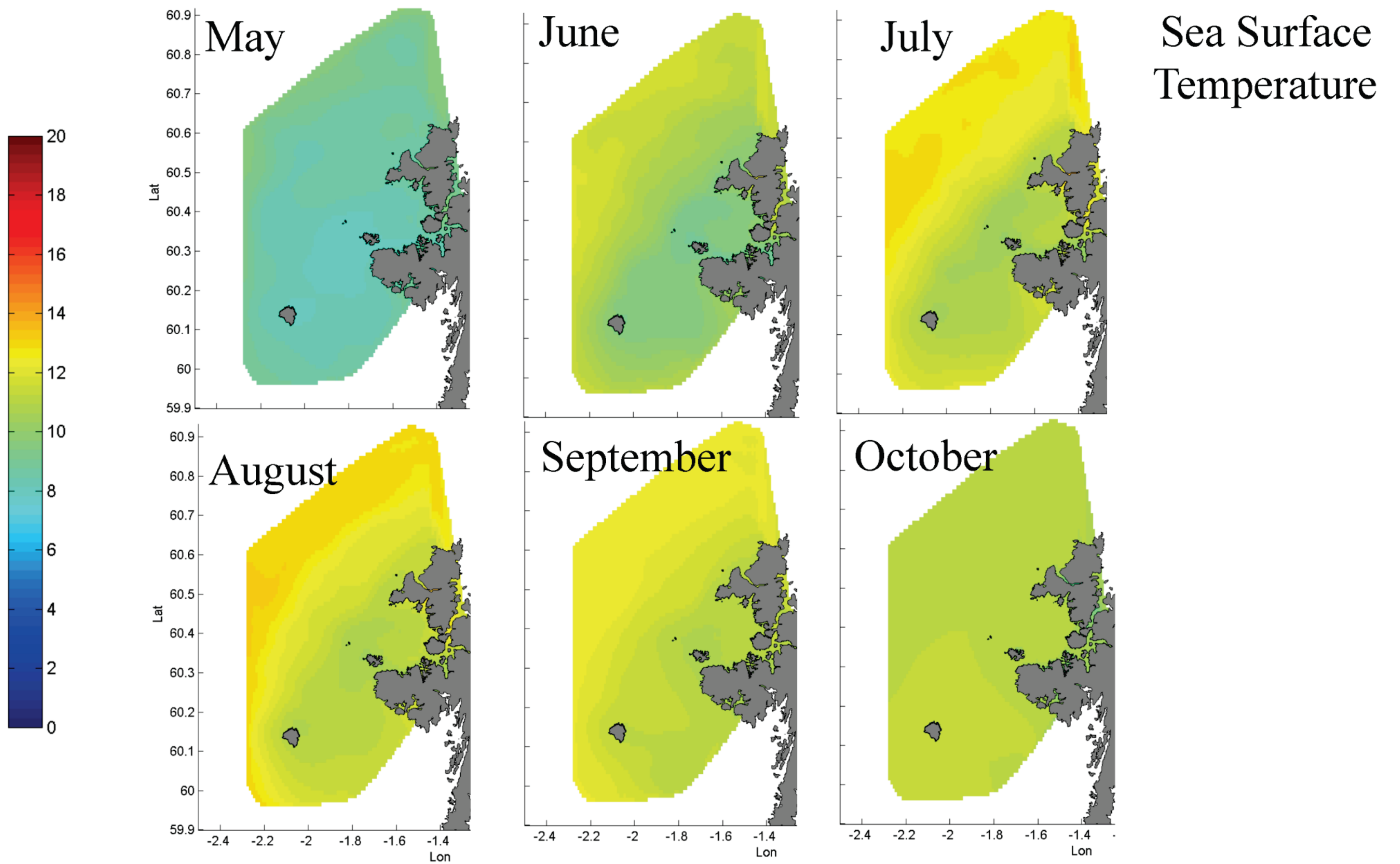
Seasonal variations in sea surface temperature, salinity and residual currents are shown in Figure 3-16 to 3-18. The SST is at its lowest in May approximately 9°C, at this time the SST is also uniform across the model domain. The increase in temperature during the summer moves in from the boundary of the model. Temperature reaches a maximum of around 14°C in August off shore of the Bay. The temperature reduces through September with temperatures becoming uniform again in October.

The SSS shows spatial variations from May to October with lower salinity water closer to land during all months. Overall SSS is highest in July and August and lowest in May and October (Figure 3-17). The seasonal variation are not very strong, this may be due to the low input of fresh water from rivers. The fresh water input into St Magnus Bay is low therefore variations in temperature and salinity are likely to be controlled by the temperature and salinity of the Atlantic Waters and the current patterns in the vicinity of the Bay.

The location of residual current flows show little seasonal variation, the main features being a northeast flow to the north of the Bay and a clockwise circulation around the Island Foula, extending to the west coast of Shetland. However the strength of the currents do vary. Residual currents are at their weakest in May increasing to a maximum in July and reducing again toward October (Figure 3-18).

### 3.6.2 Summary

Model runs have been carried out to reproduce the hydrodynamic conditions in St Magnus Bay corresponding to the climatology during the period May to October. The input data used was taken from the Shelf Model for boundary conditions, CEH G2G data for rivers and ECMWF averaged data for the meteorological forcing. The model was run for six months, the results have been compared with sea surface temperature and salinity climatological data sets and residual currents for the months of May, August and October. These results compared well with the available data. Only weak seasonal variations in sea surface temperature, salinity and residuals were observed.

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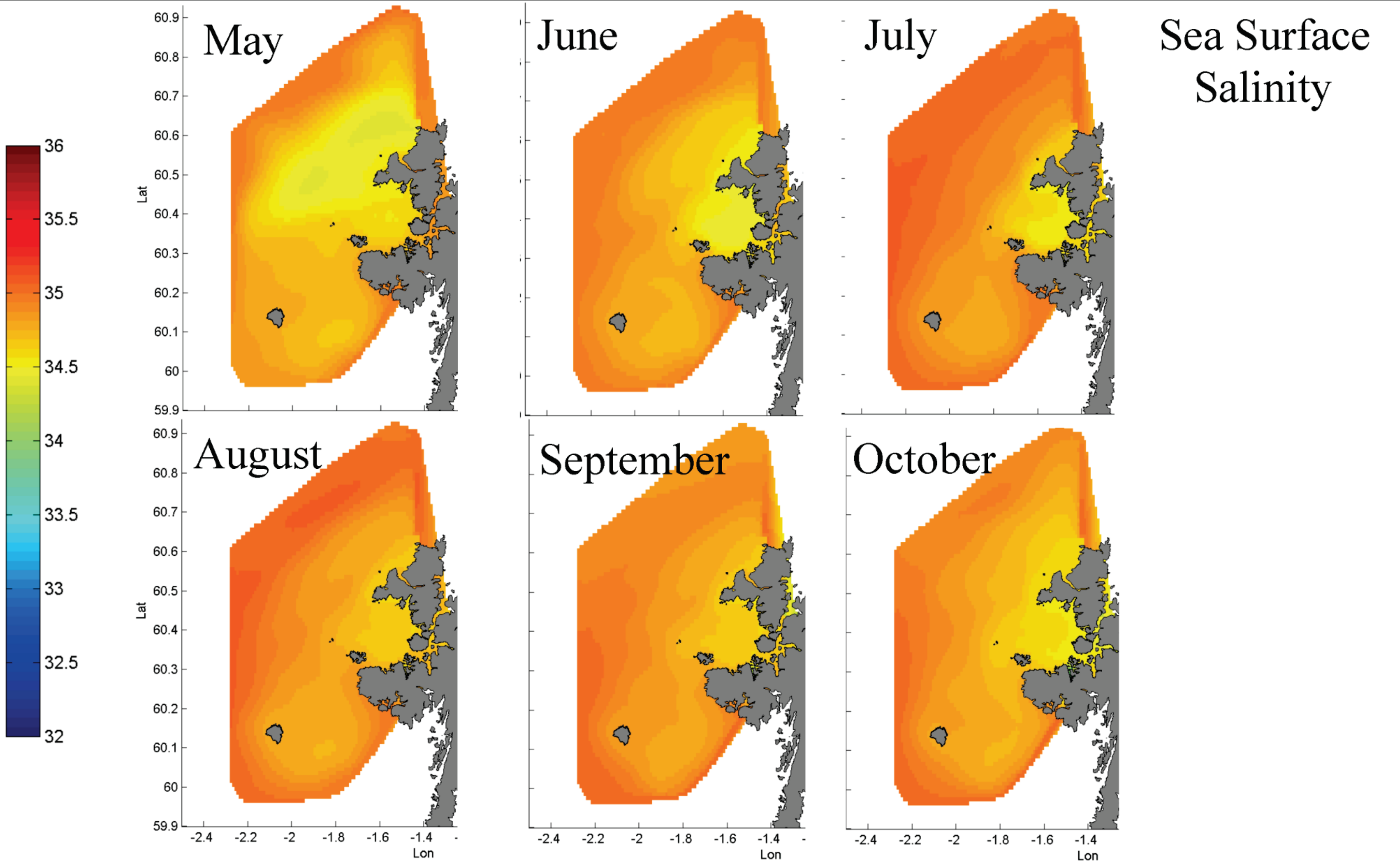


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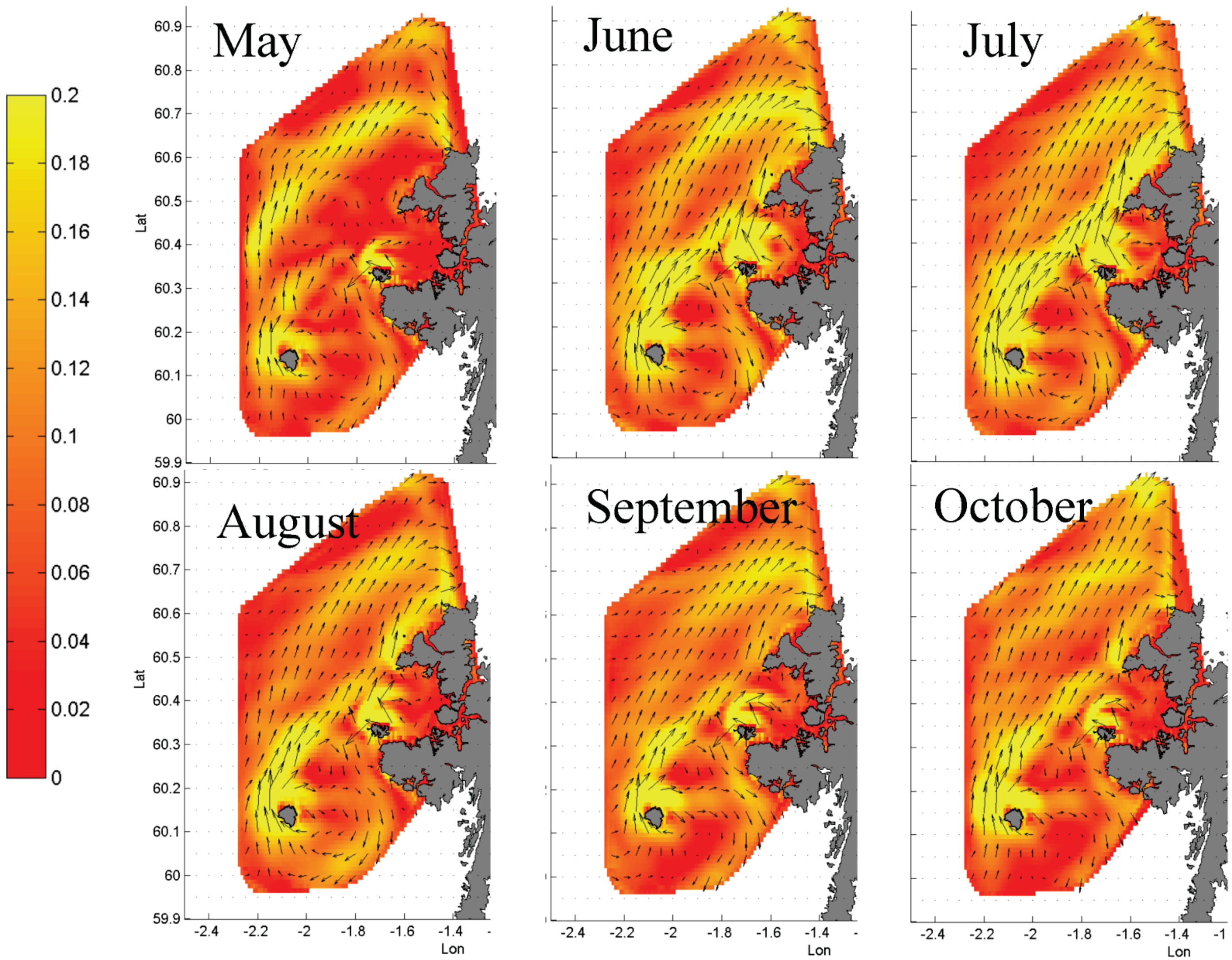


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| Marine Scotland | ch2m | St Magnus Bay Model | Monthly average sea surface residual currents from May to October from the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
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# 4 Summary and Conclusions

A 3D hydrodynamic model for the St Magnus Bay (SMB) area has been developed and calibrated against measured data for the periods of October 2012, May 2009 and October 2001. The calibration runs were driven by boundary conditions taken from the Pentland Firth and Orkney Waters (PFOW) model, whose boundary condition in turn came from the AMM model. Met forcing was provided by the Met Office and fluvial inputs came from CEH.

The calibration results were compared with measured data from a number of sources. Comparison of water levels, current speed and direction, temperature and salinity were made showing the model has been calibrated adequately. Generally current speeds are low within the bay and sensitivity test during model calibration highlighted the importance of wind, which has an equal influence on current speeds as the tides.

The six month long climatology run (May to October) was driven by boundary conditions from the Shelf Model, fluvial data from CEH G2G and meteorological forcings were from averaging of ECMWF data. Results have been compared with sea surface temperature and salinity climatological data sets and residual currents for the months of May, August and October. These results compared well with the available data. Only weak seasonal variations in sea surface temperature, salinity and residuals were observed over the six months.

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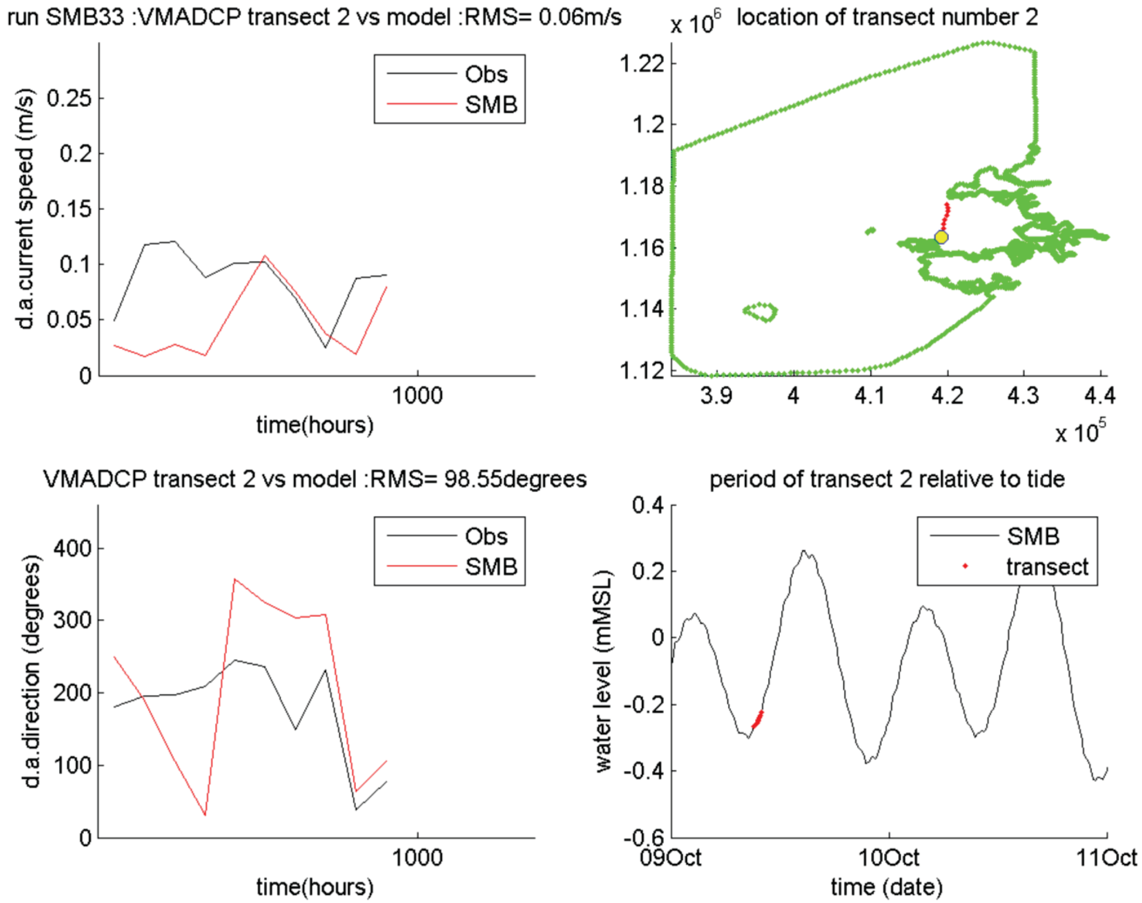
# Appendix A

Transect comparisons

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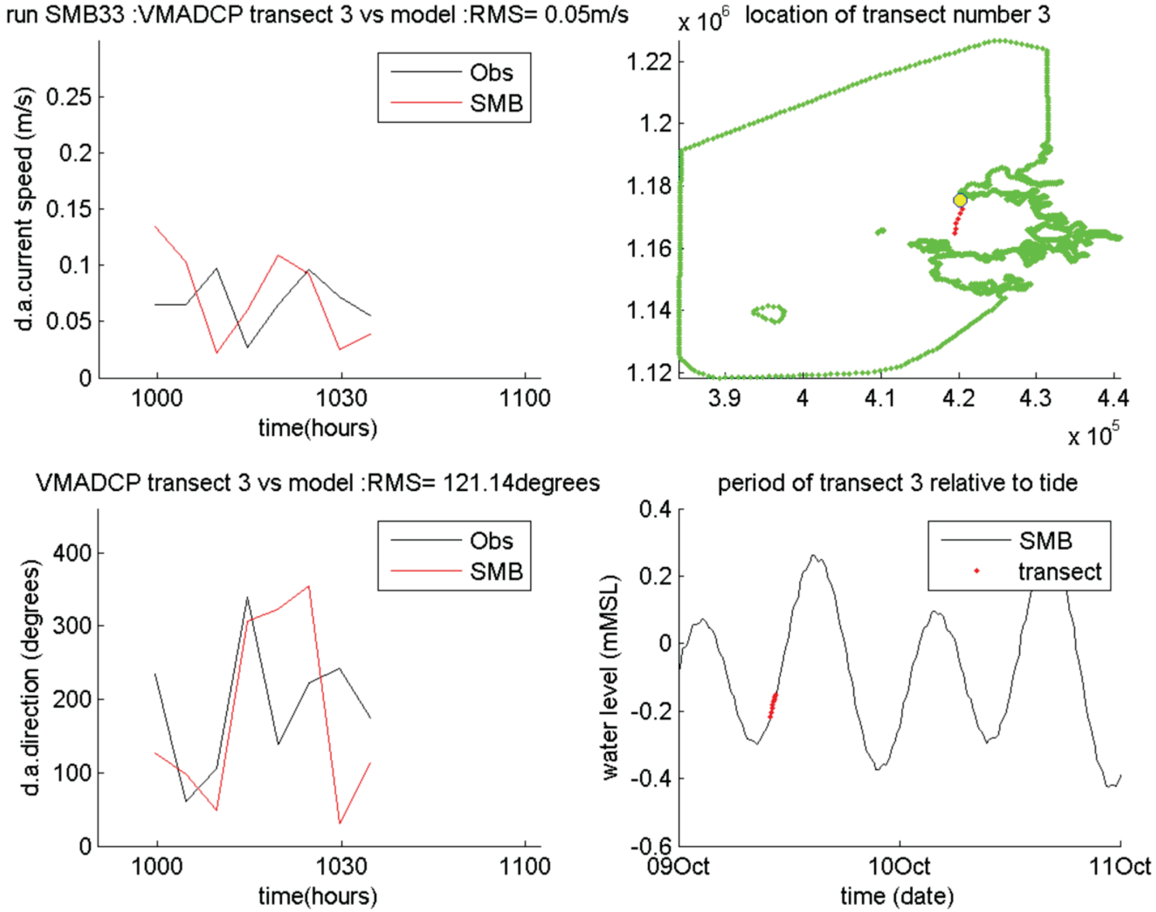


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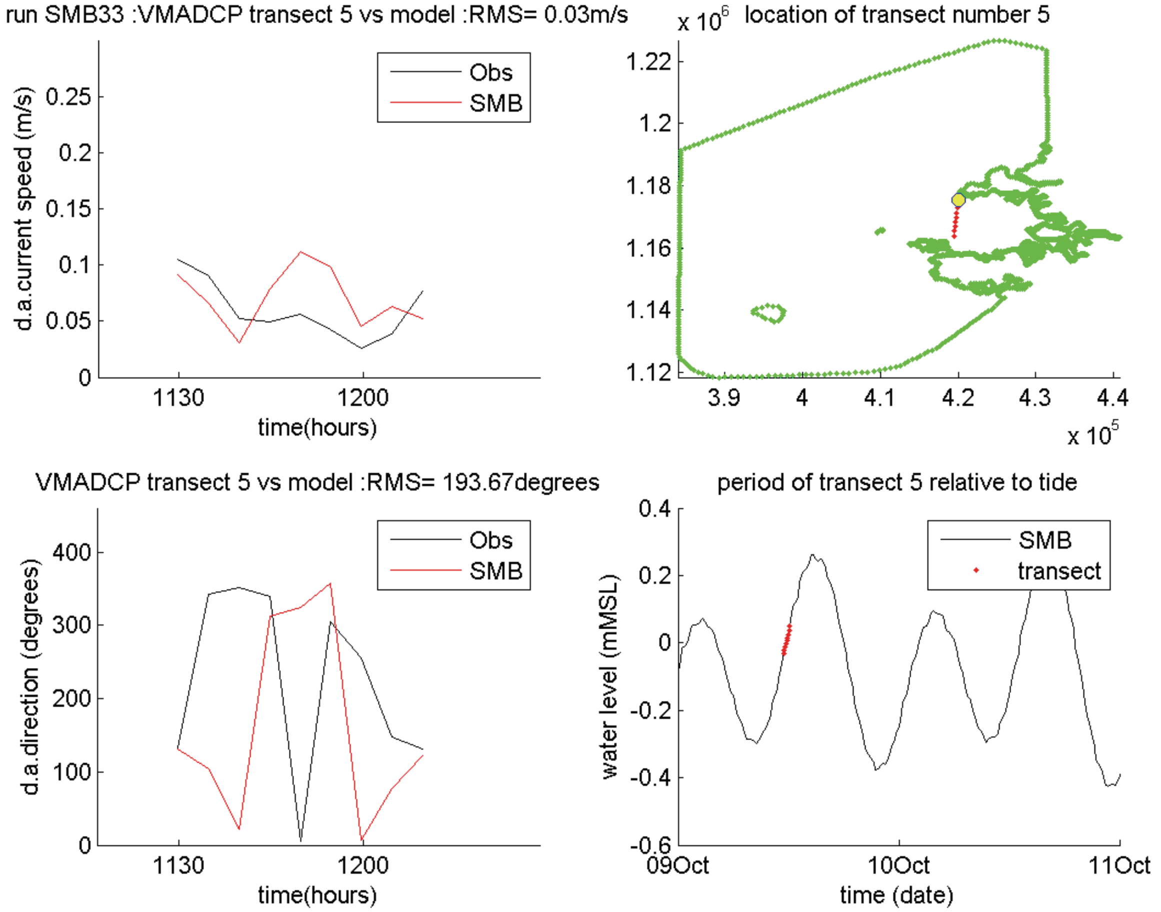


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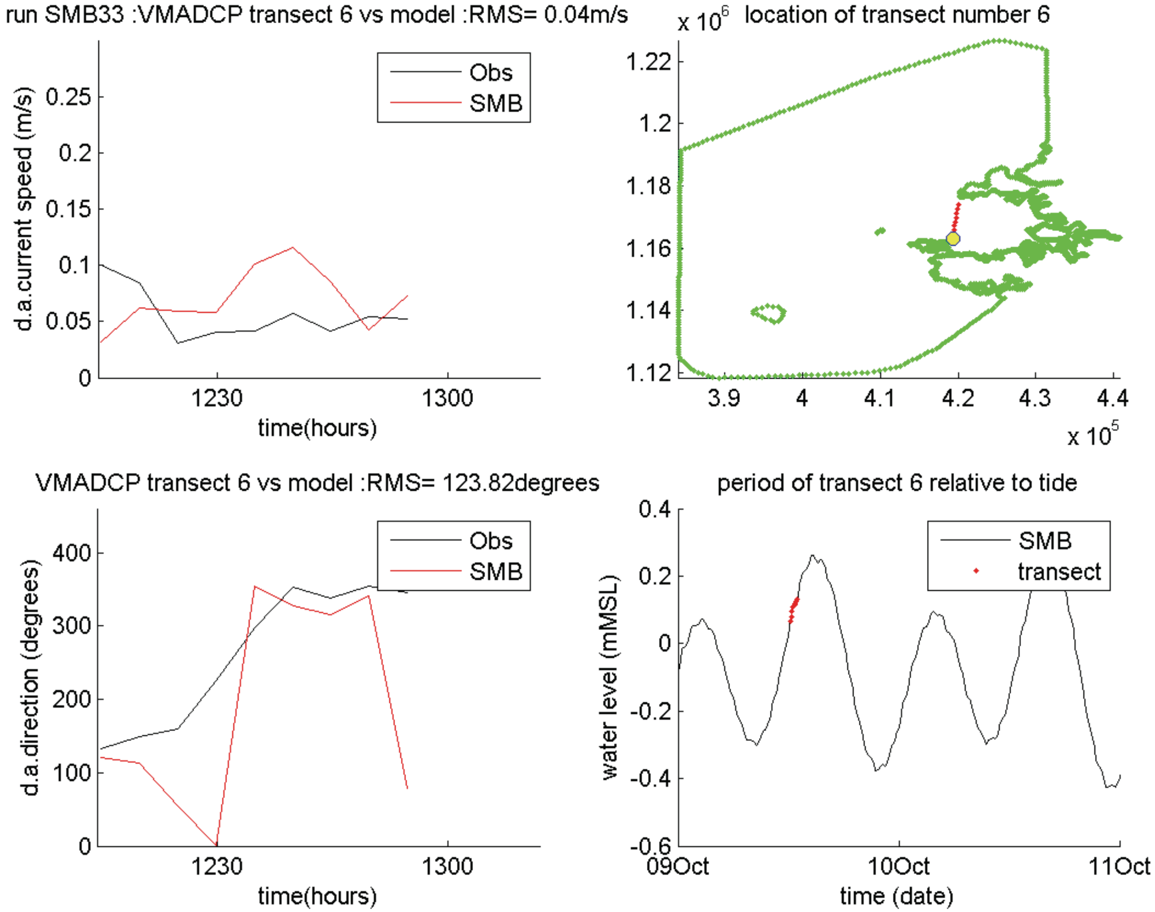


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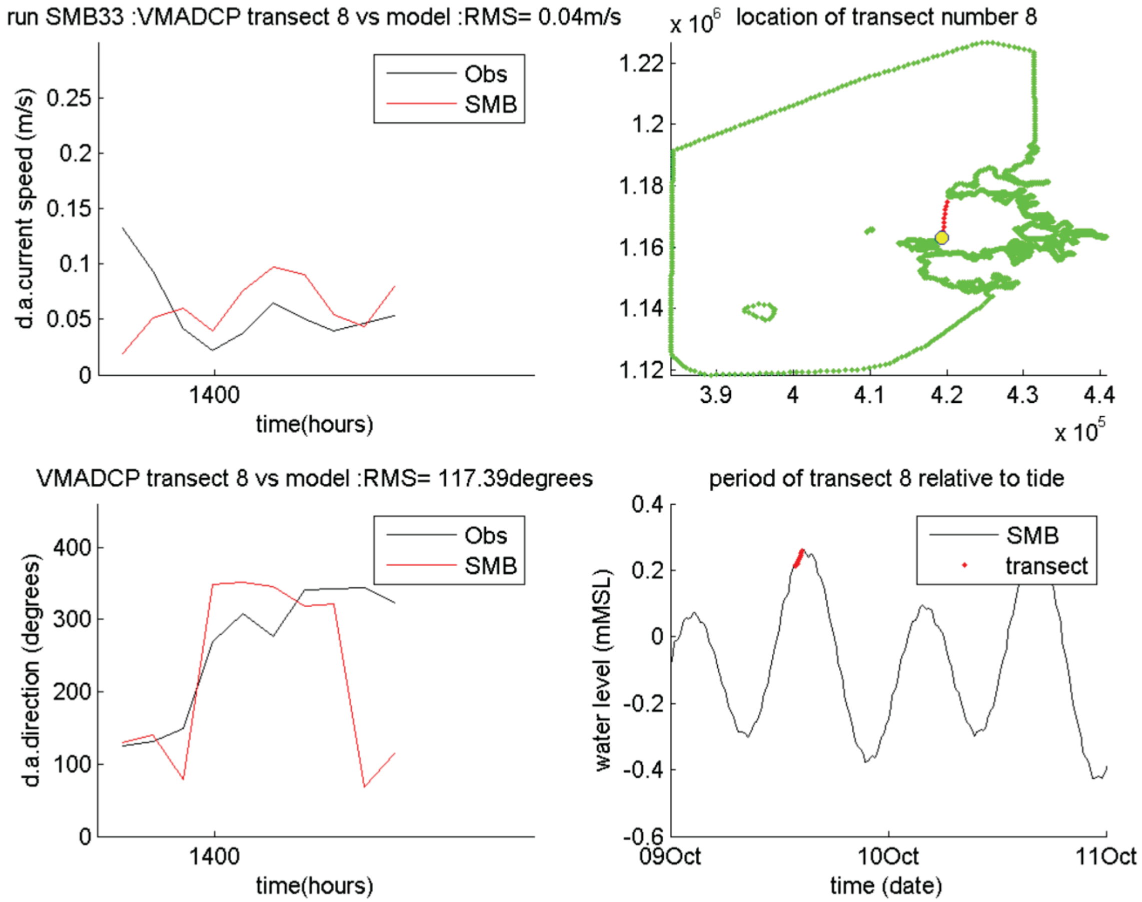


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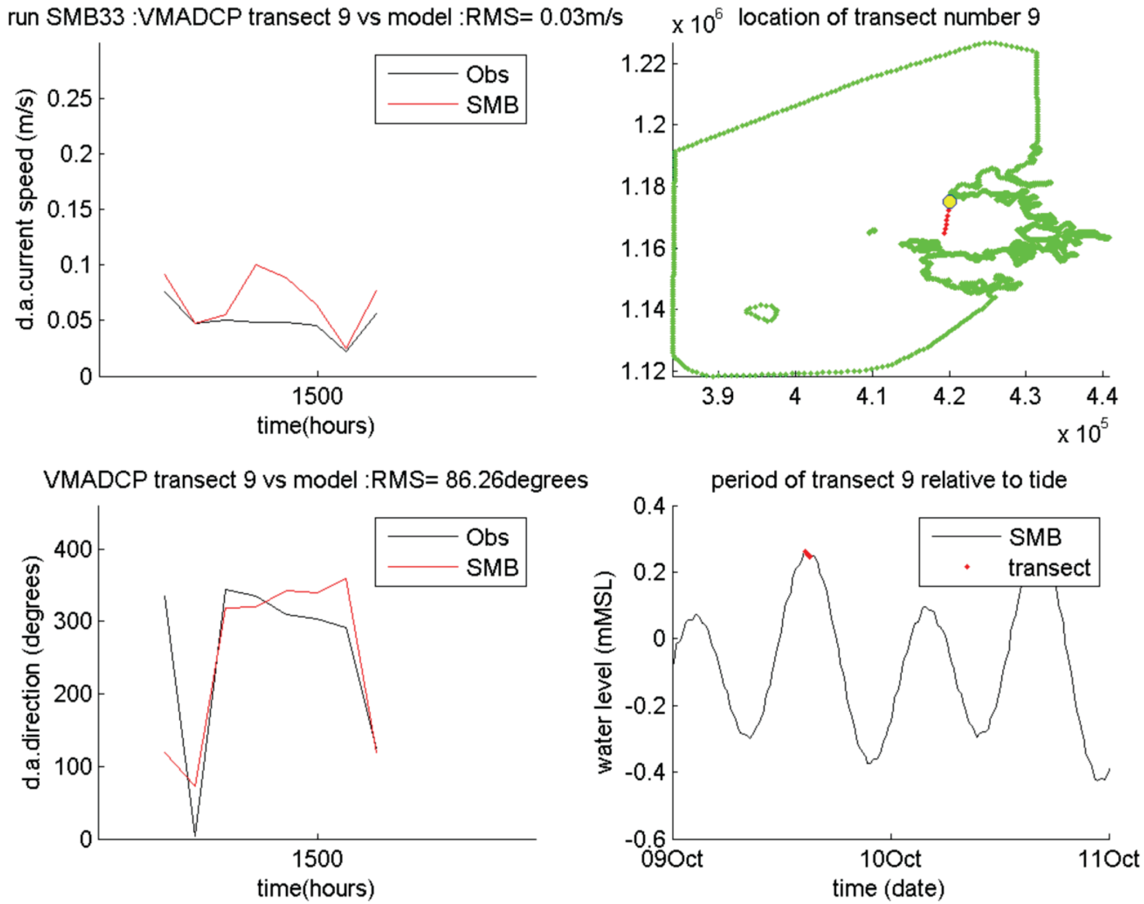


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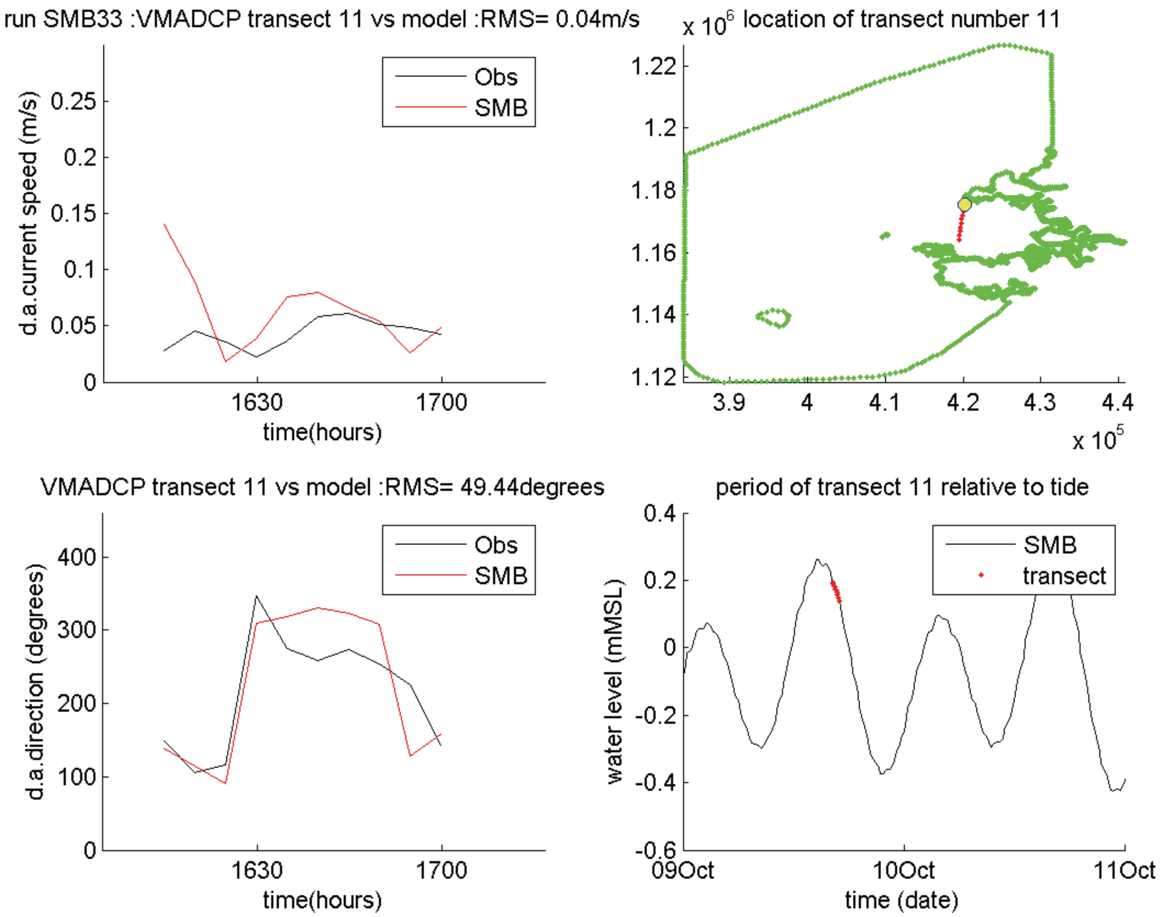


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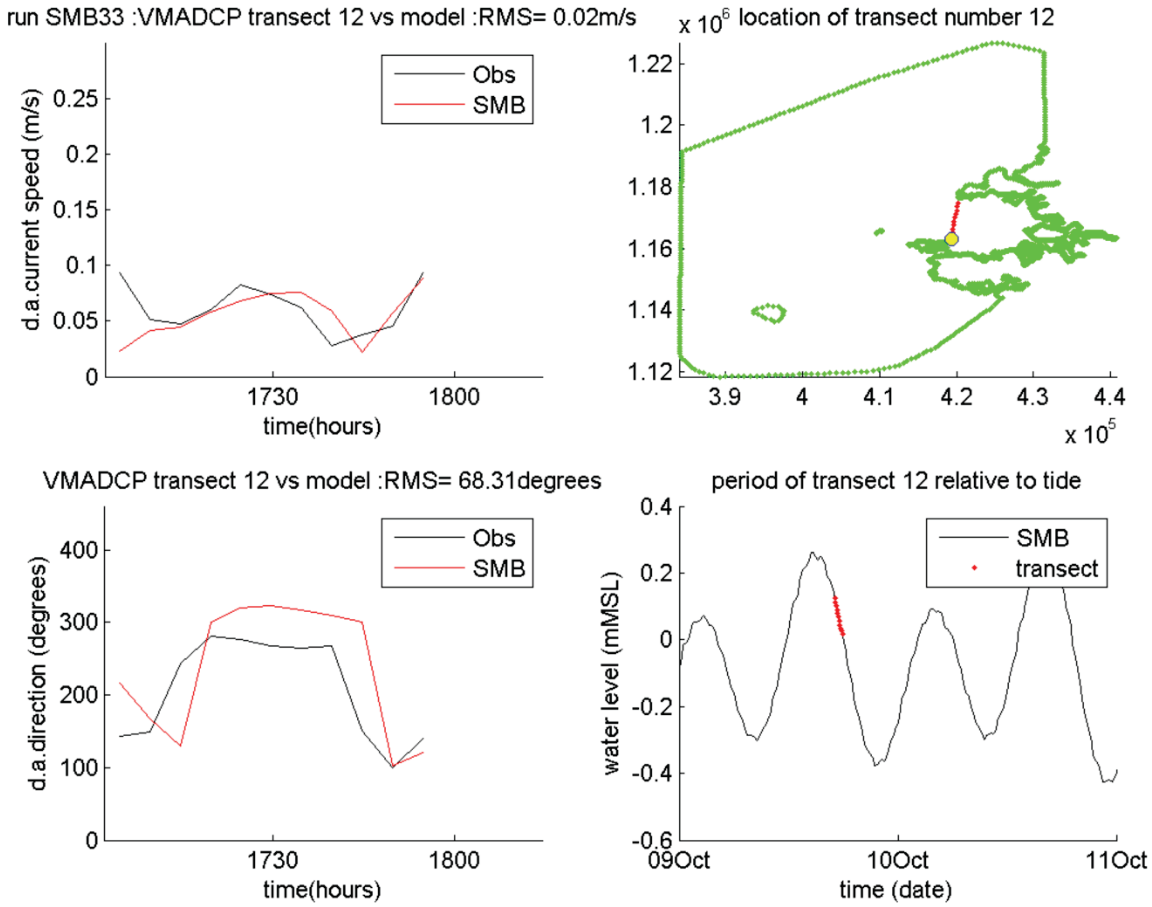


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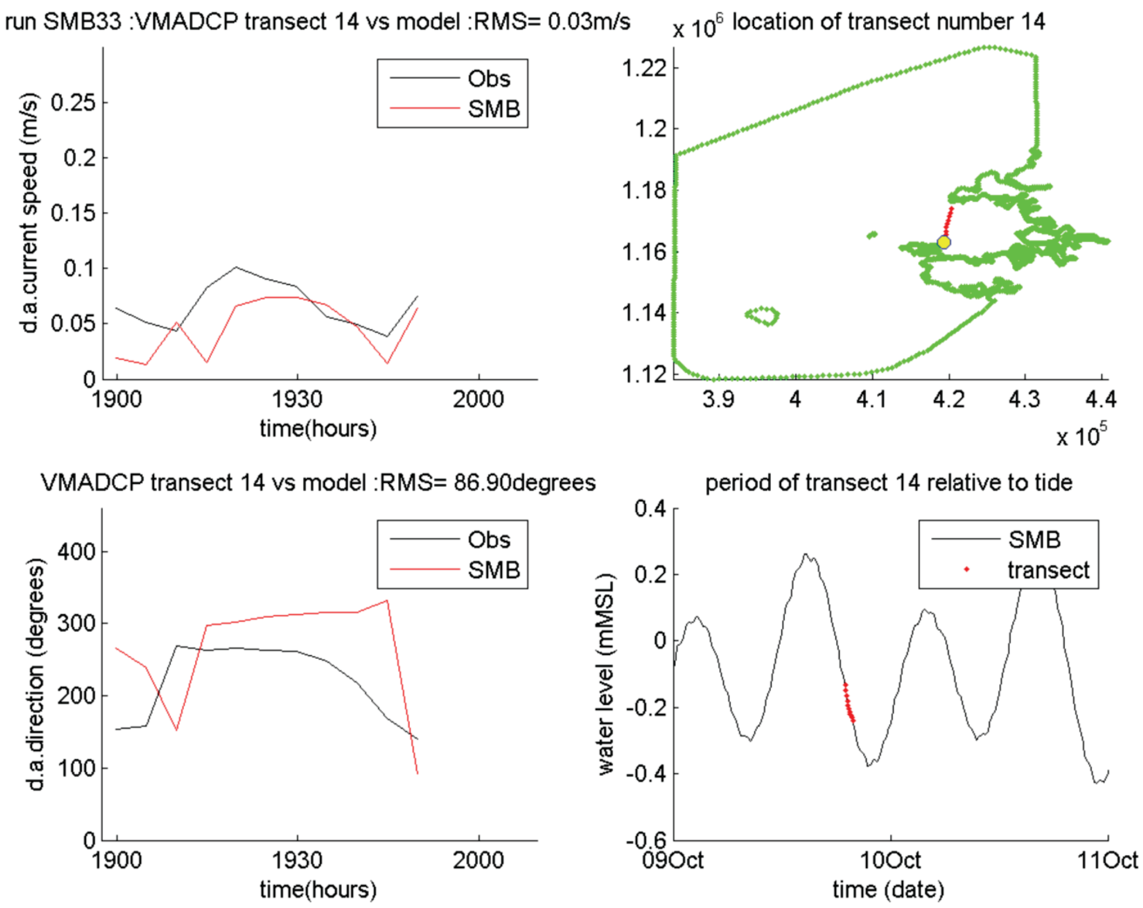


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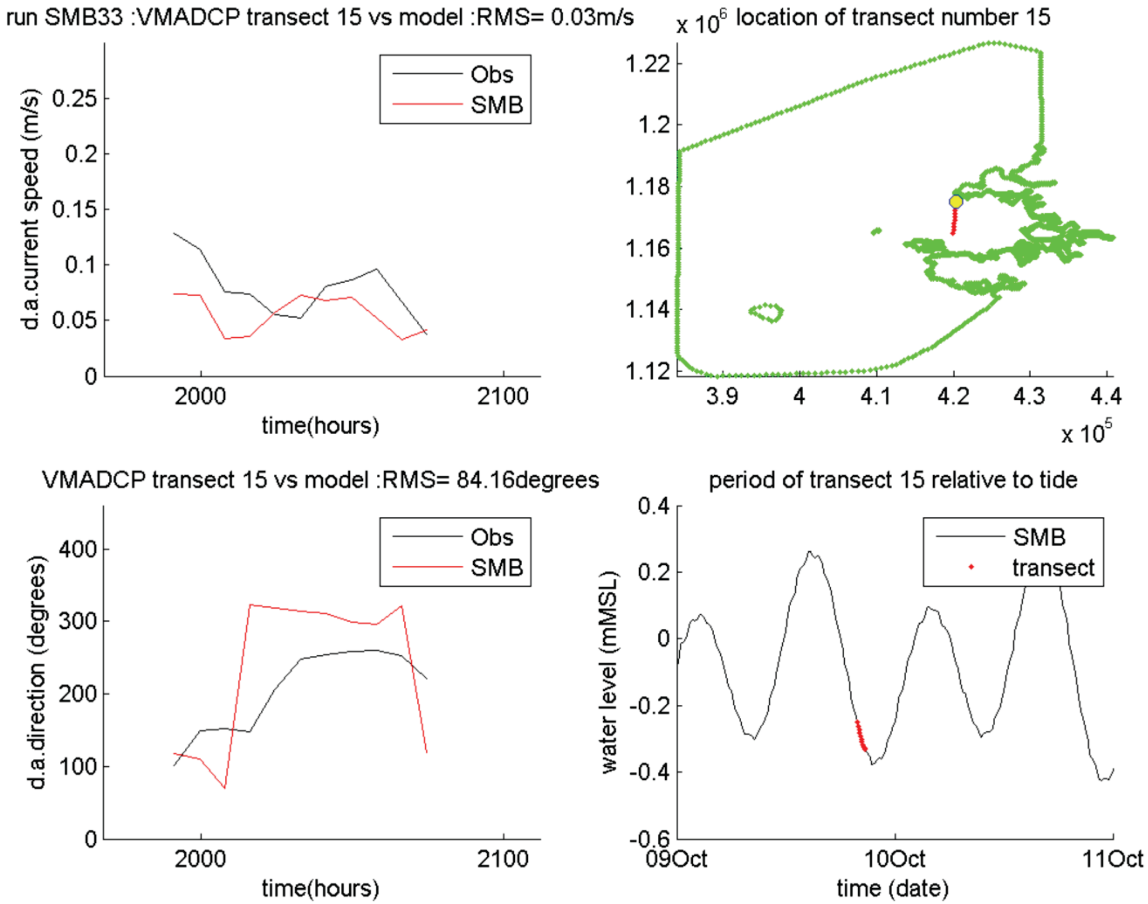


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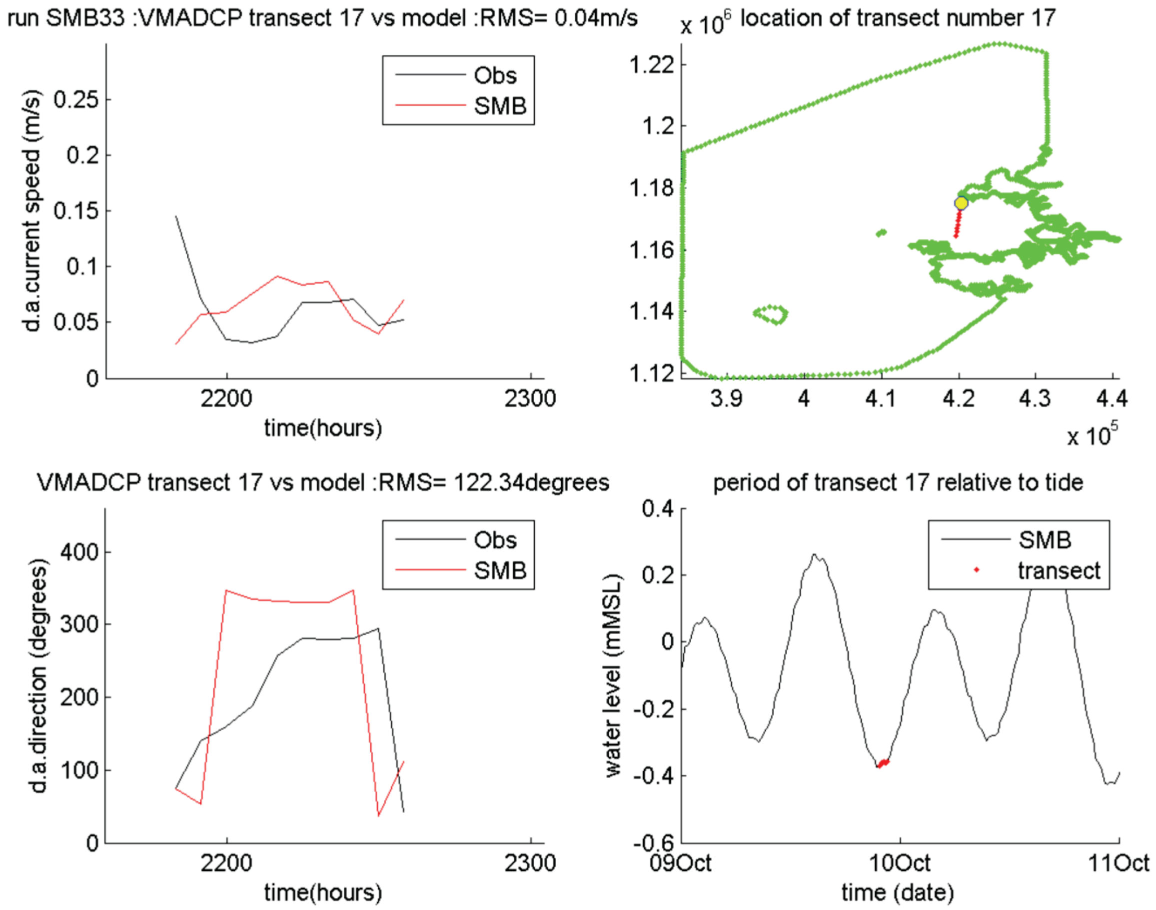


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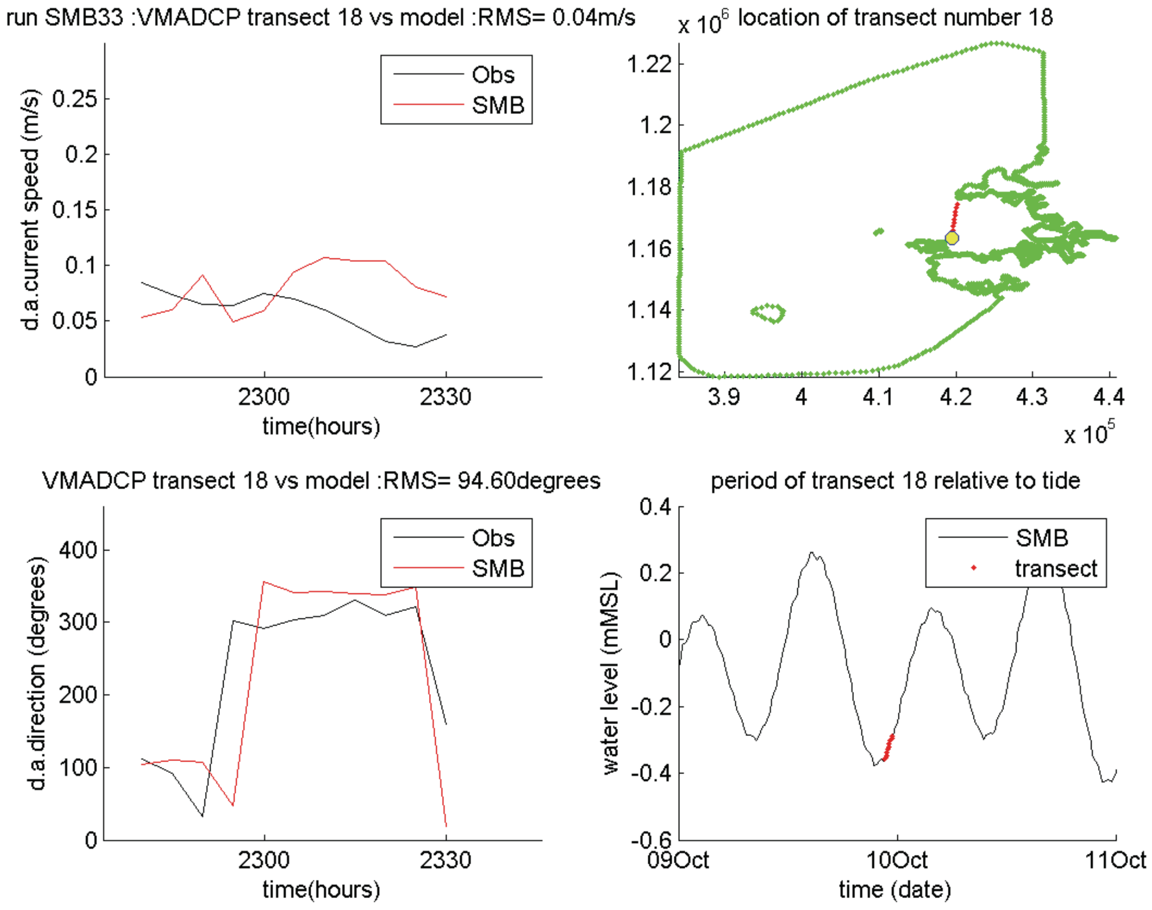


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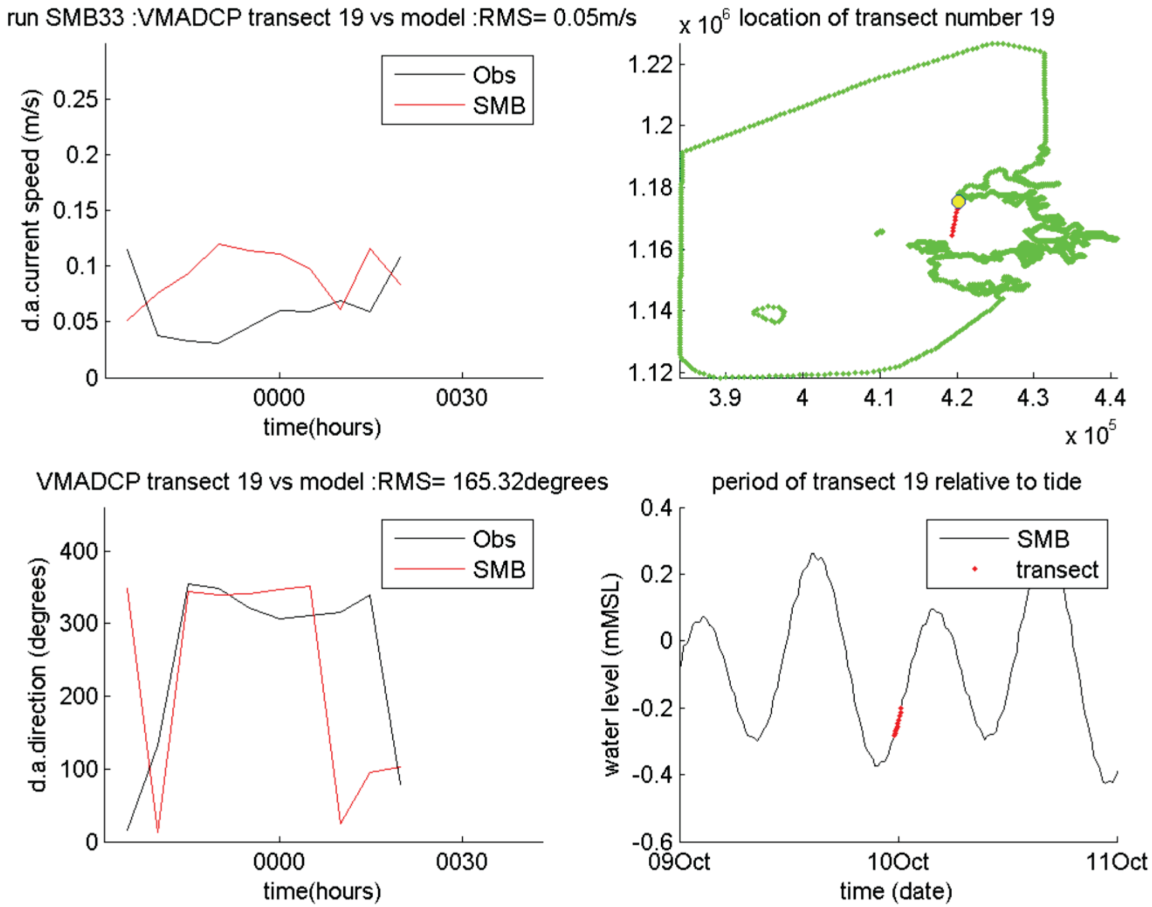


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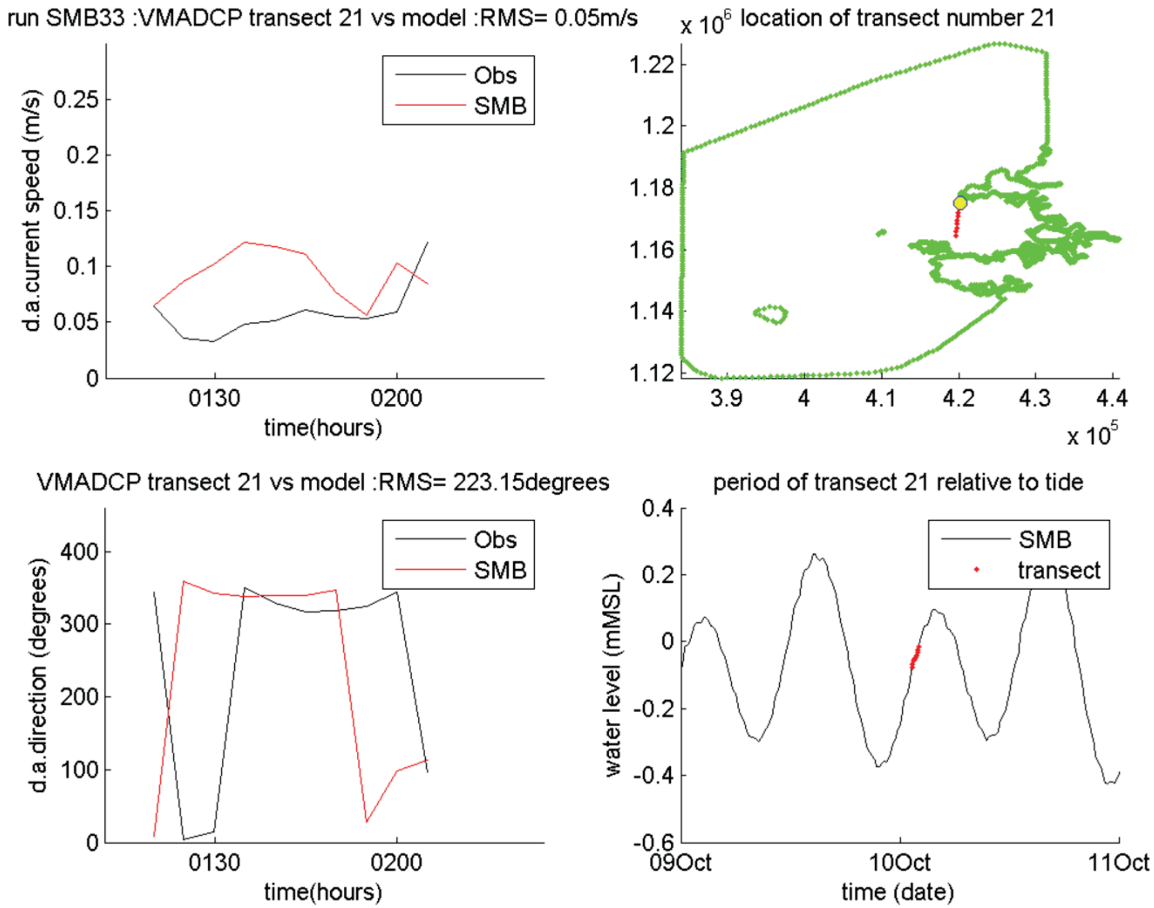


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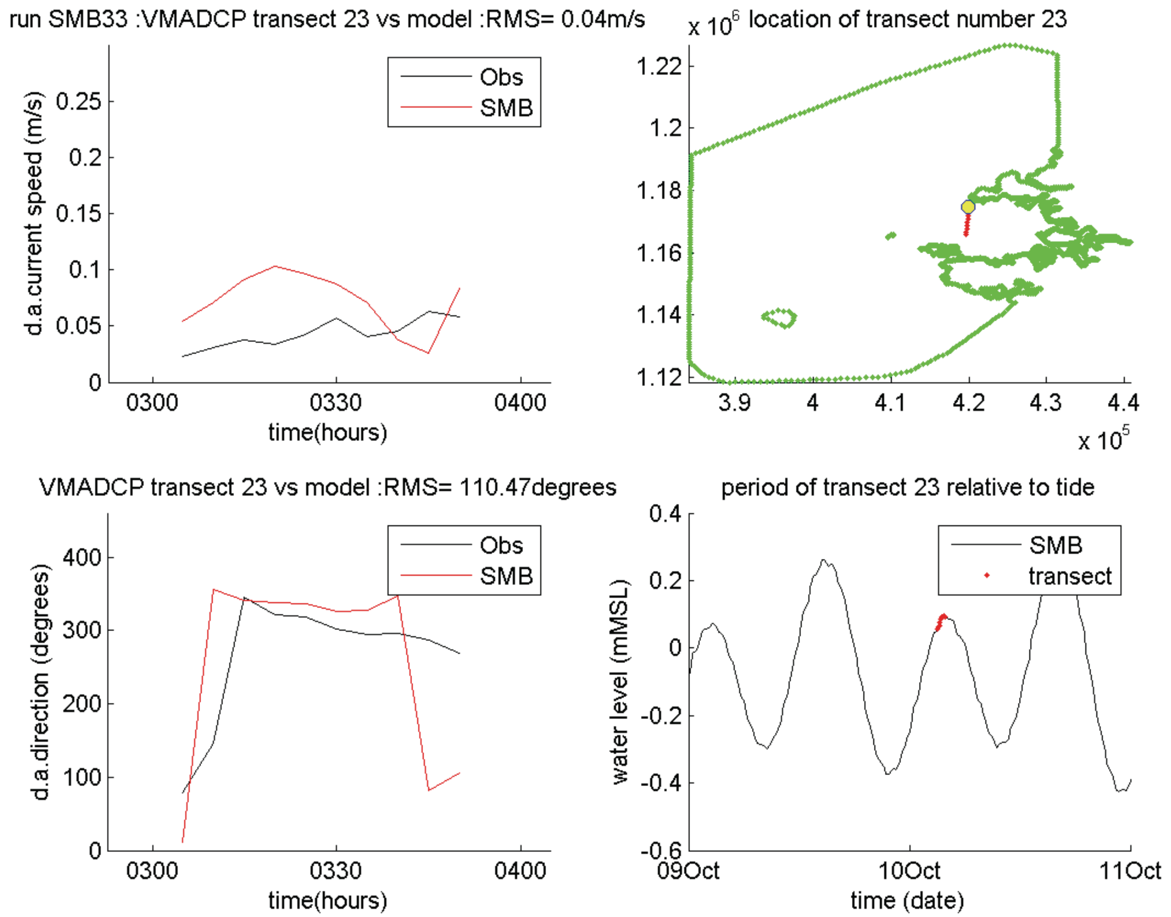


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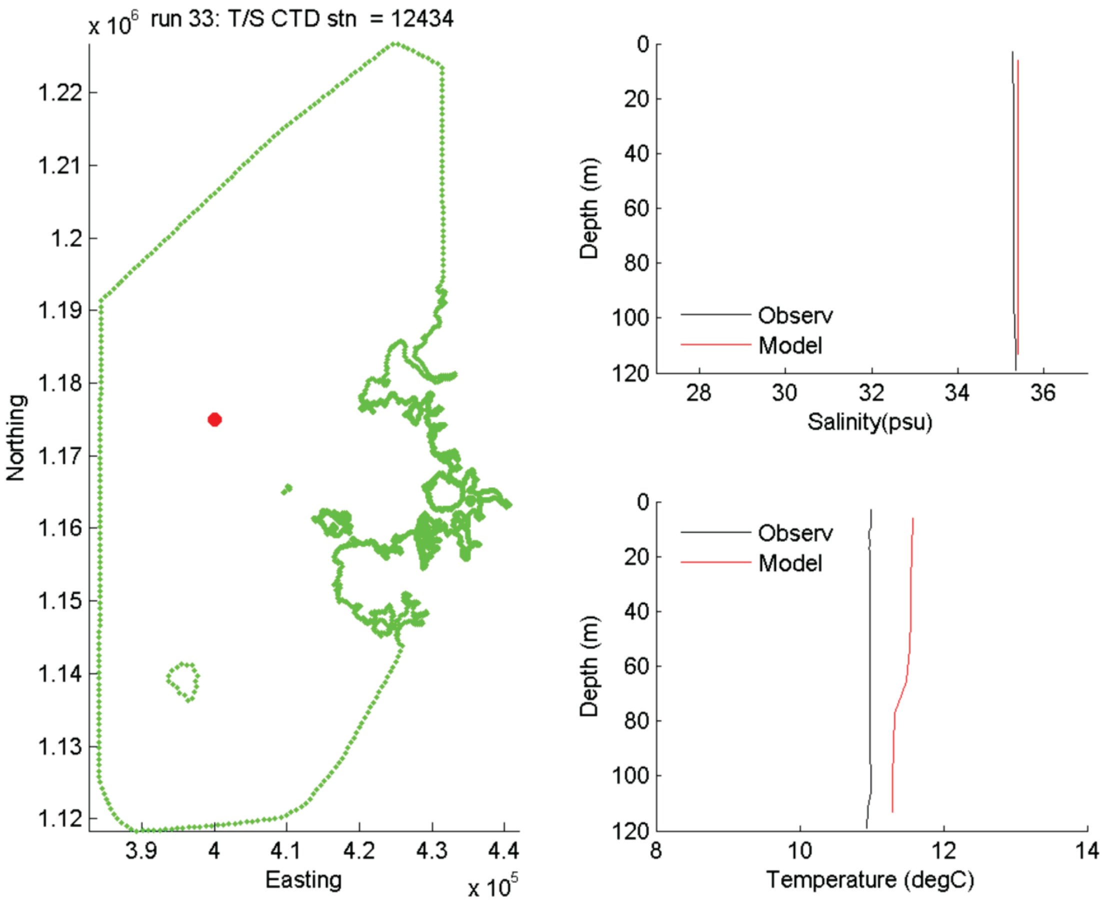
# Appendix B

Temperature and salinity profile comparisons

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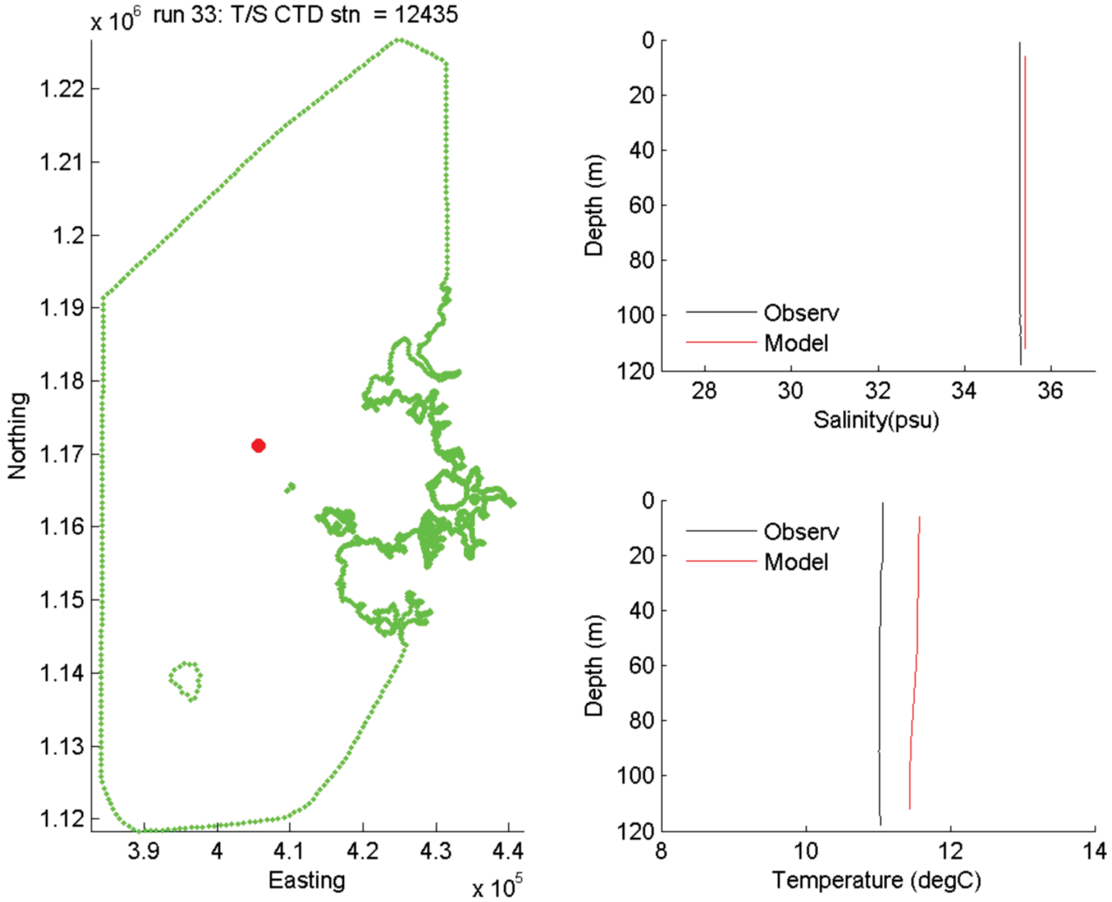


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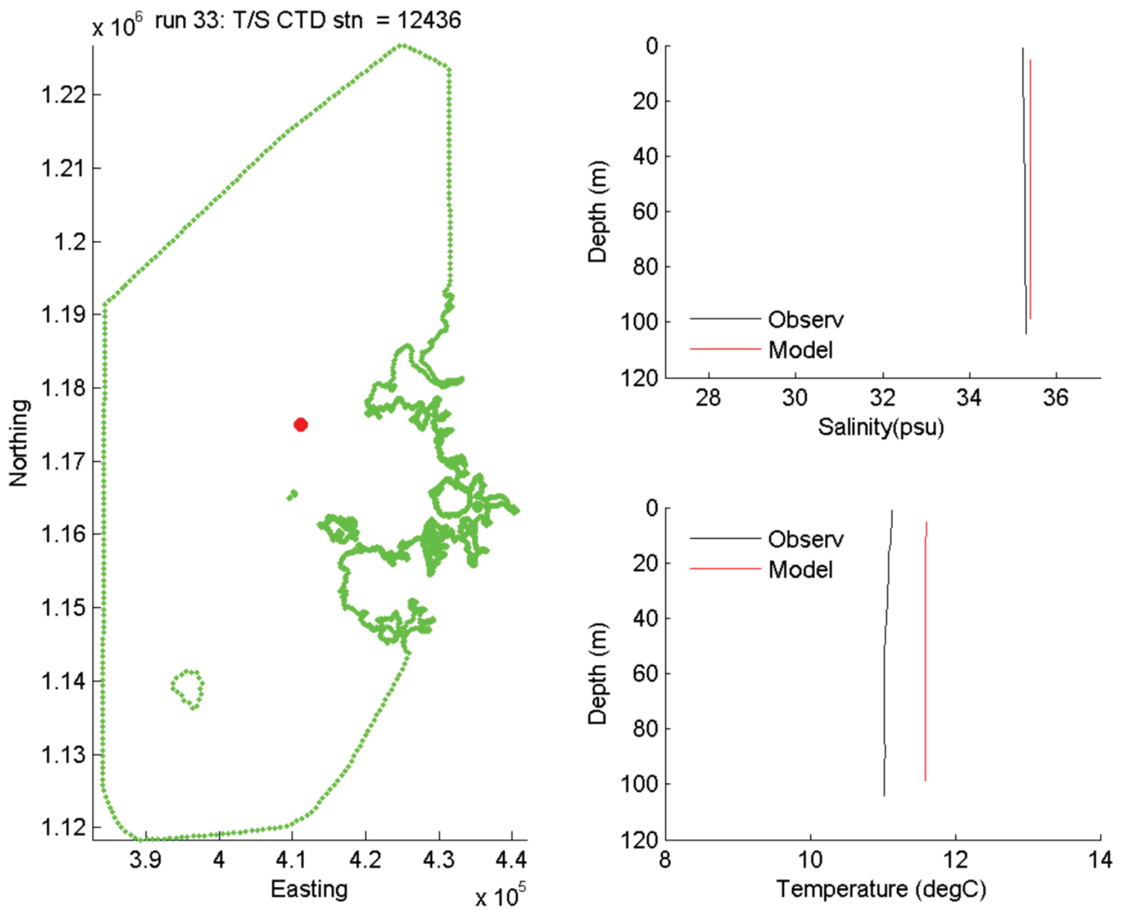


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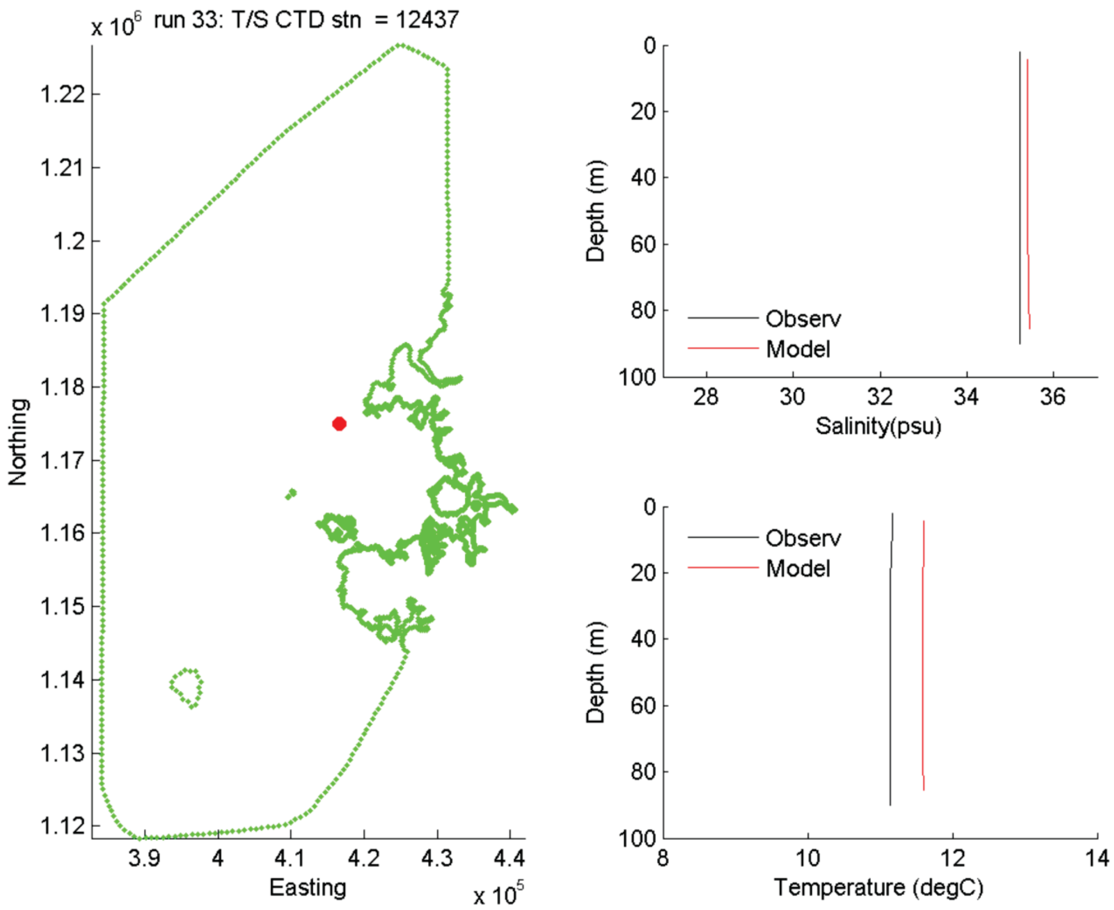


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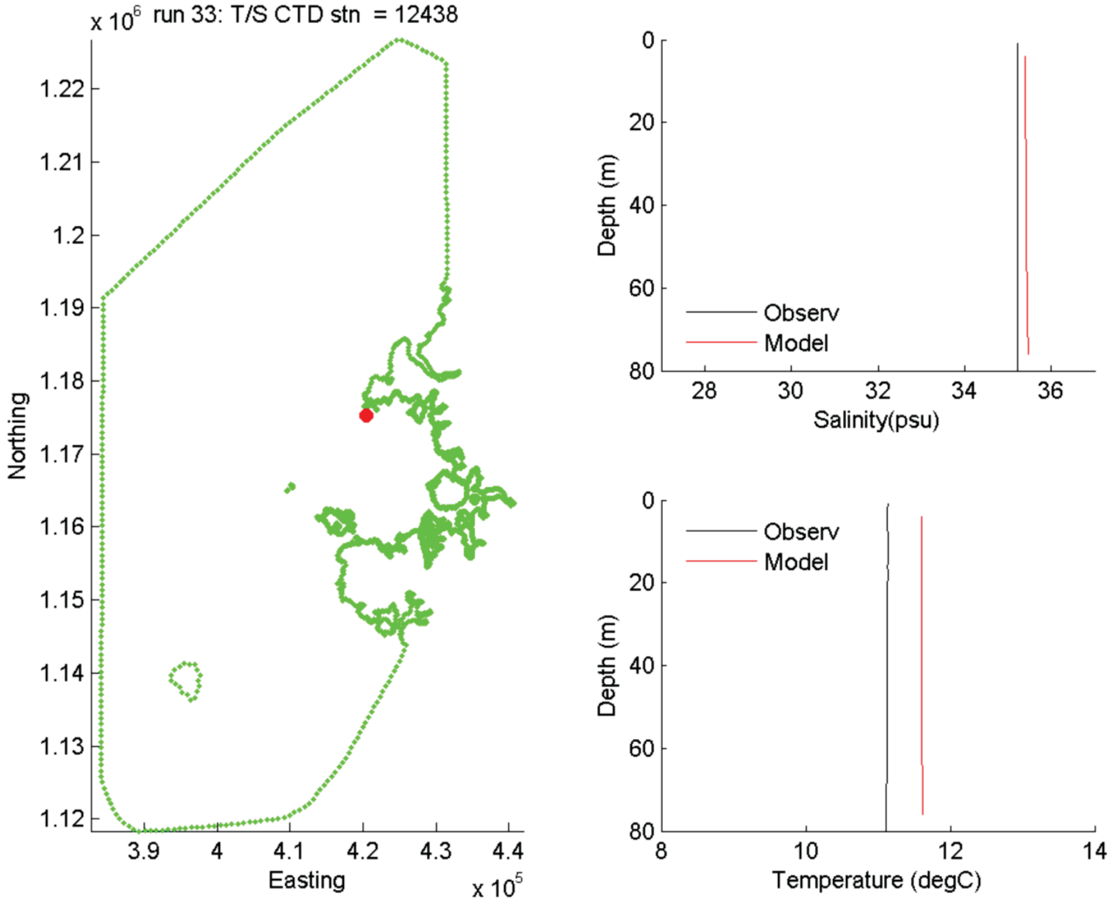


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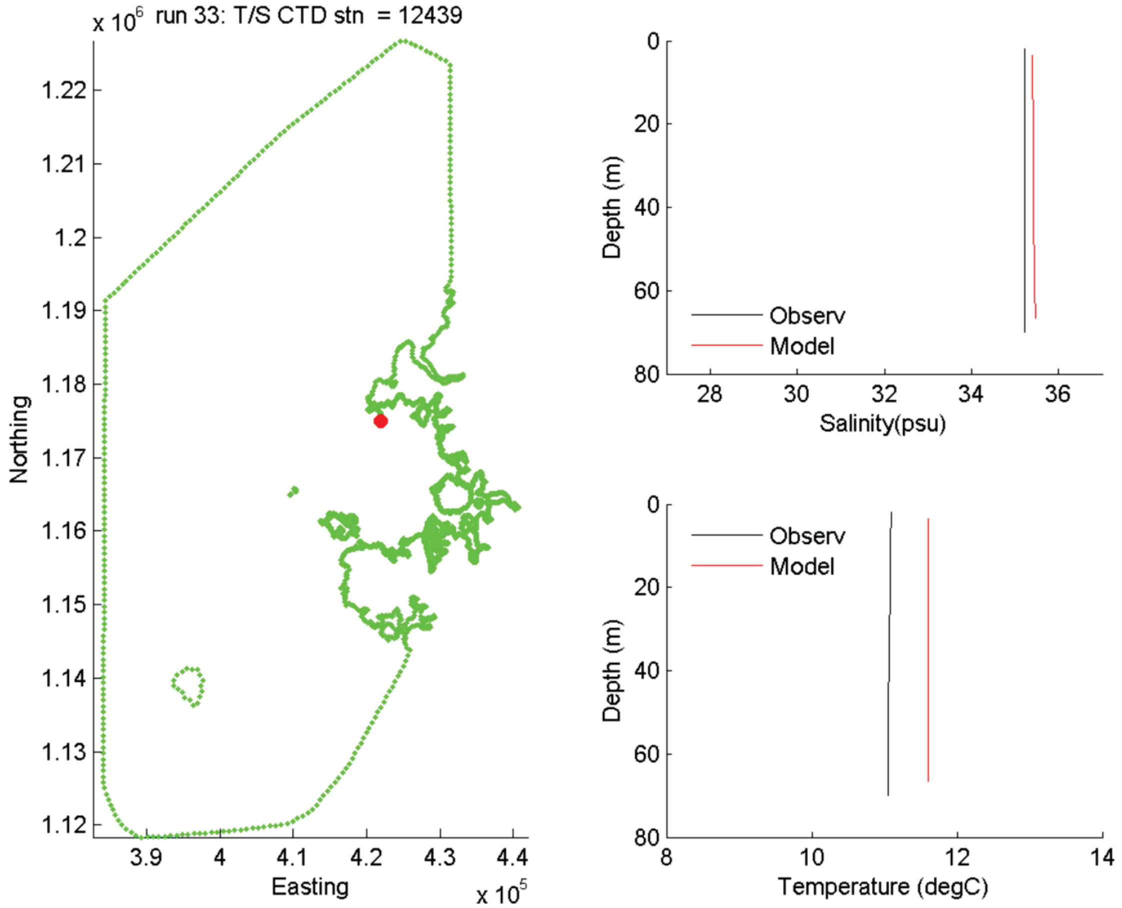


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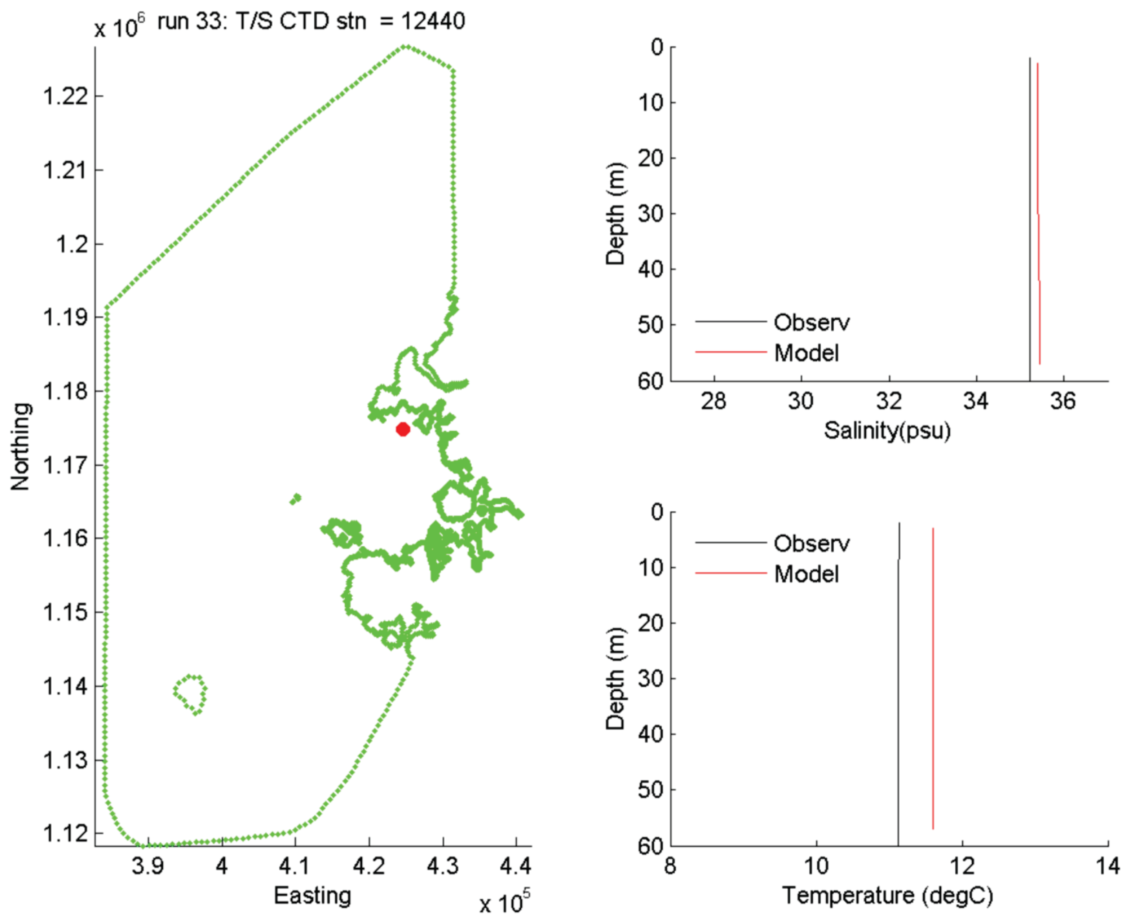


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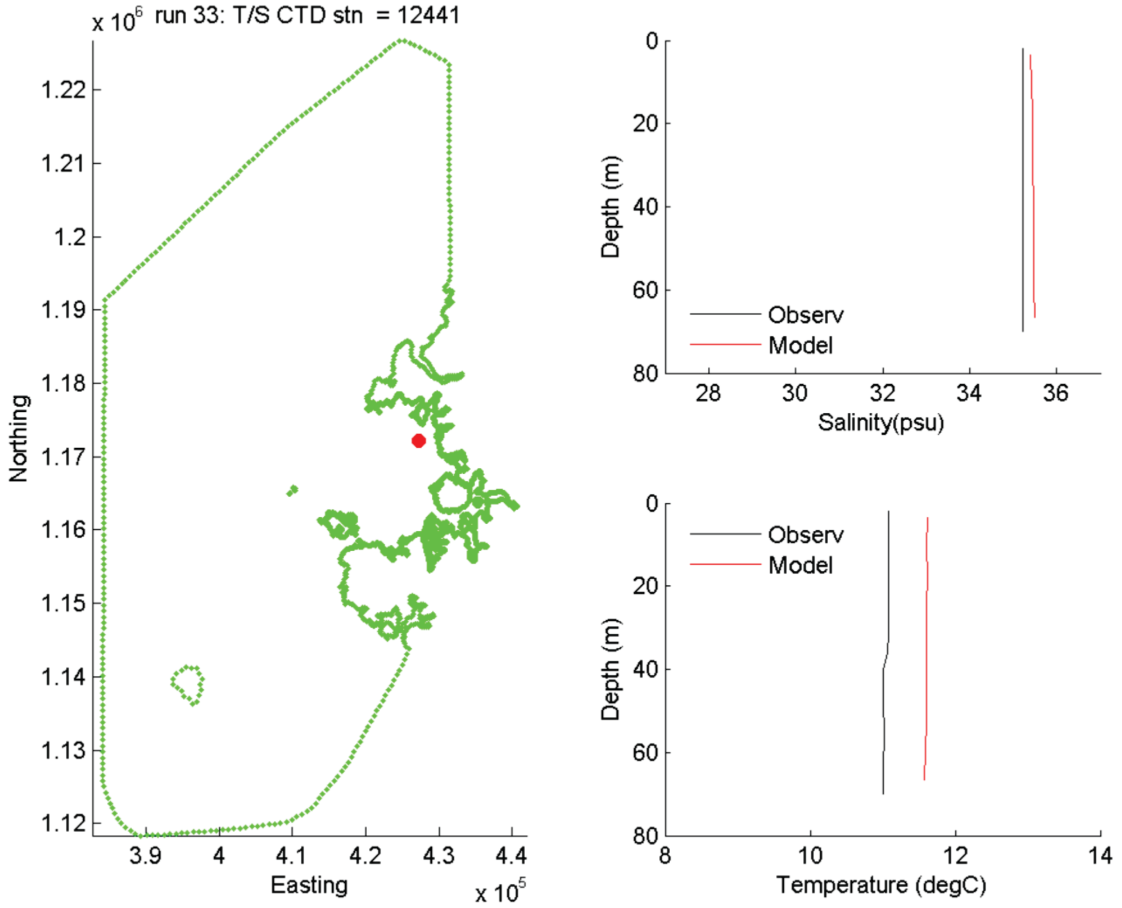


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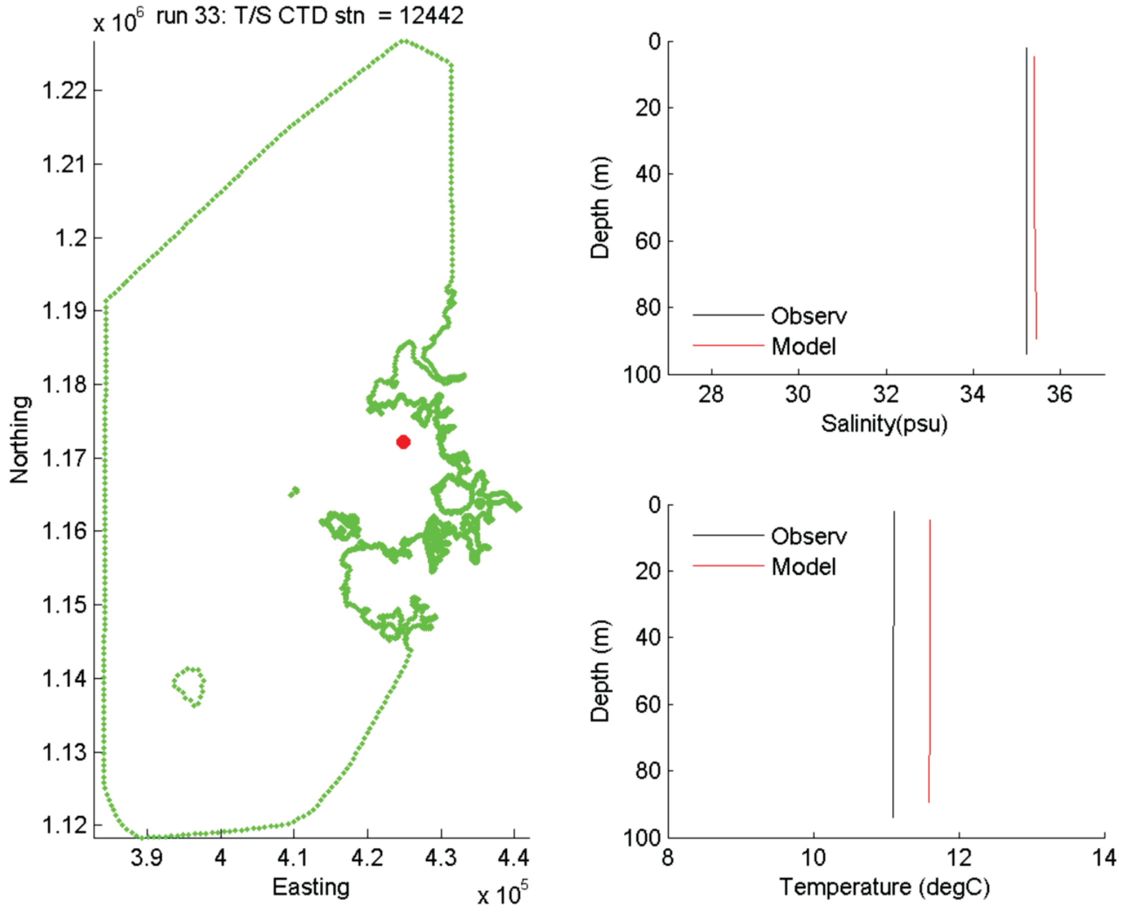


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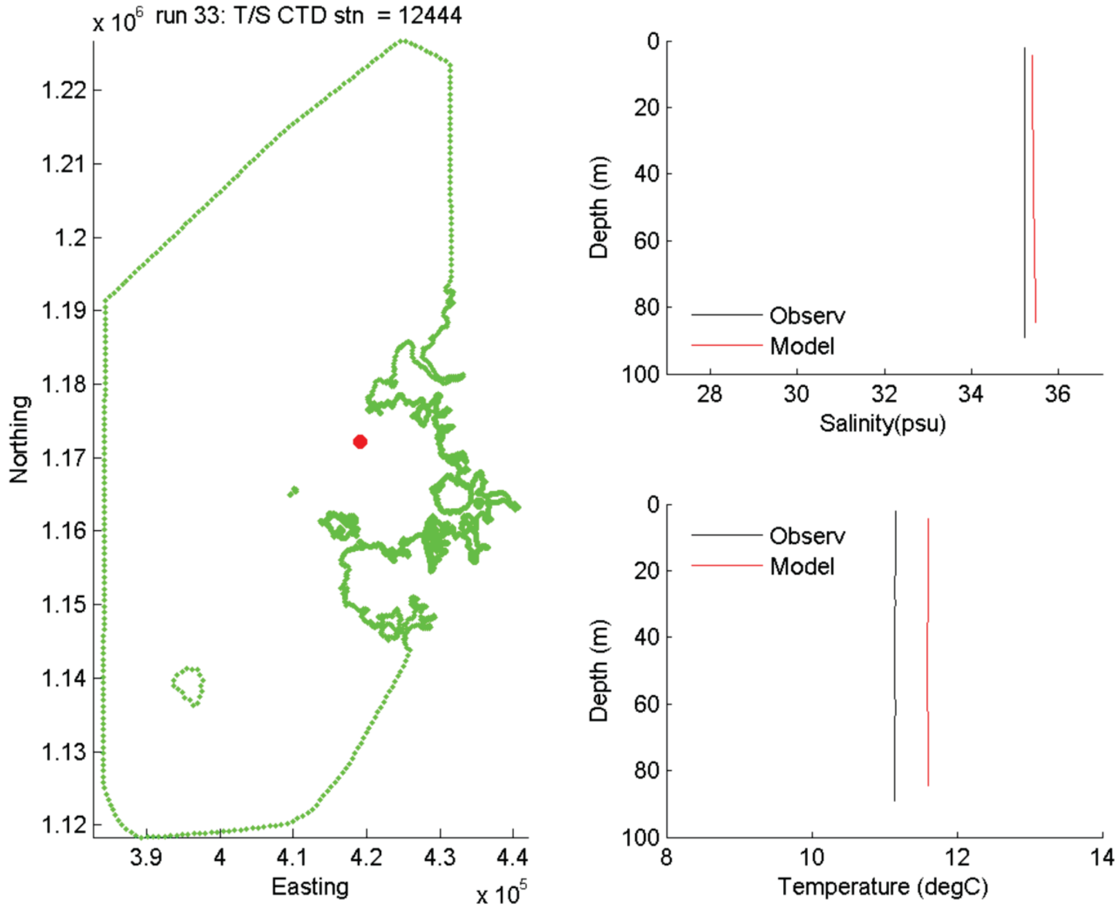


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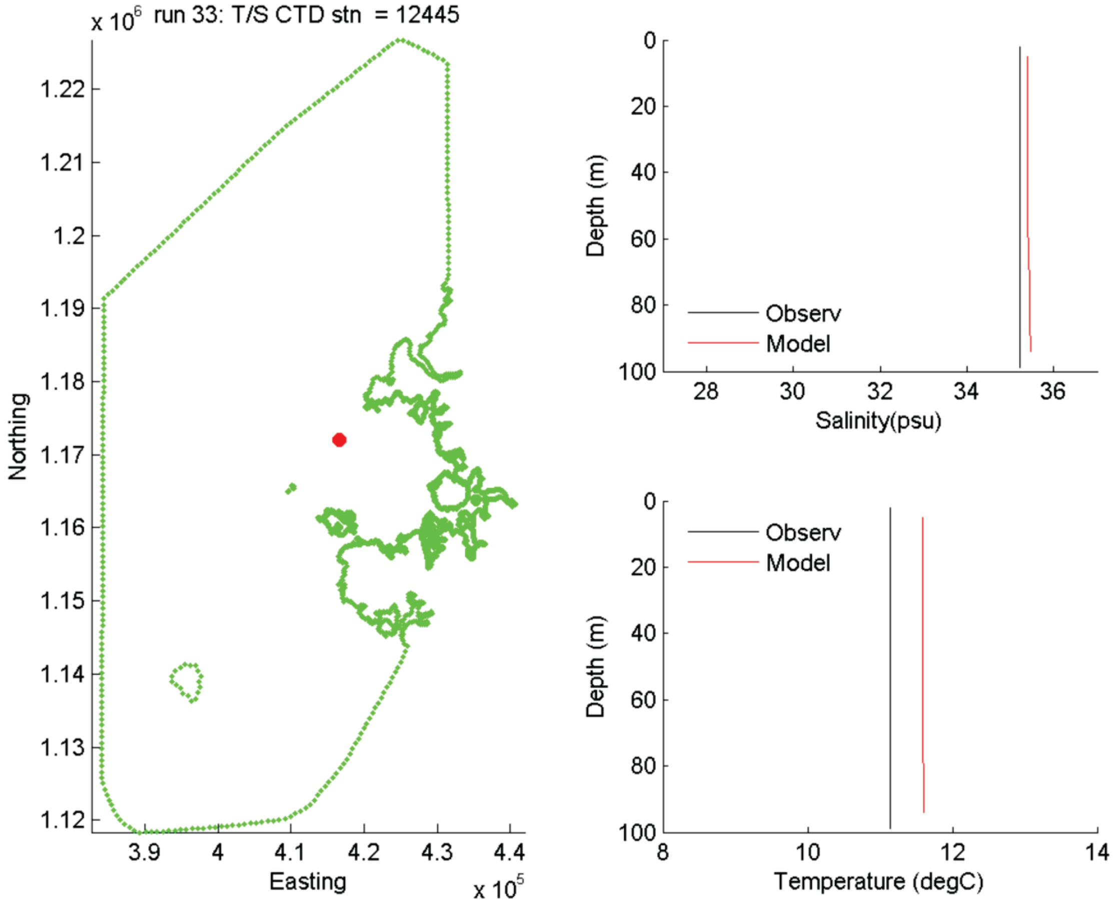


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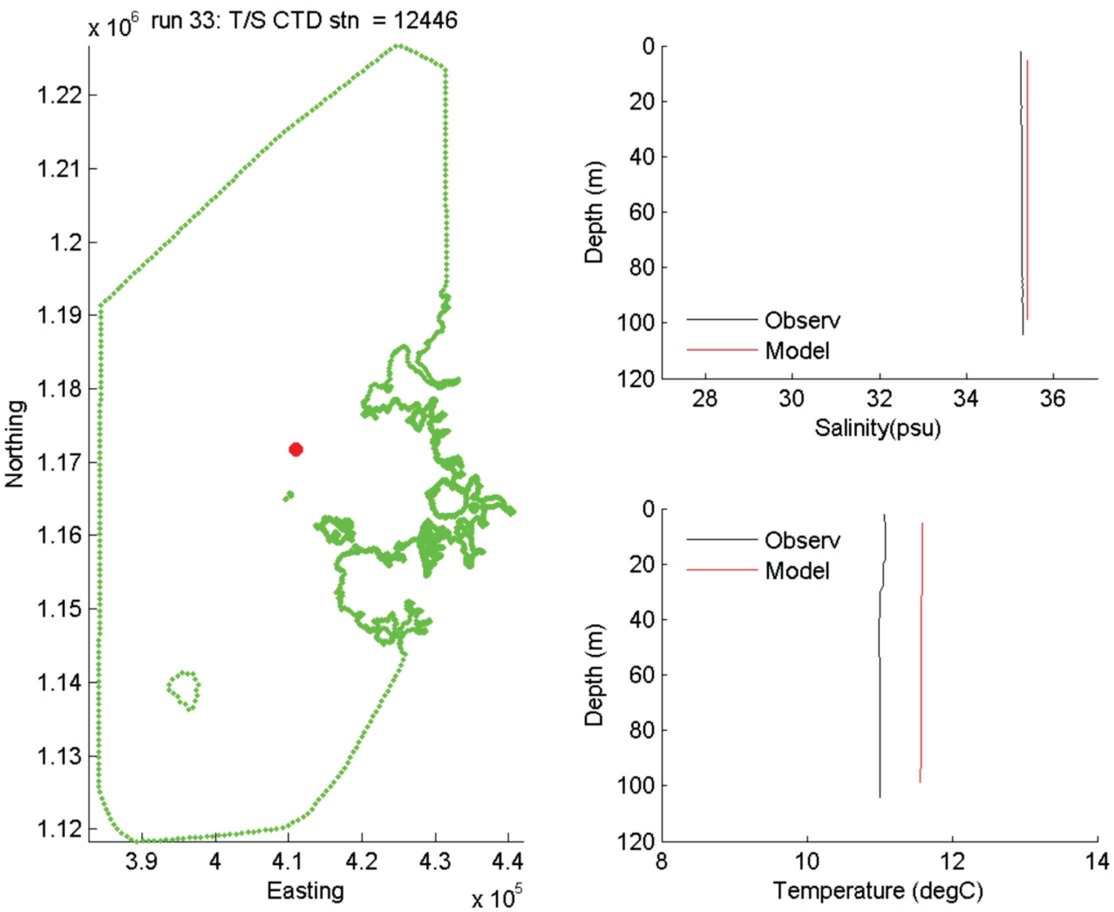


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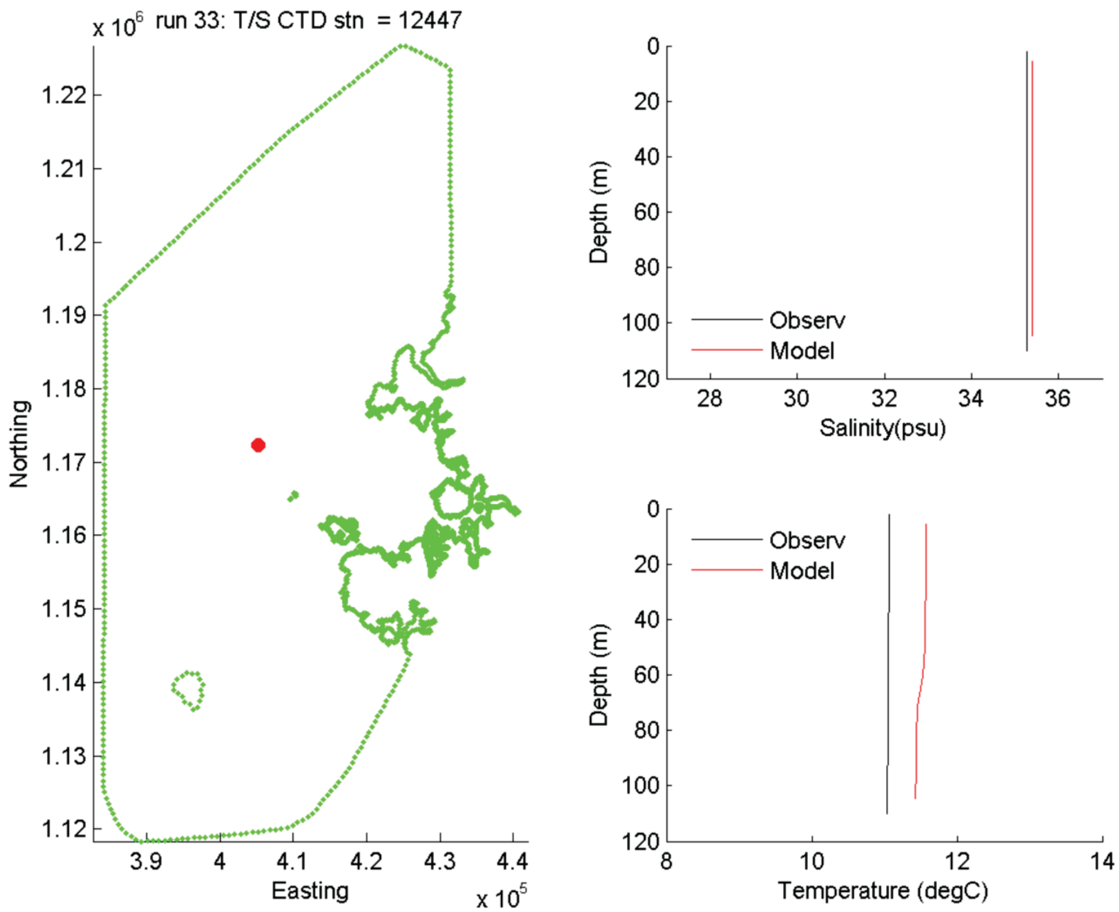
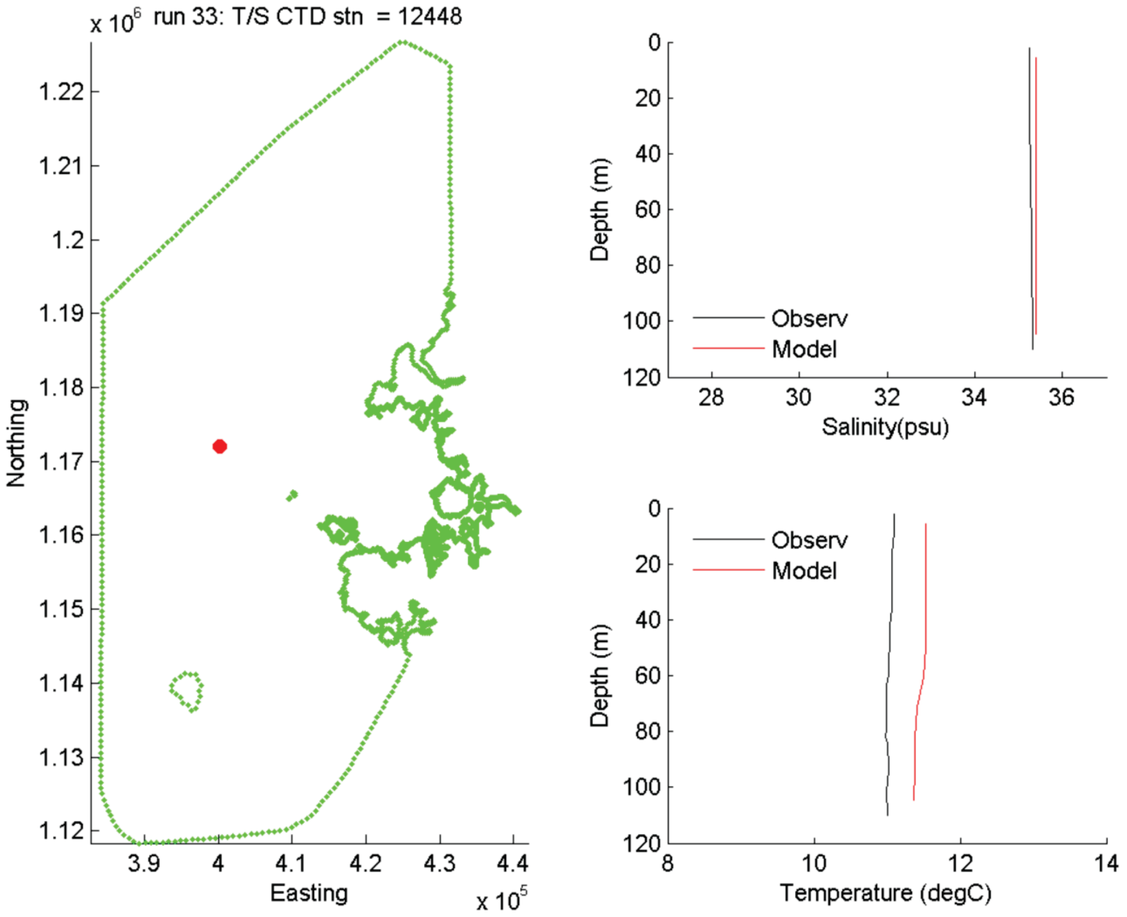
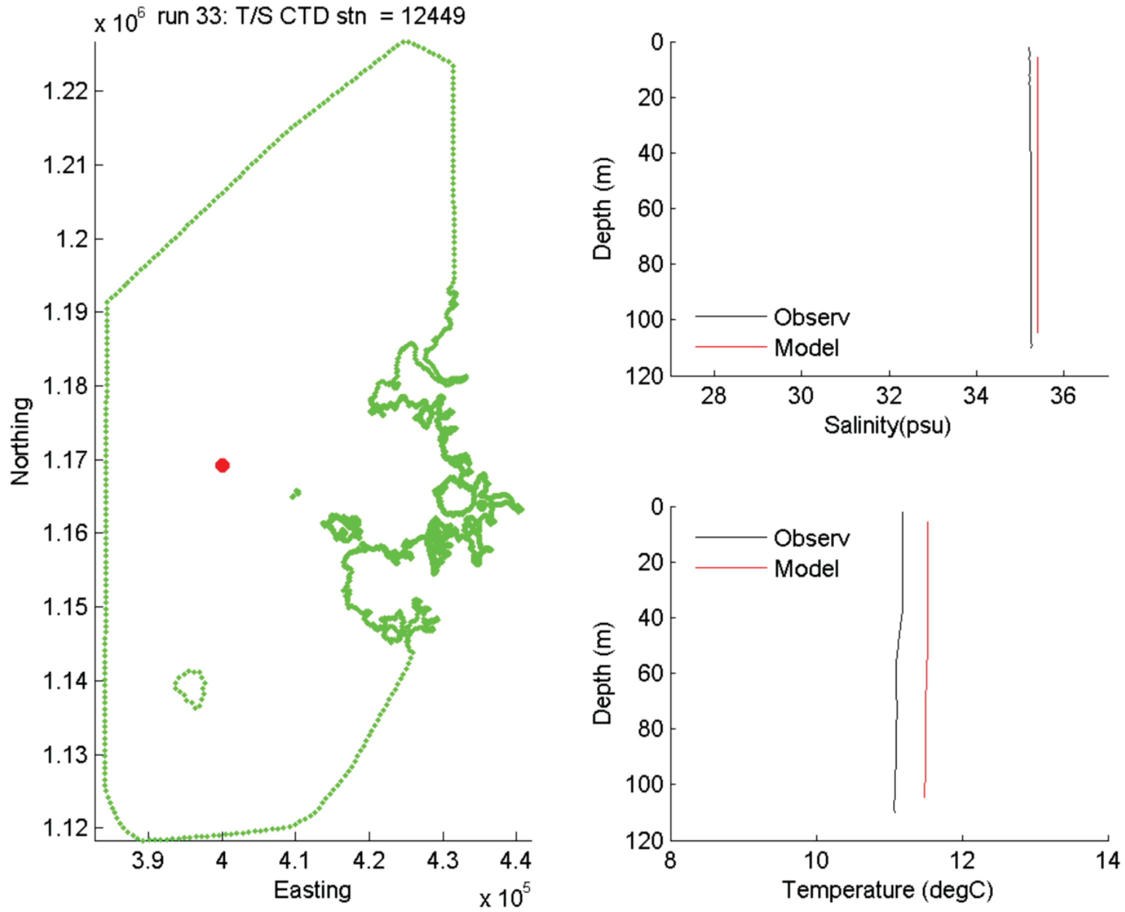
| | | | | Designed DMP | Drawn | Date 14/112012 |



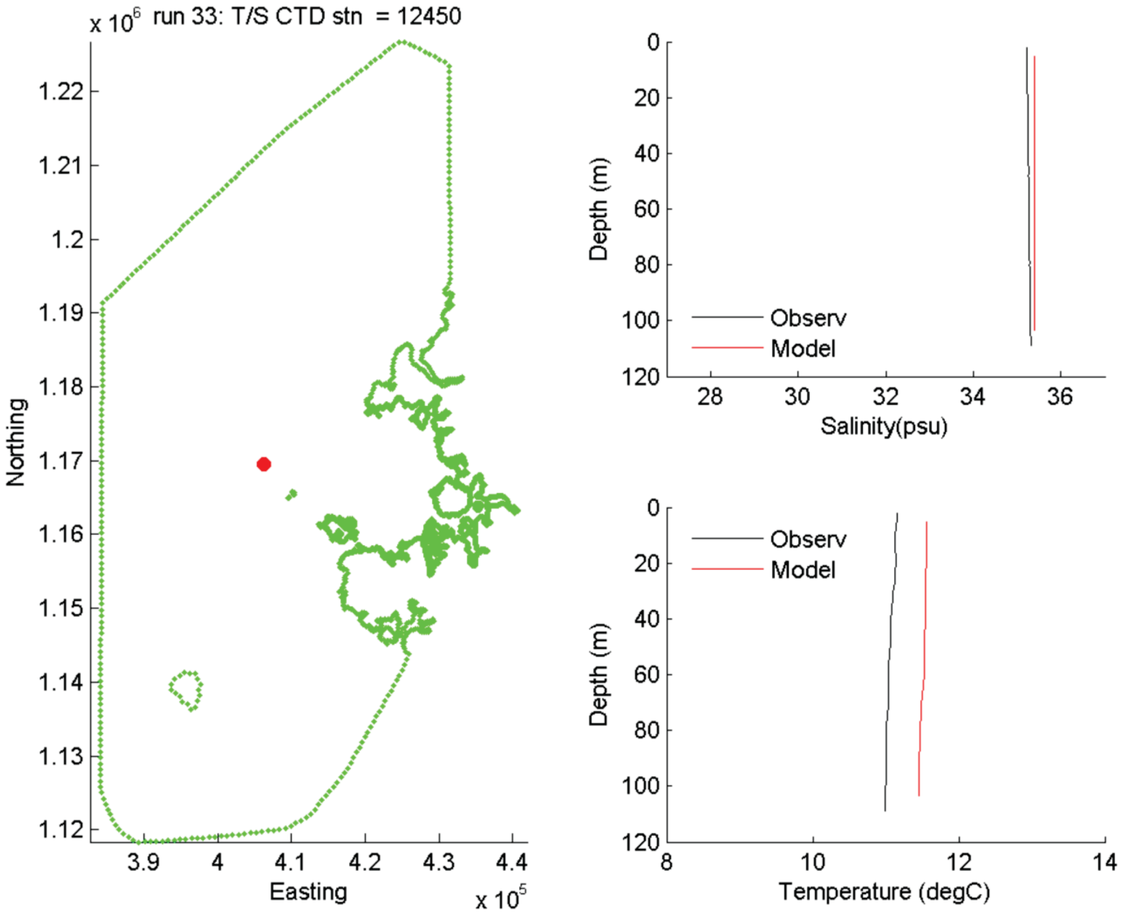

| Client | Consulting Engineer | Project: | Figure Title: | Figure B13 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



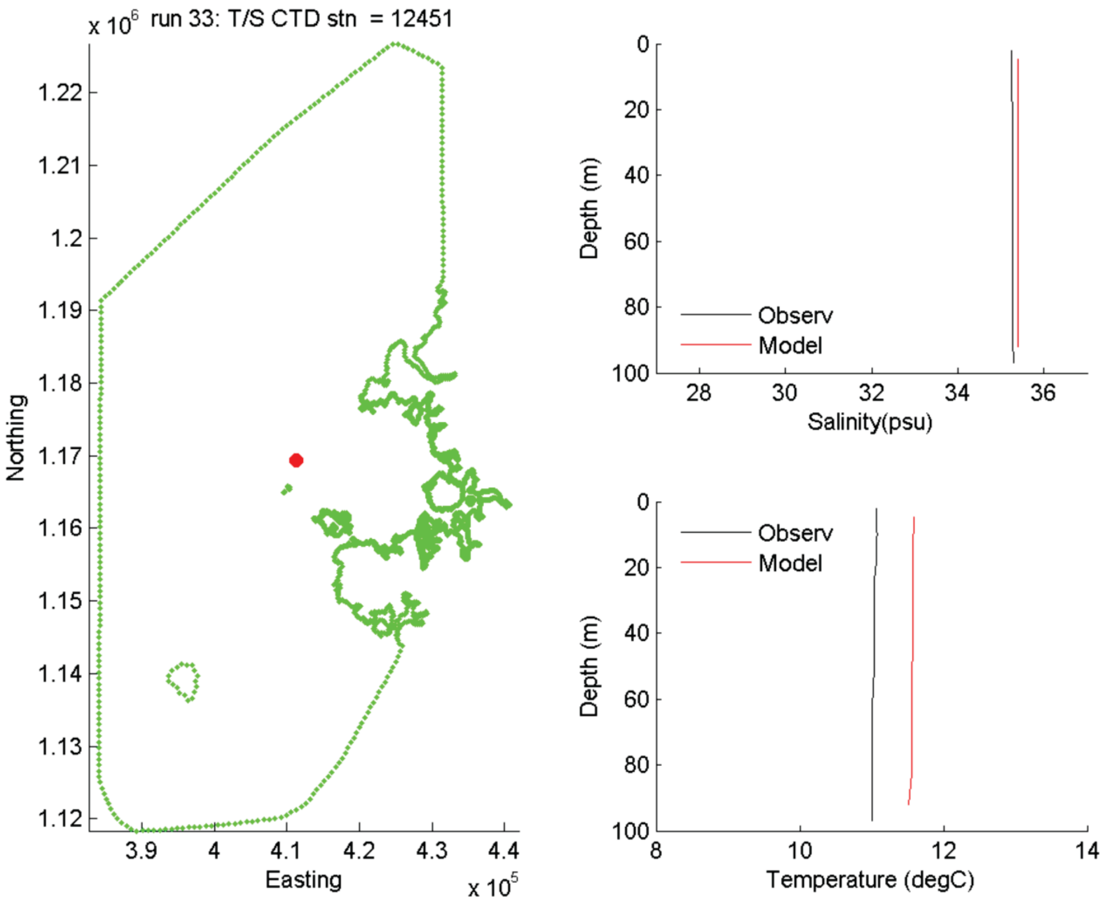

| Client | Consulting Engineer | Project: | Figure Title: | Figure B14 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



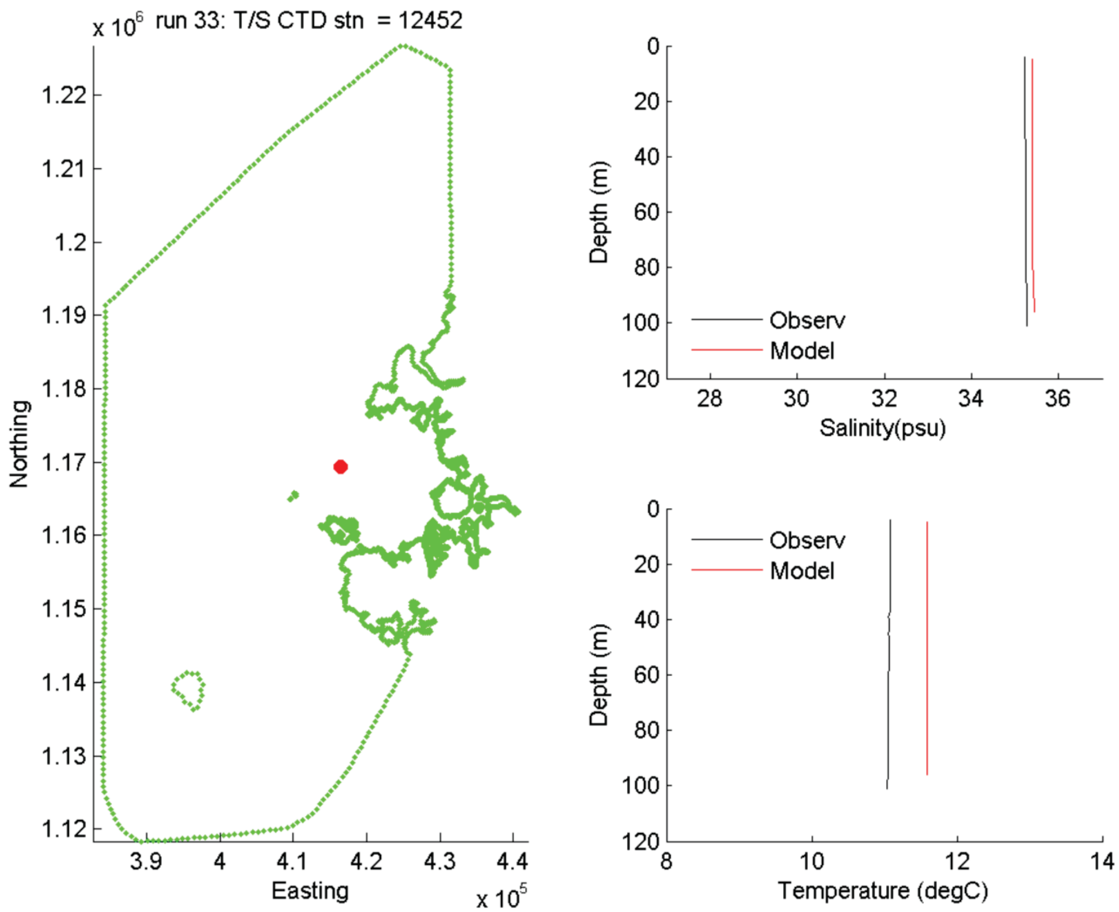

| Client | Consulting Engineer | Project: | Figure Title: | Figure B15 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



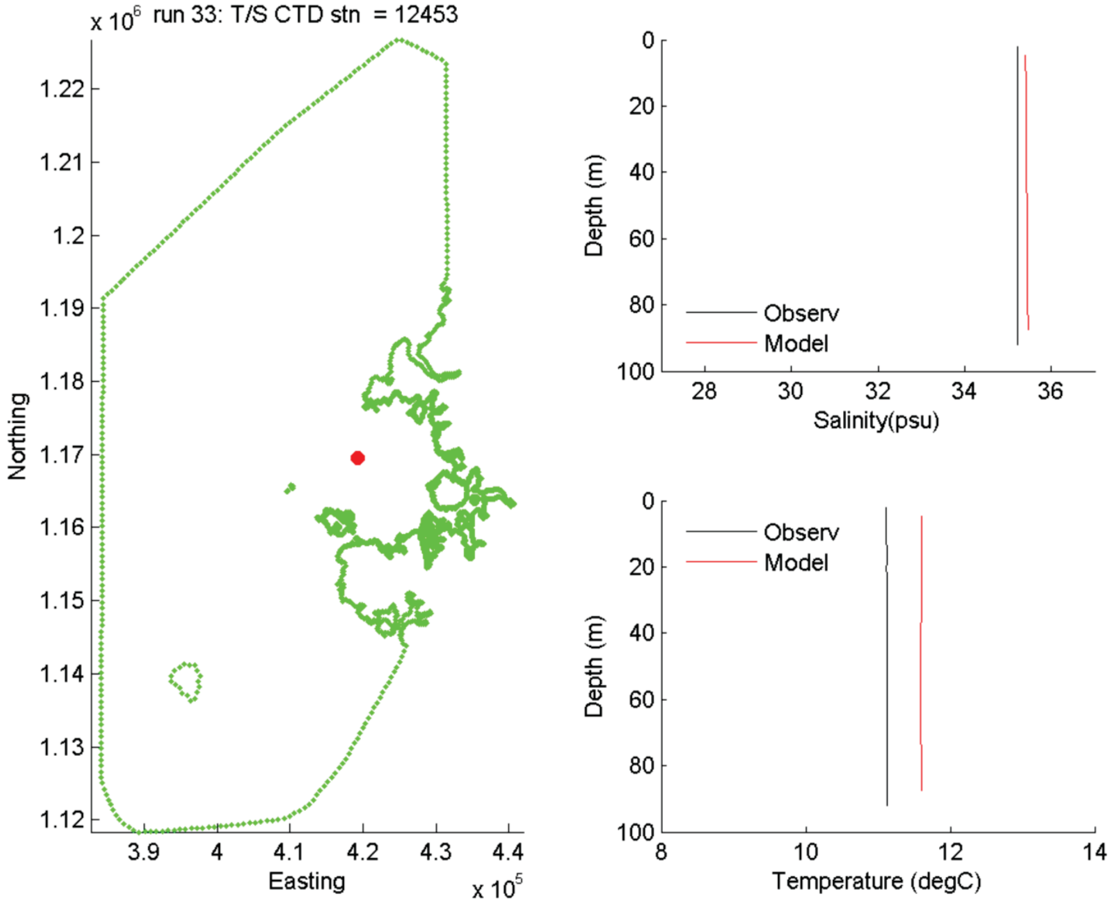

| Client | Consulting Engineer | Project: | Figure Title: | Figure B16 |
|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked: DMP; Scale: Not to scale; Rev.: 0; Designed: DMP; Drawn: ; Date: 14/112012 |



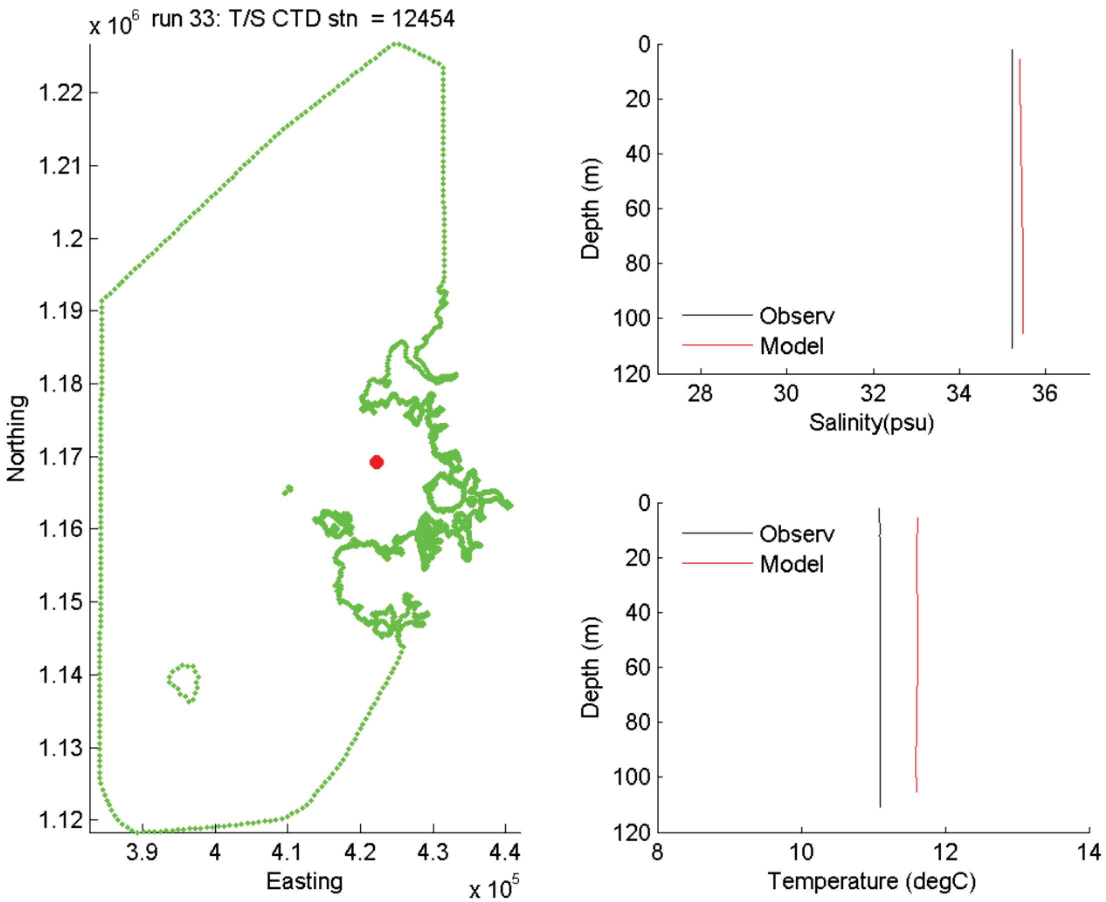

| Client | Consulting Engineer | Project: | Figure Title: | Figure B17 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



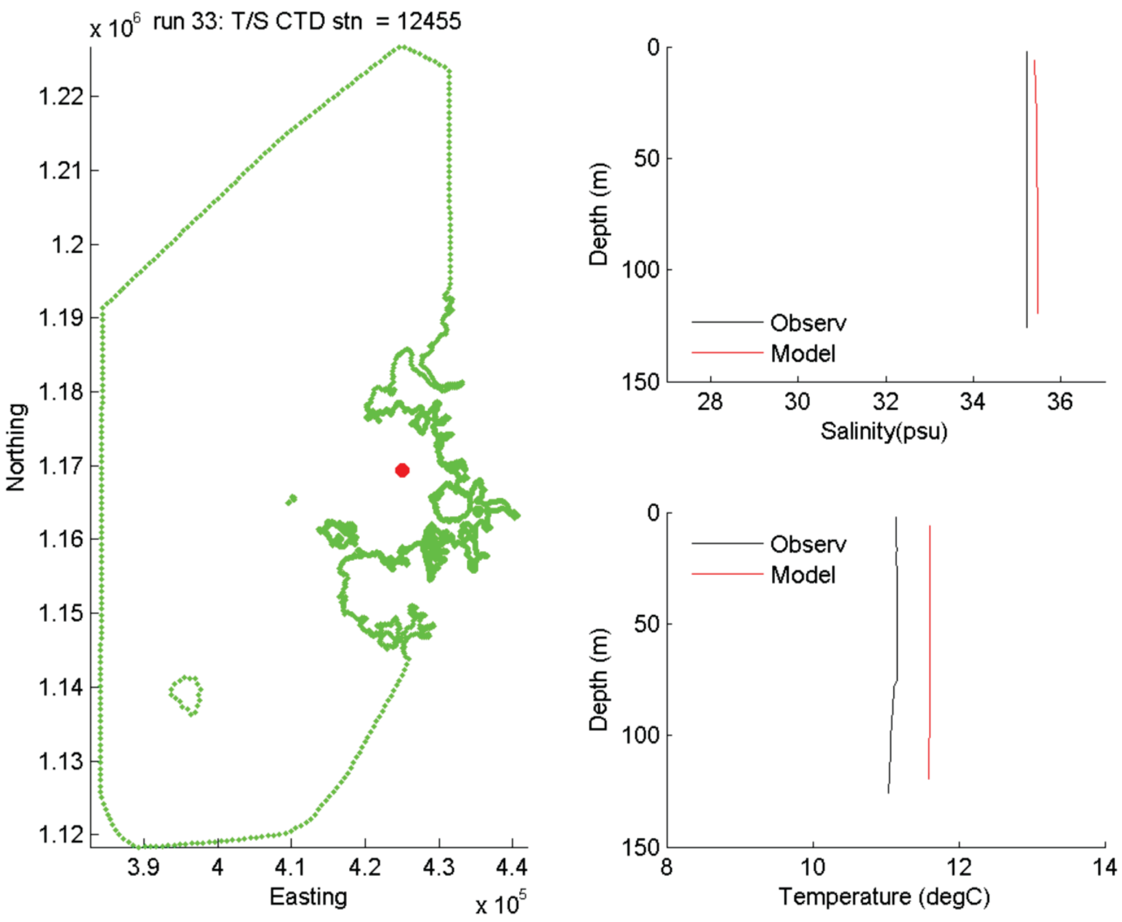

| Client | Consulting Engineer | Project: | Figure Title: | Figure B18 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



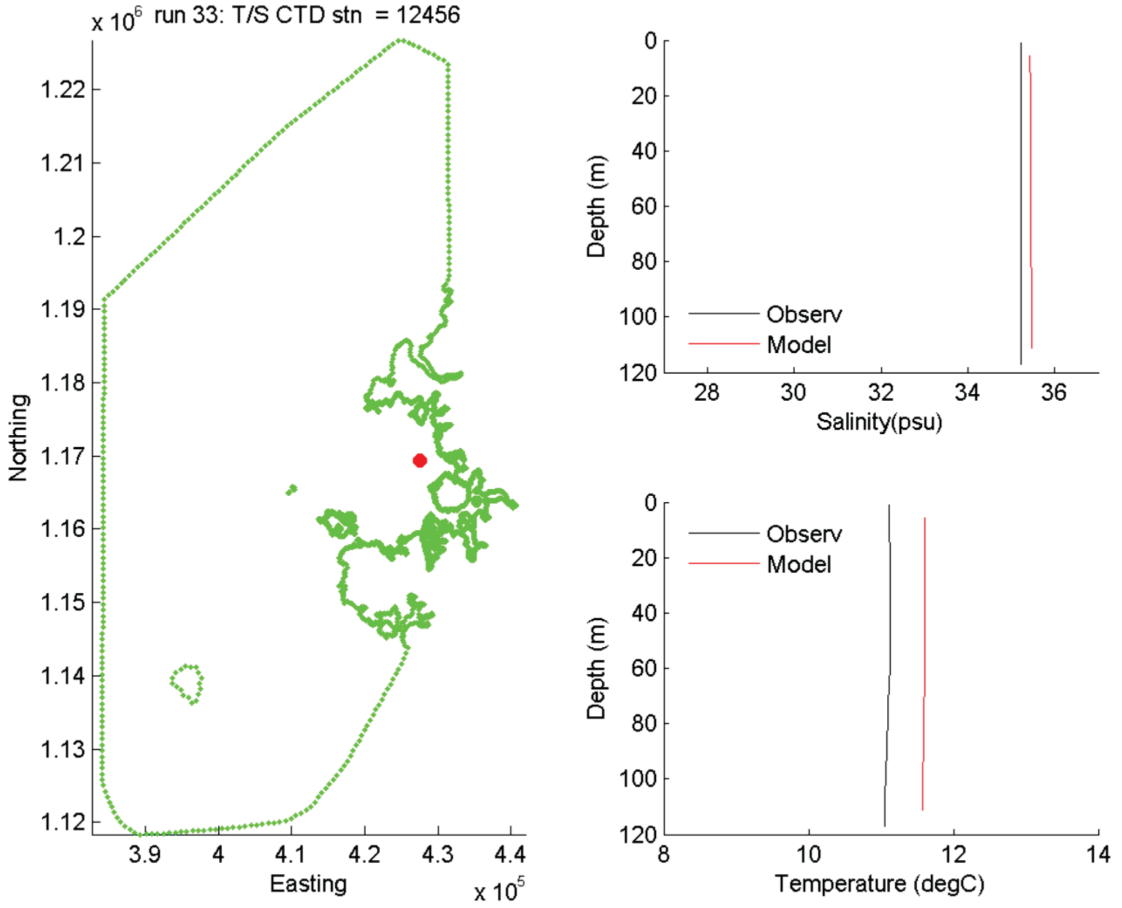

| Client | Consulting Engineer | Project: | Figure Title: | Figure B19 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



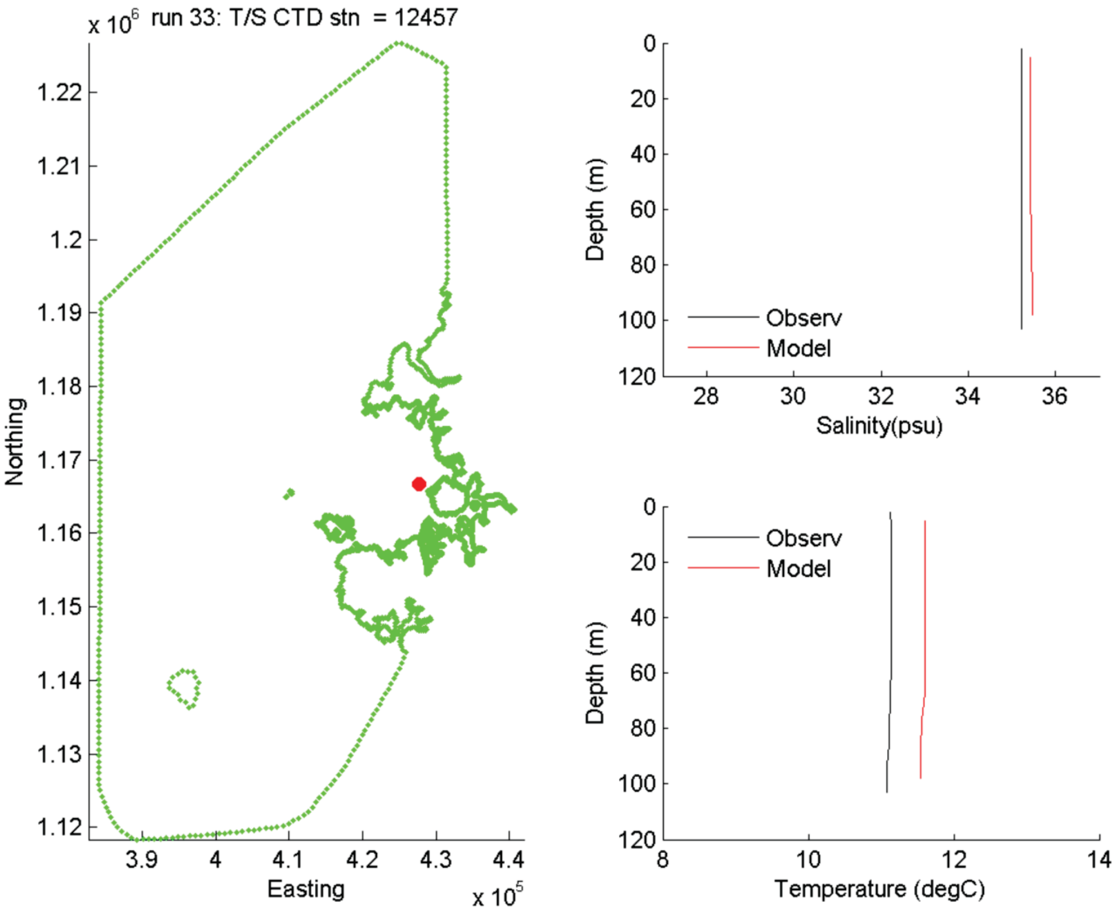

| Client | Consulting Engineer | Project: | Figure Title: | Figure B20 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



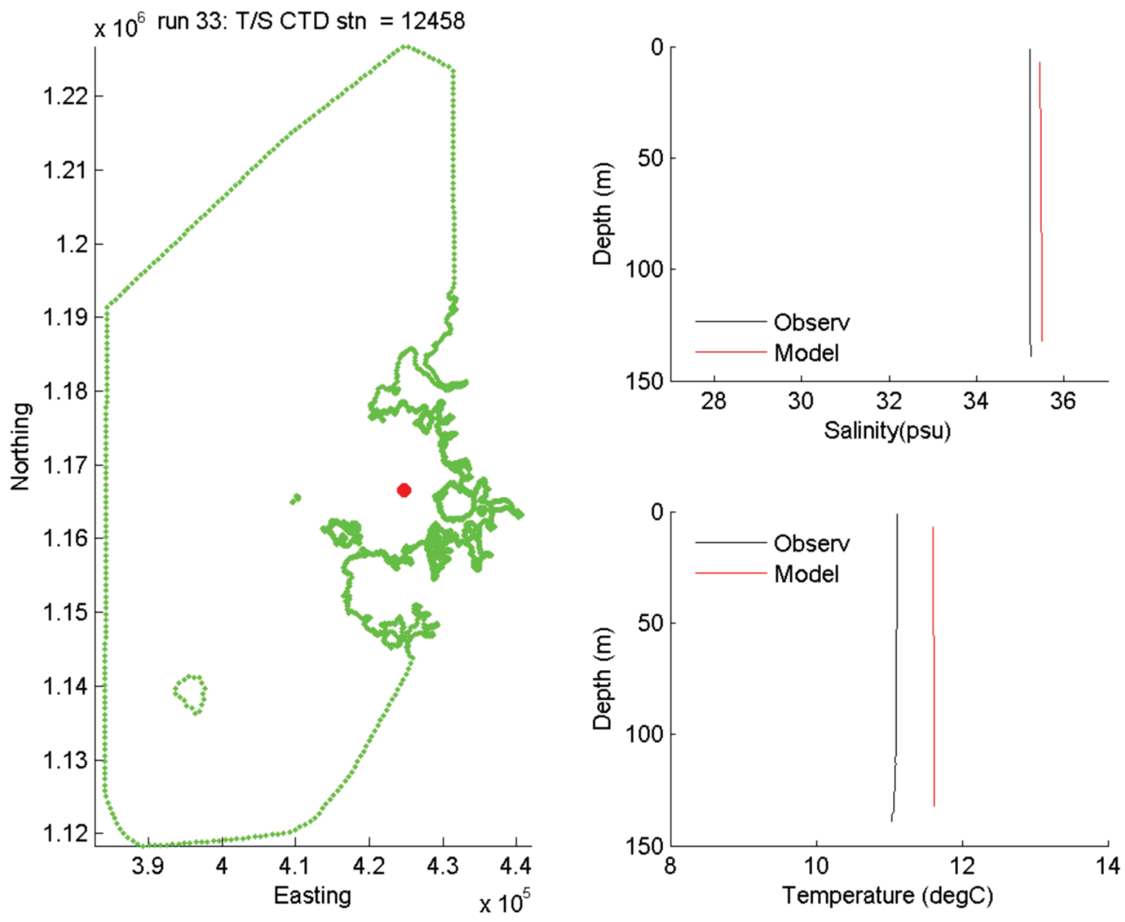

| Client | Consulting Engineer | Project: | Figure Title: | Figure B21 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



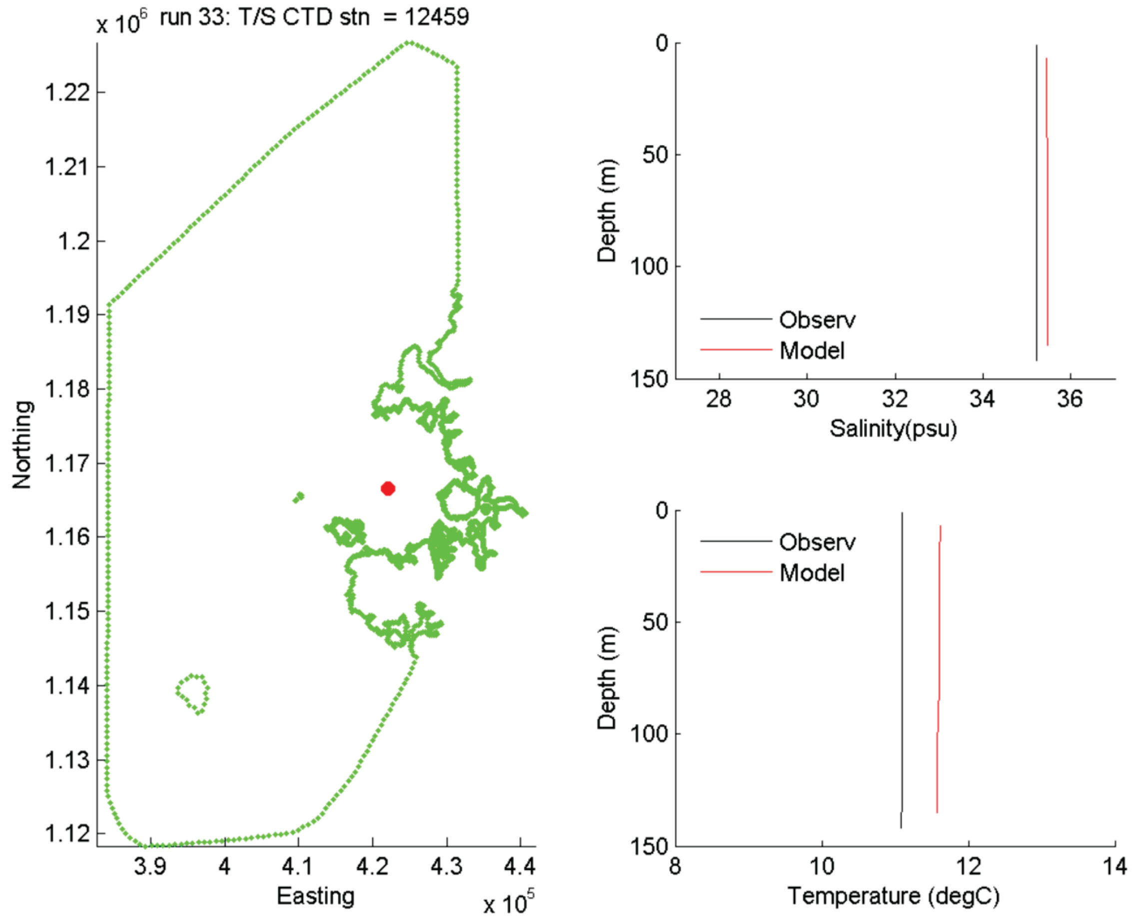

| Client | Consulting Engineer | Project: | Figure Title: | Figure B22 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



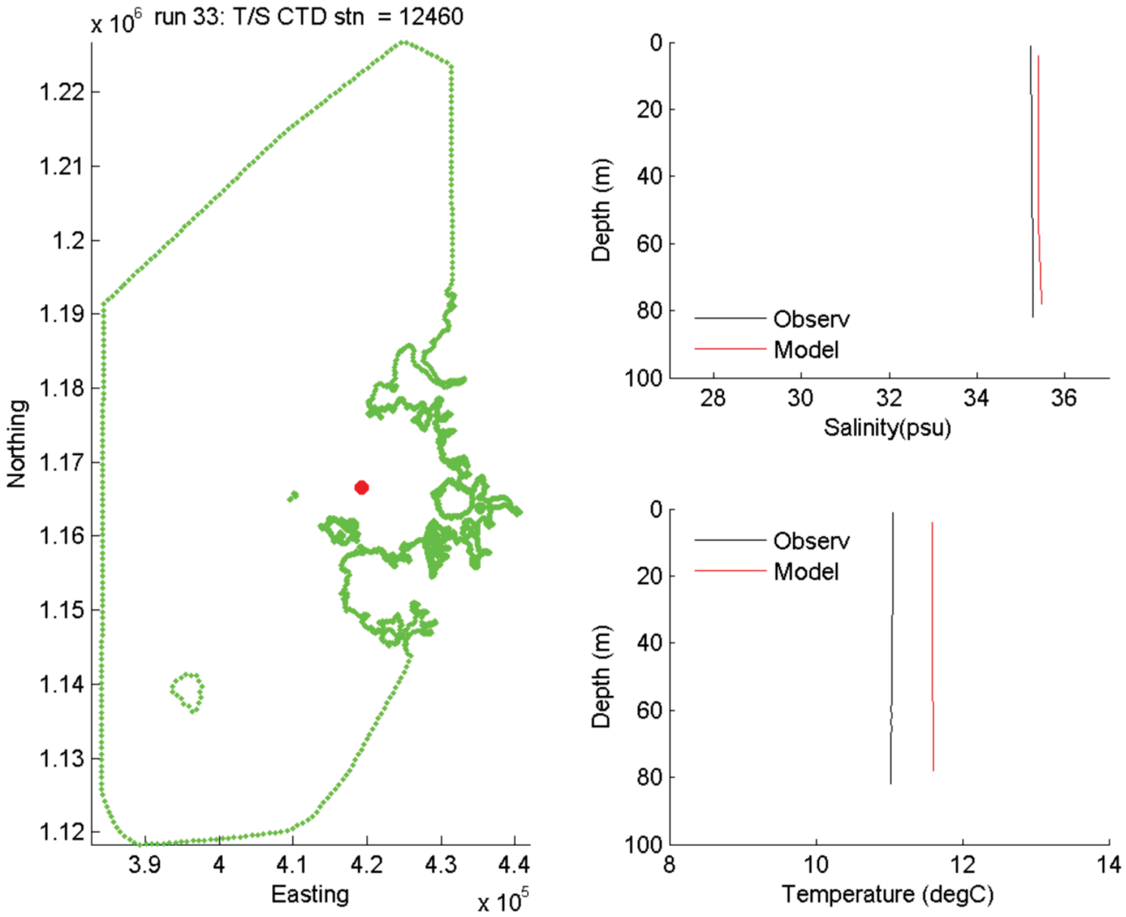

| Client | Consulting Engineer | Project: | Figure Title: | Figure B23 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



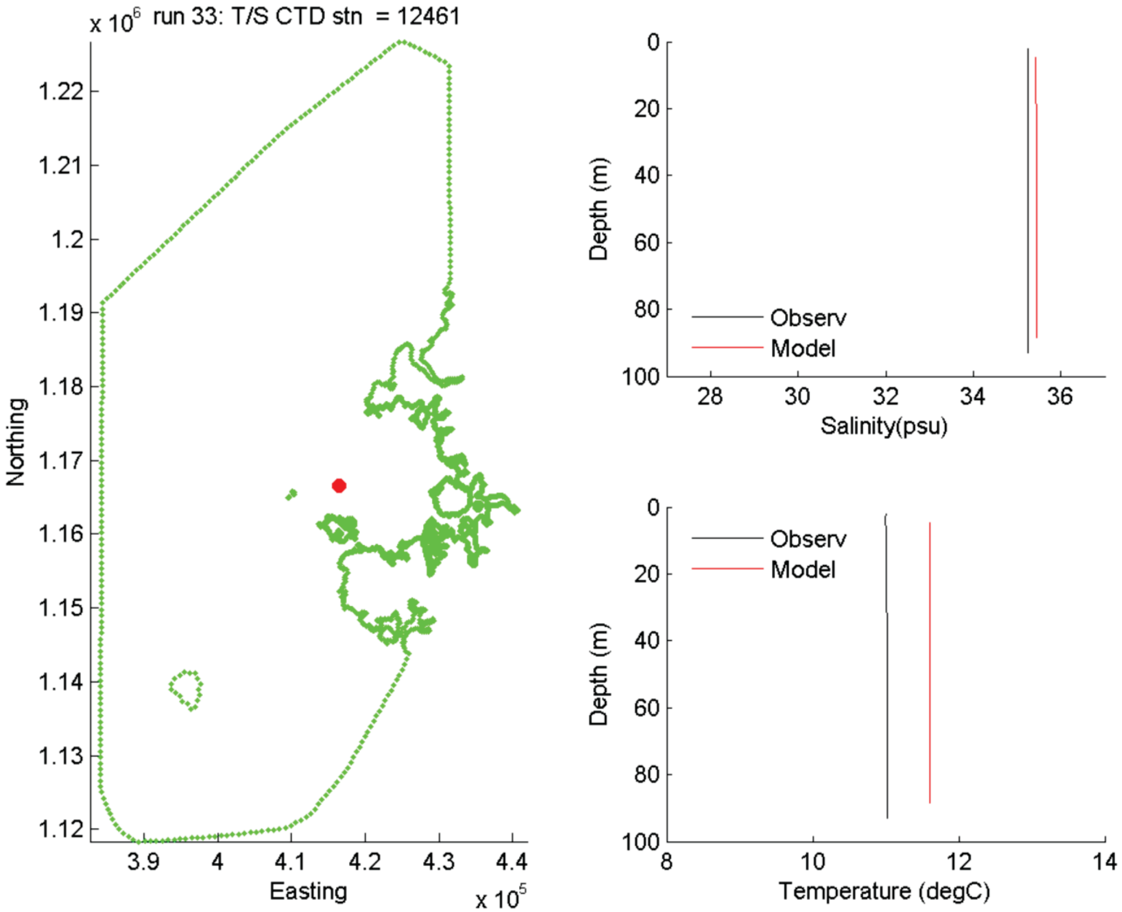

| Client | Consulting Engineer | Project: | Figure Title: | Figure B24 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



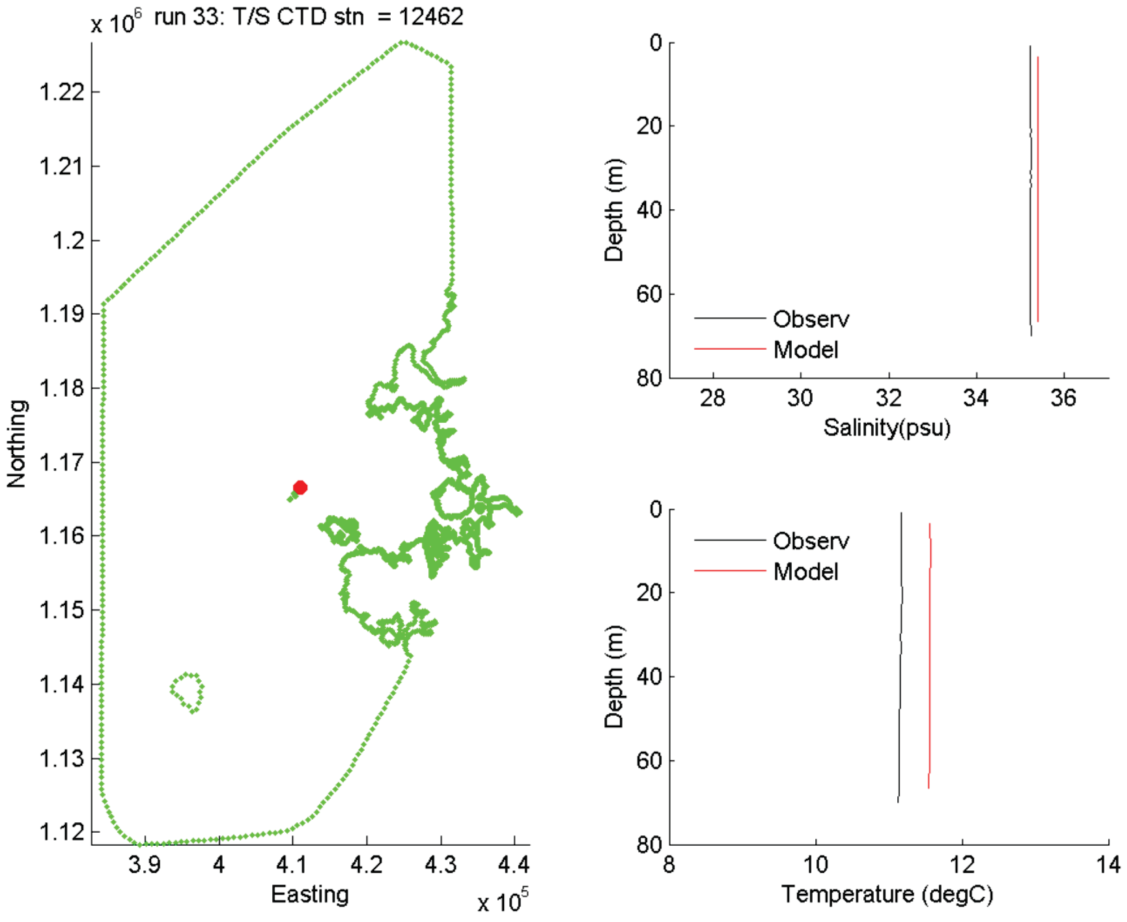

| Client | Consulting Engineer | Project: | Figure Title: | Figure B25 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



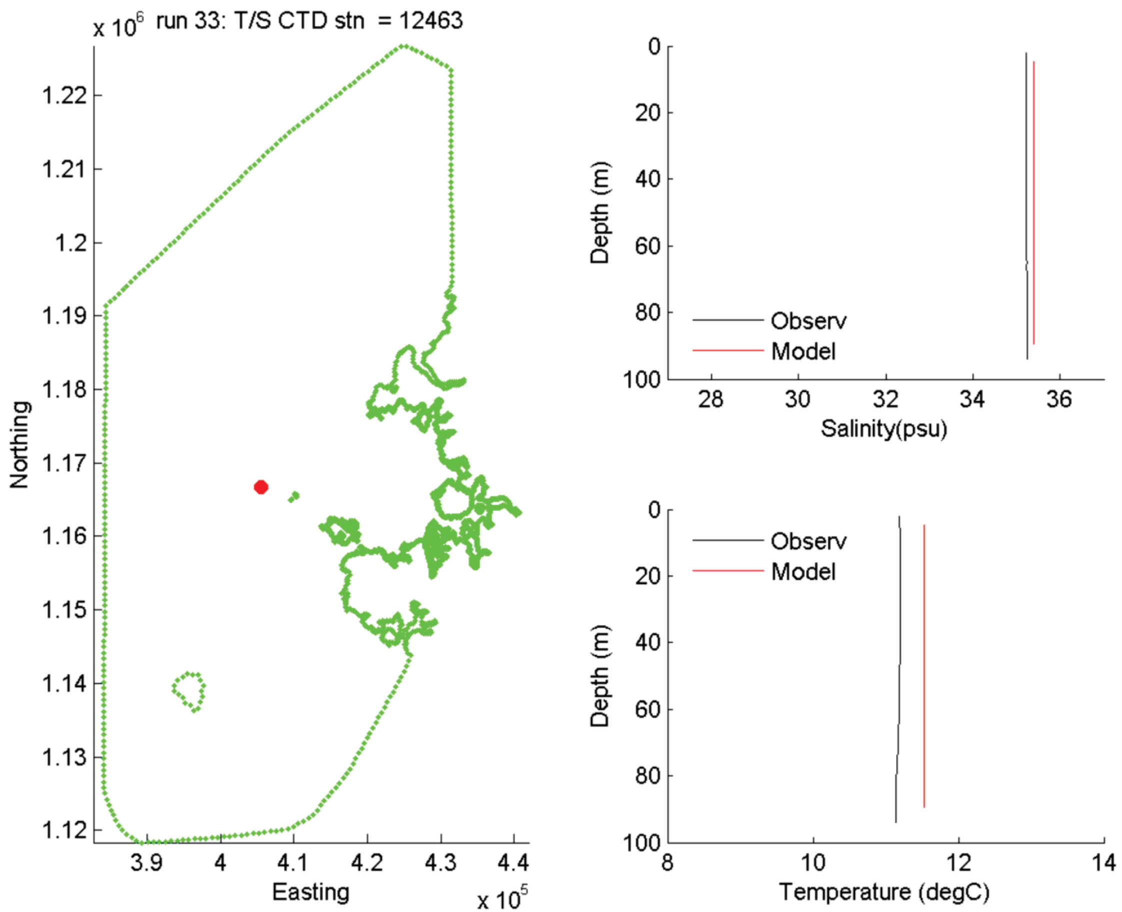

| Client | Consulting Engineer | Project: | Figure Title: | Figure B26 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



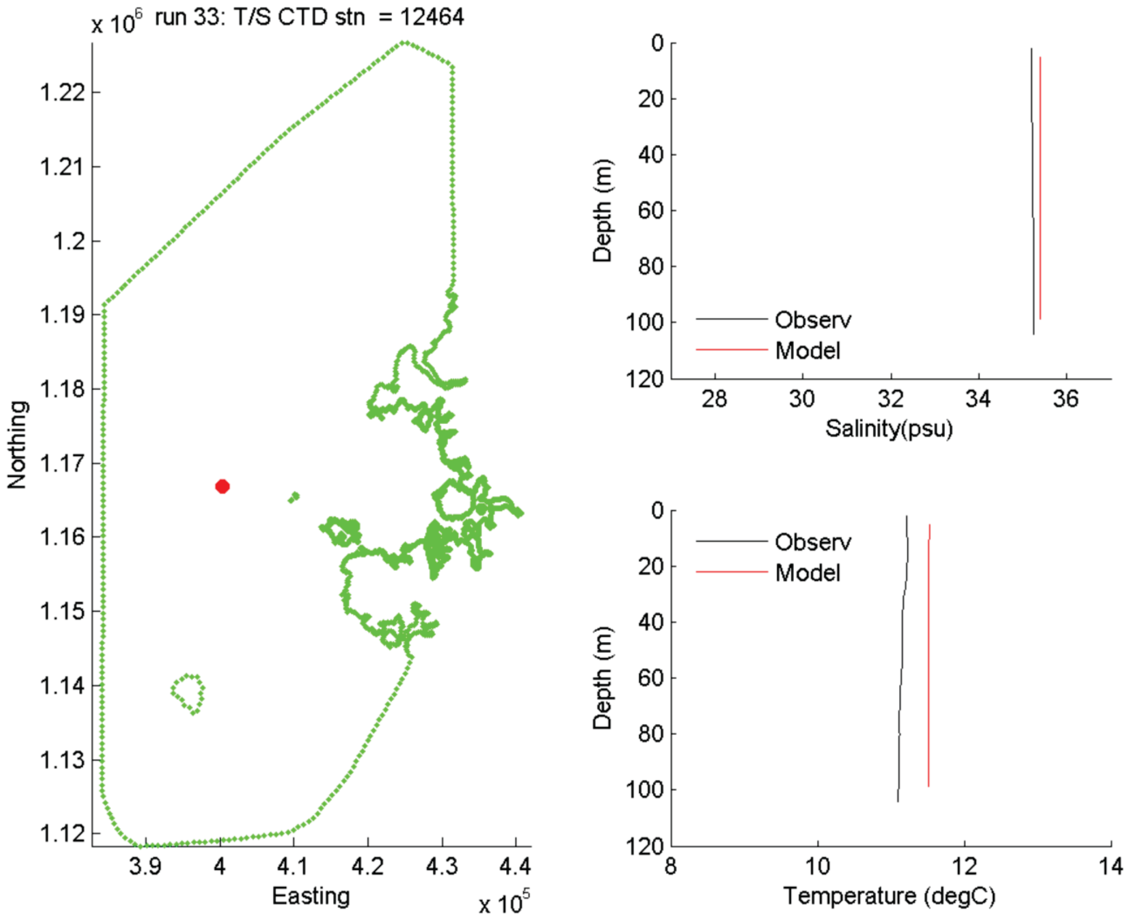

| Client | Consulting Engineer | Project: | Figure Title: | Figure B27 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



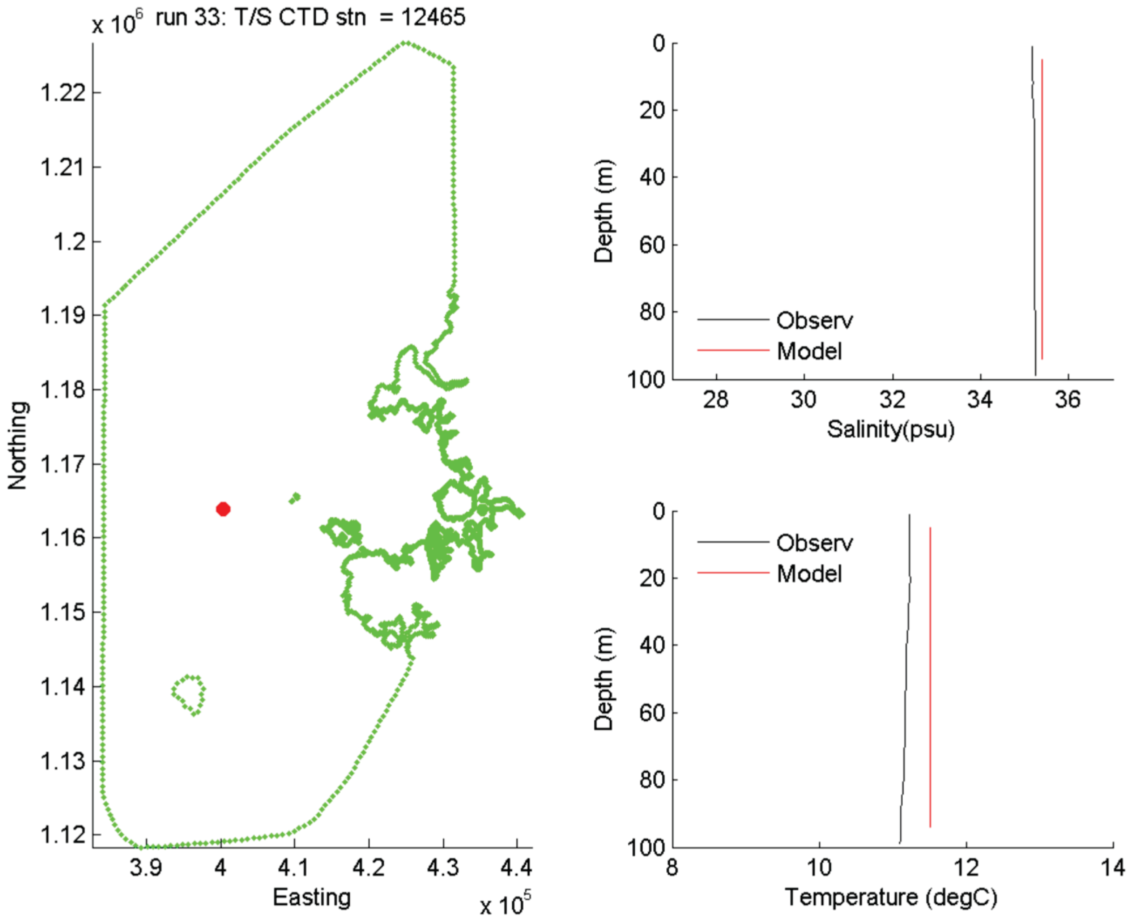

| Client | Consulting Engineer | Project: | Figure Title: | Figure B28 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



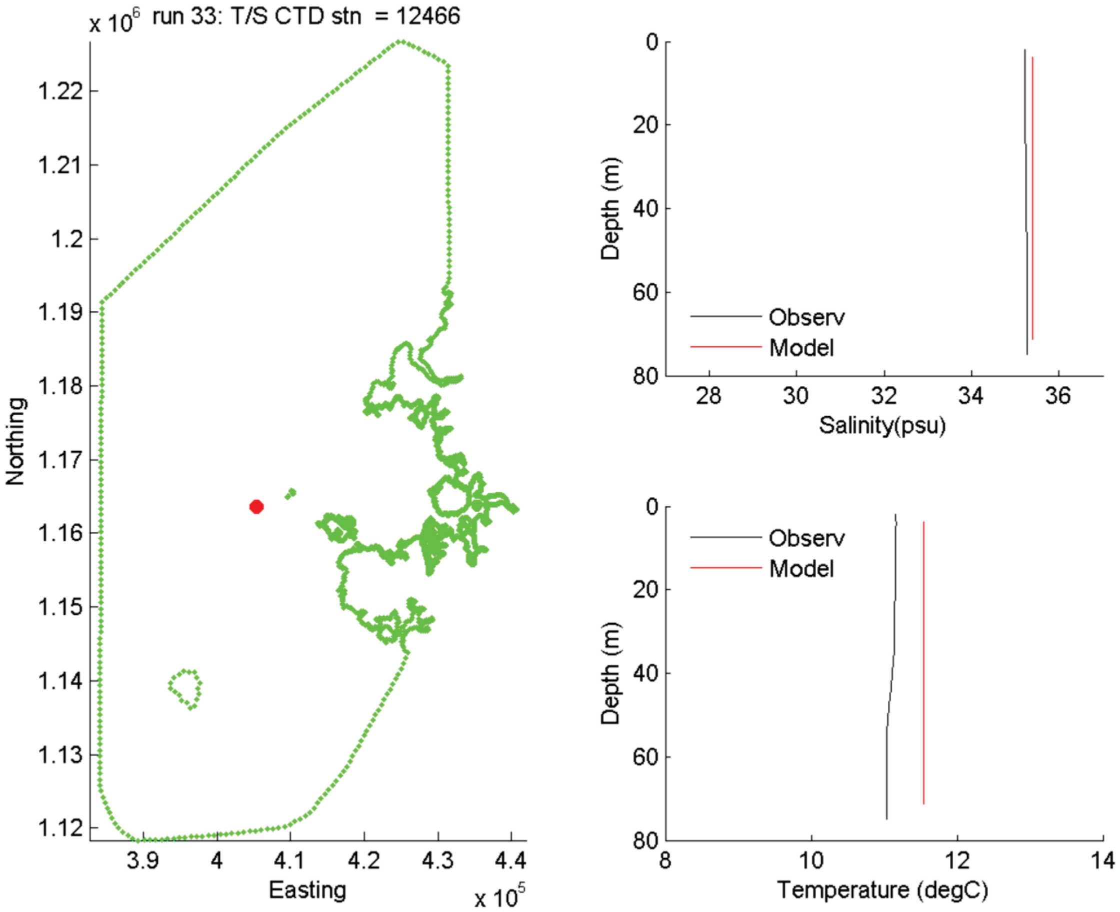

| Client | Consulting Engineer | Project: | Figure Title: | Figure B29 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



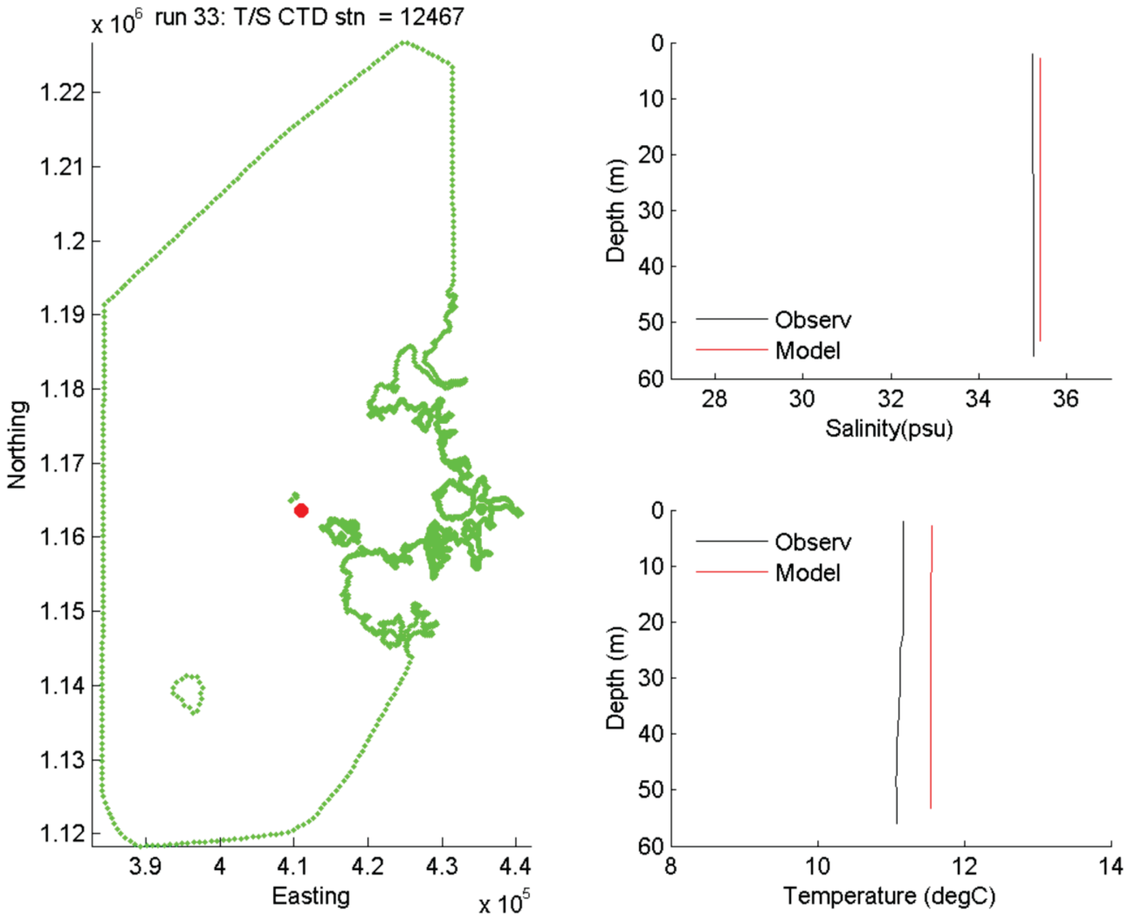

| Client | Consulting Engineer | Project: | Figure Title: | Figure B30 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



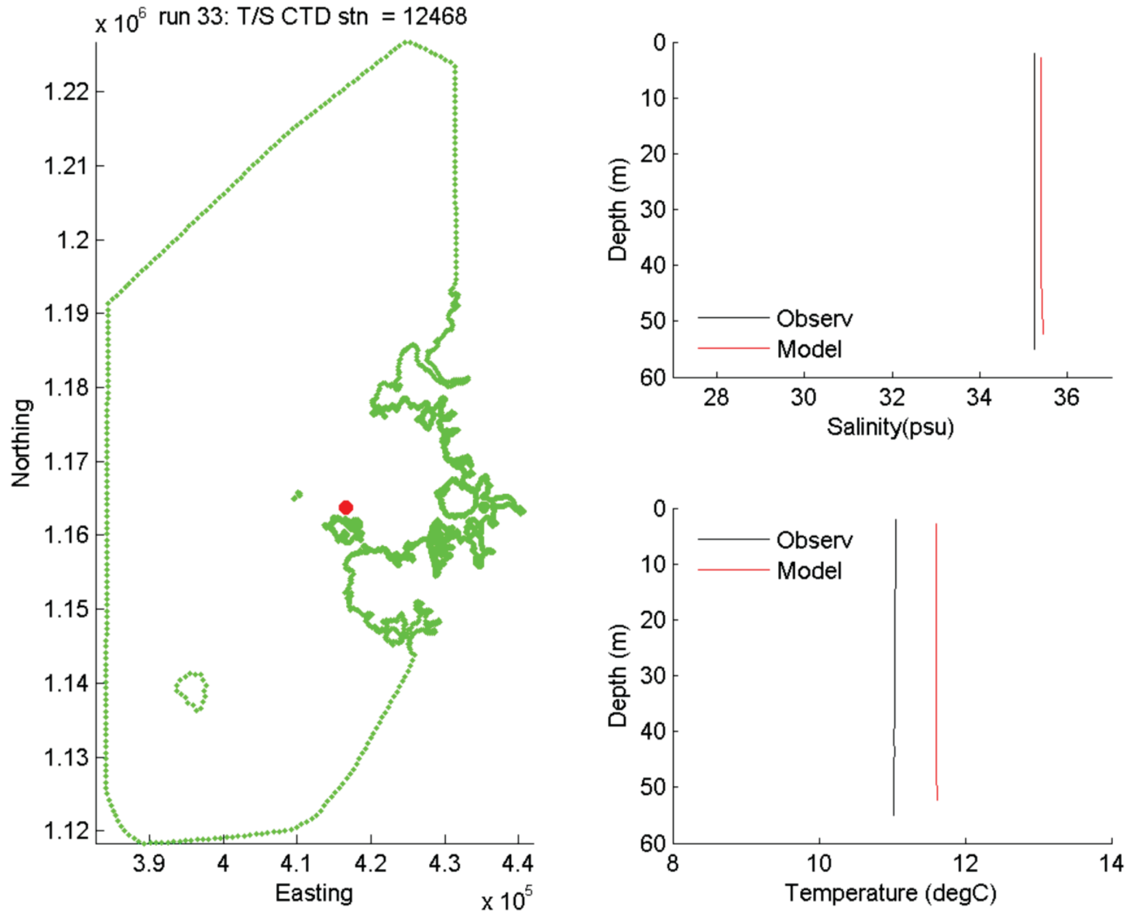

| Client | Consulting Engineer | Project: | Figure Title: | Figure B31 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B32 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B33 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B34 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
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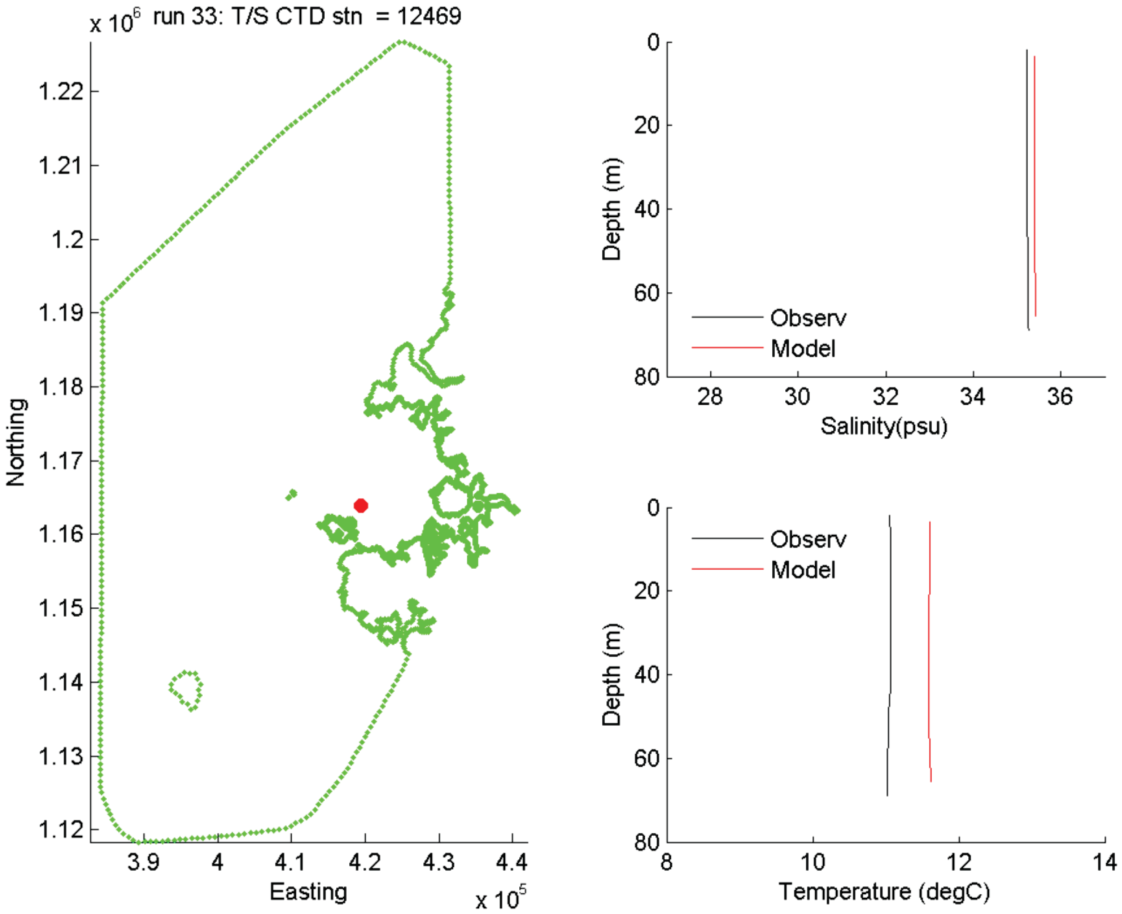


| Client | Consulting Engineer | Project: | Figure Title: | Figure B35 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
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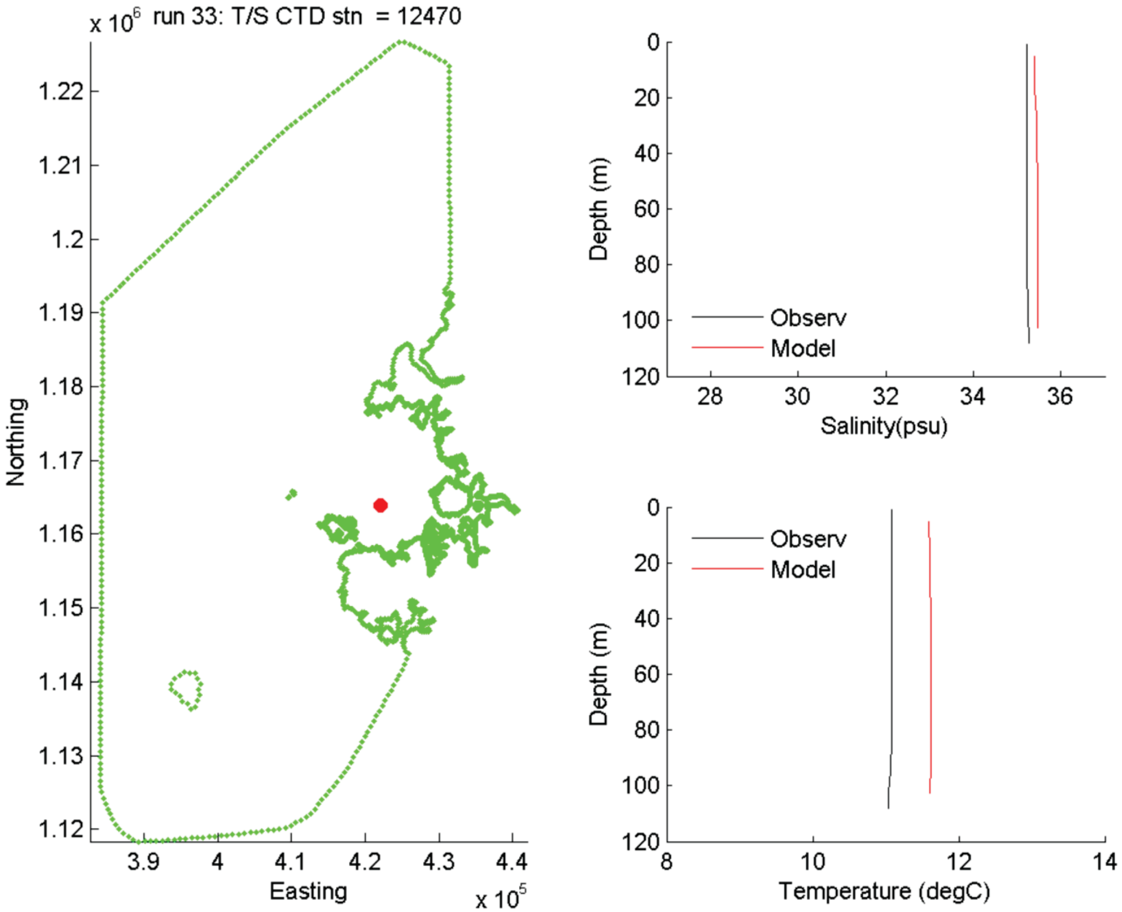


| Client | Consulting Engineer | Project: | Figure Title: | Figure B36 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
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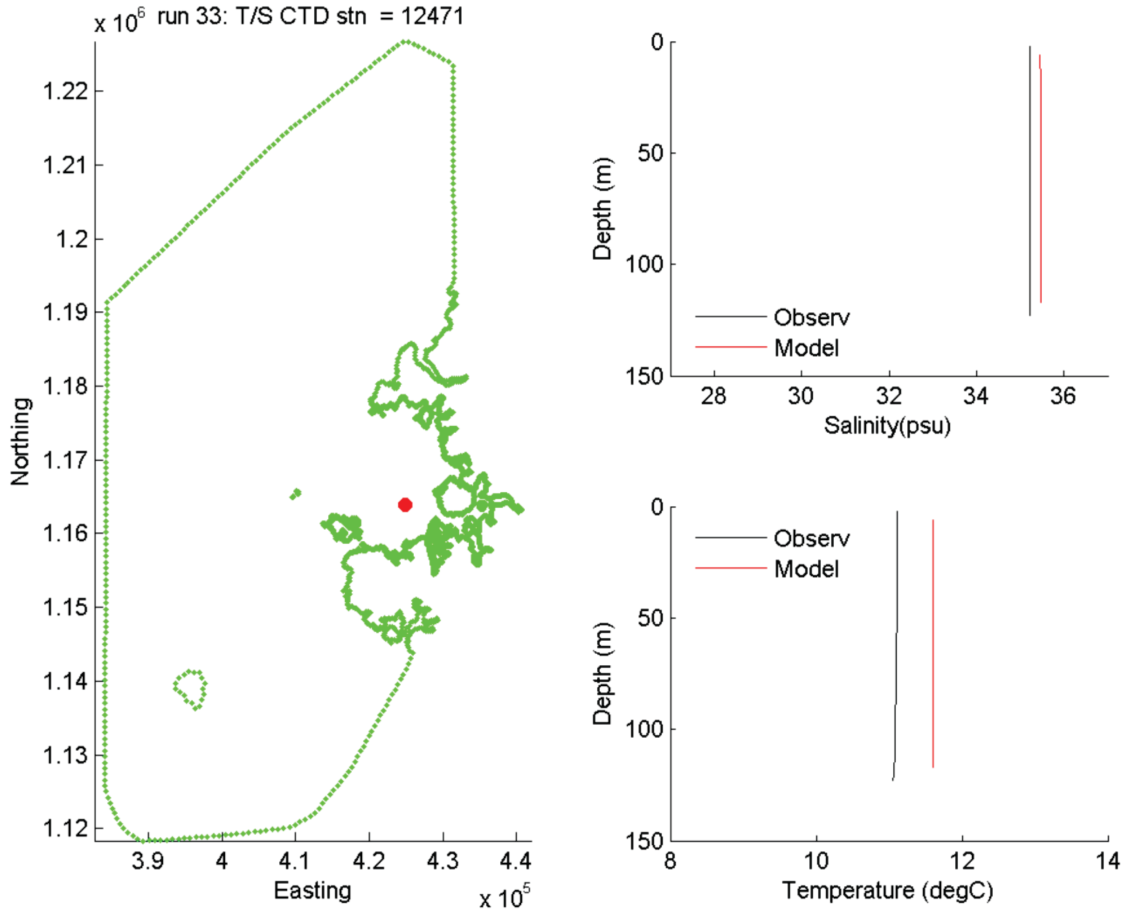
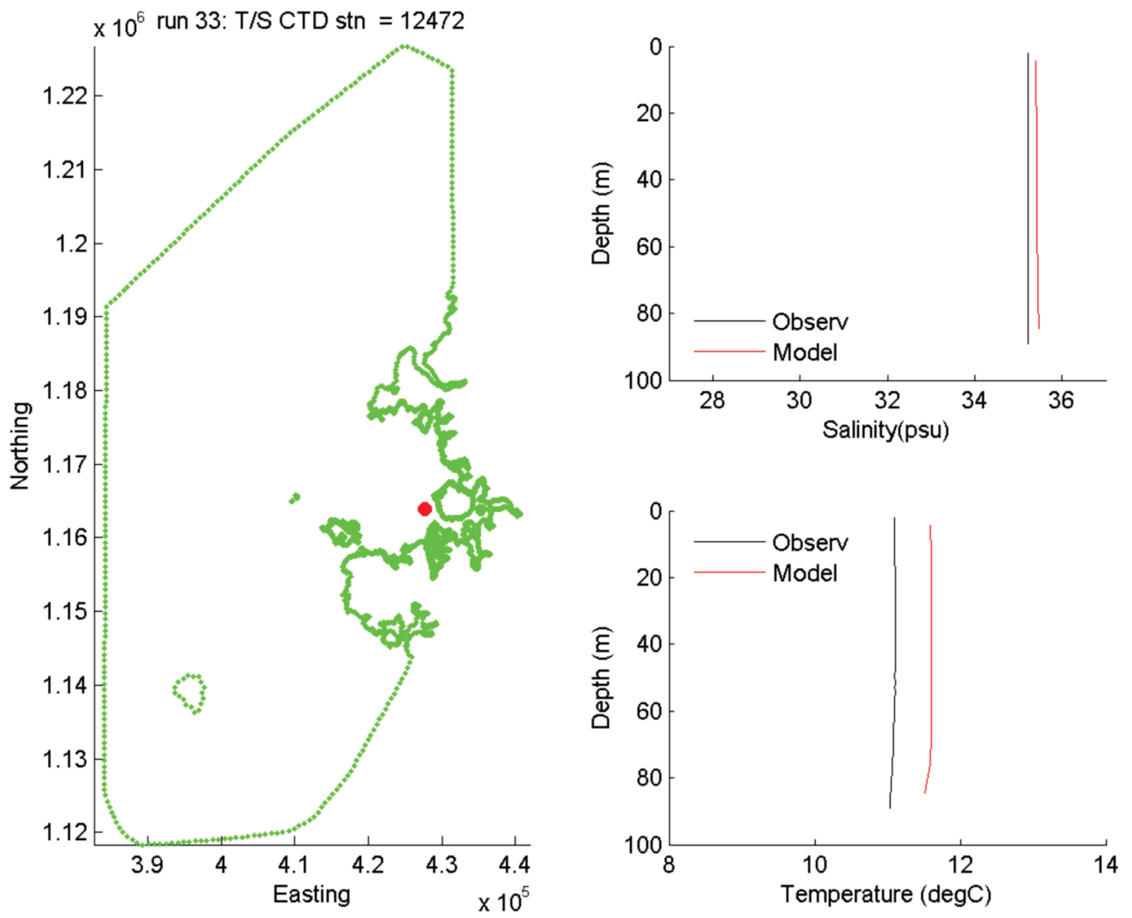
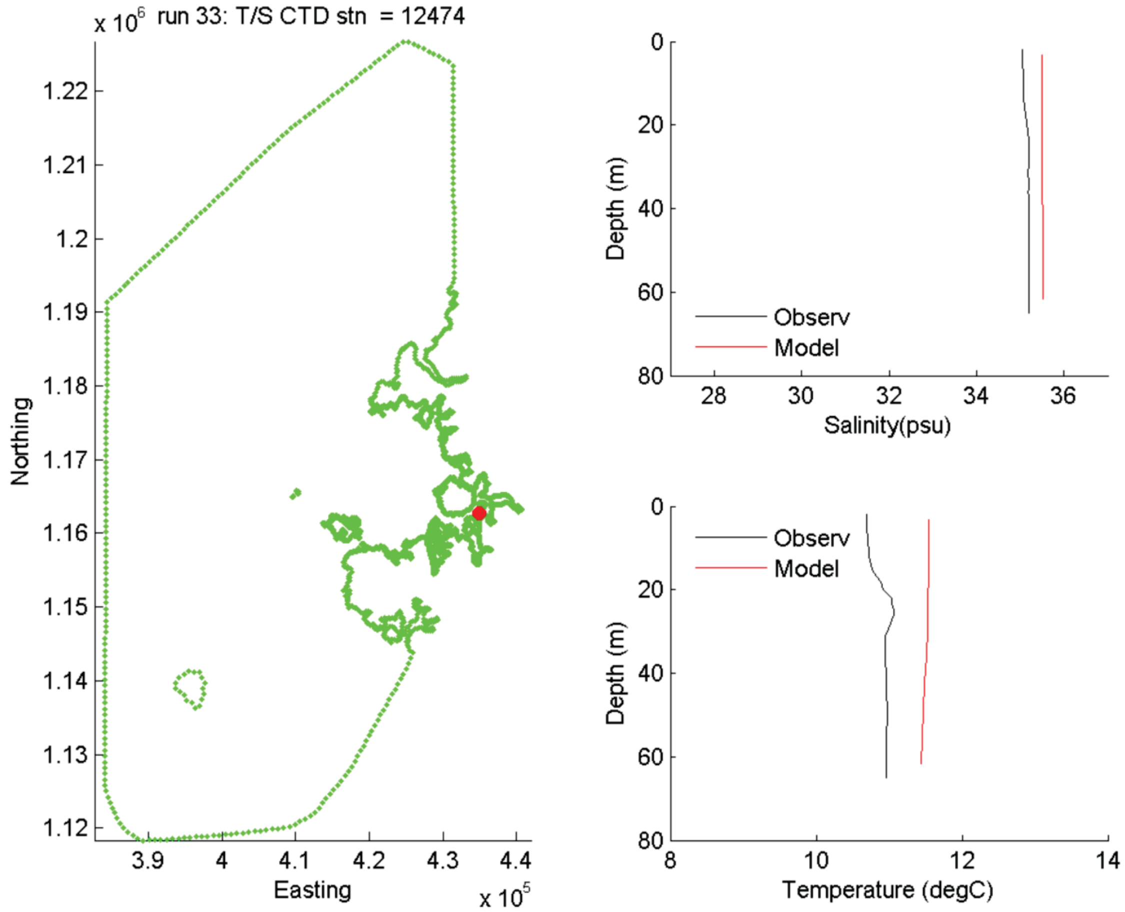


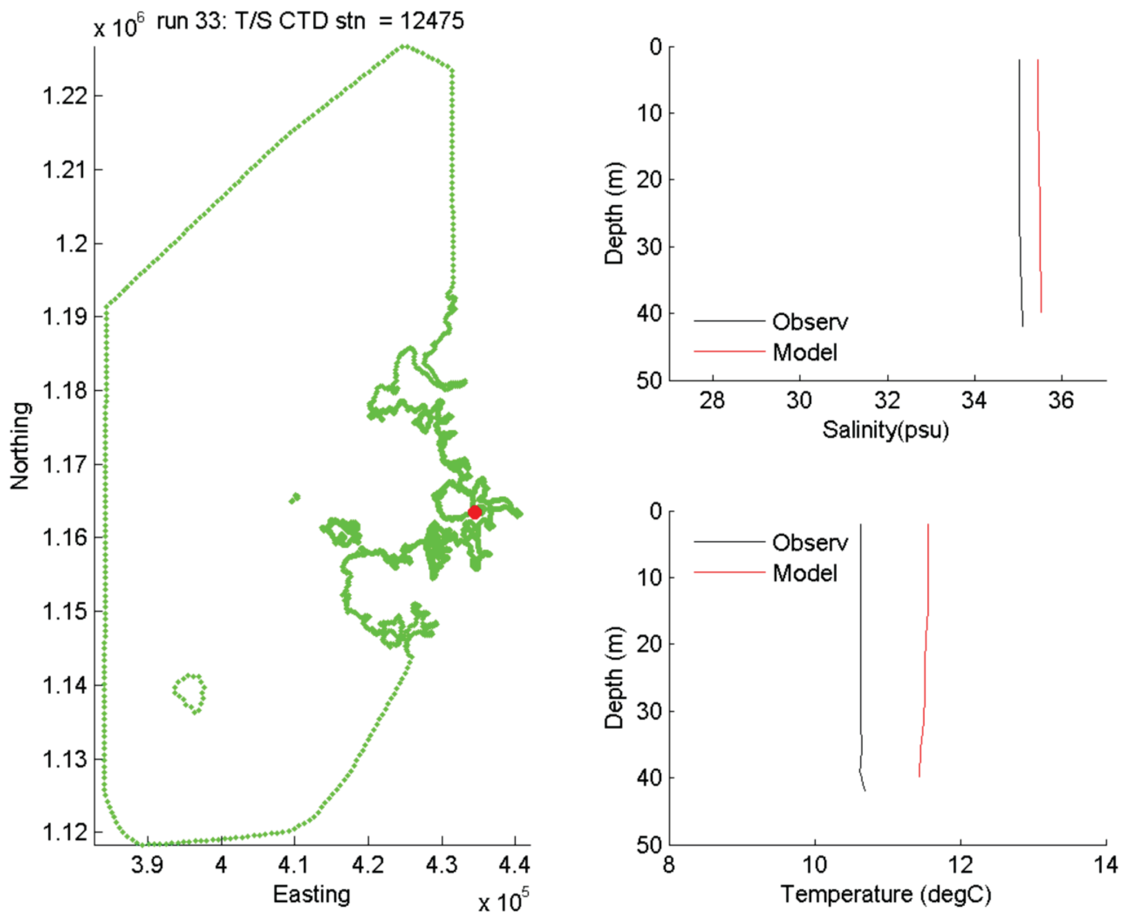

| Client | Consulting Engineer | Project: | Figure Title: | Figure B37 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



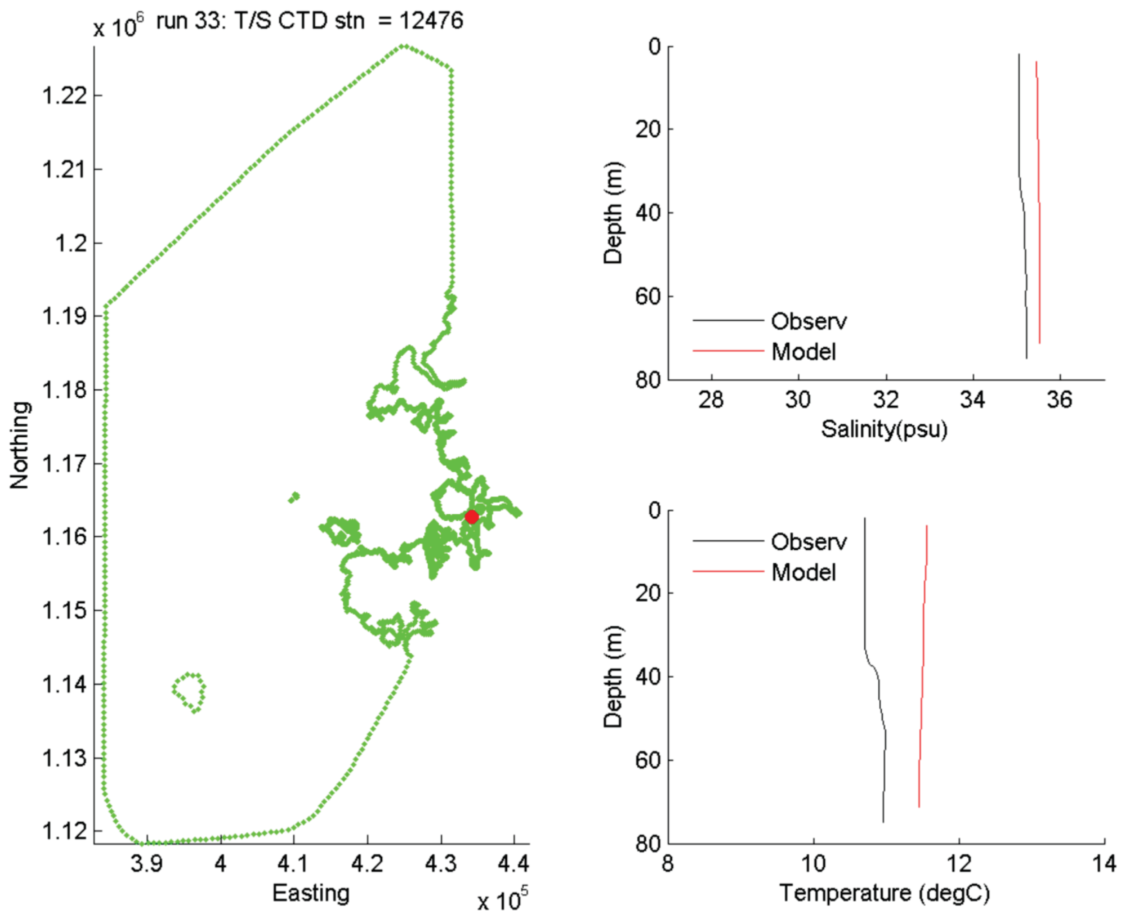

| Client | Consulting Engineer | Project: | Figure Title: | Figure B38 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



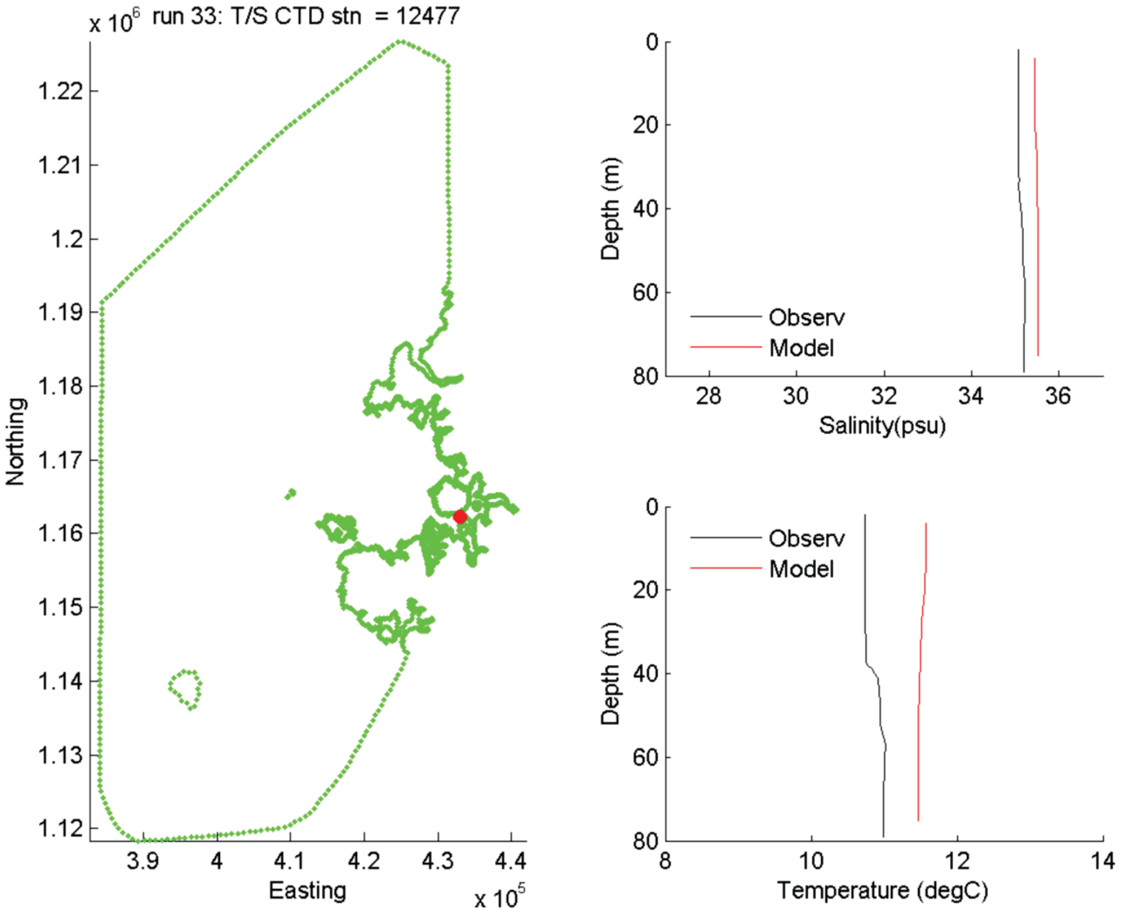

| Client | Consulting Engineer | Project: | Figure Title: | Figure B39 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



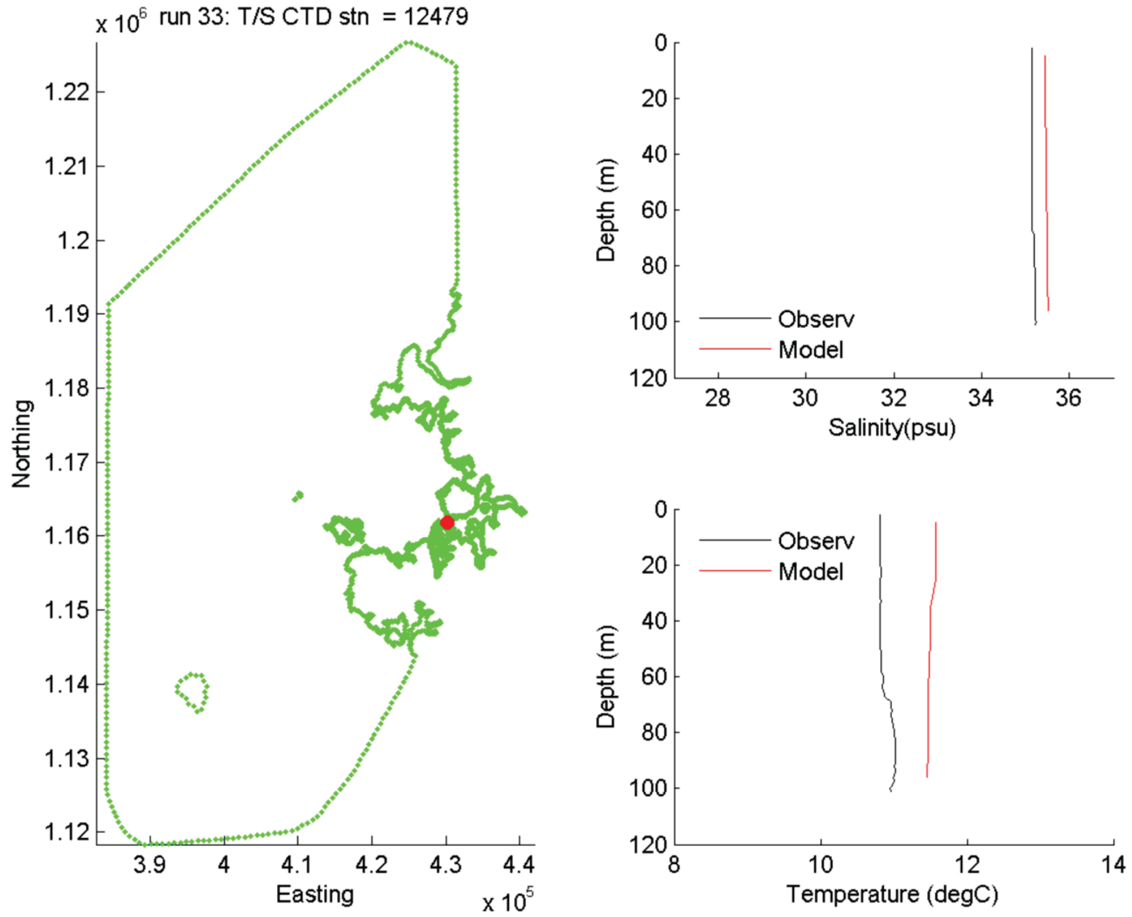

| Client | Consulting Engineer | Project: | Figure Title: | Figure B40 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: DMP | Drawn: | Date: 14/112012 |



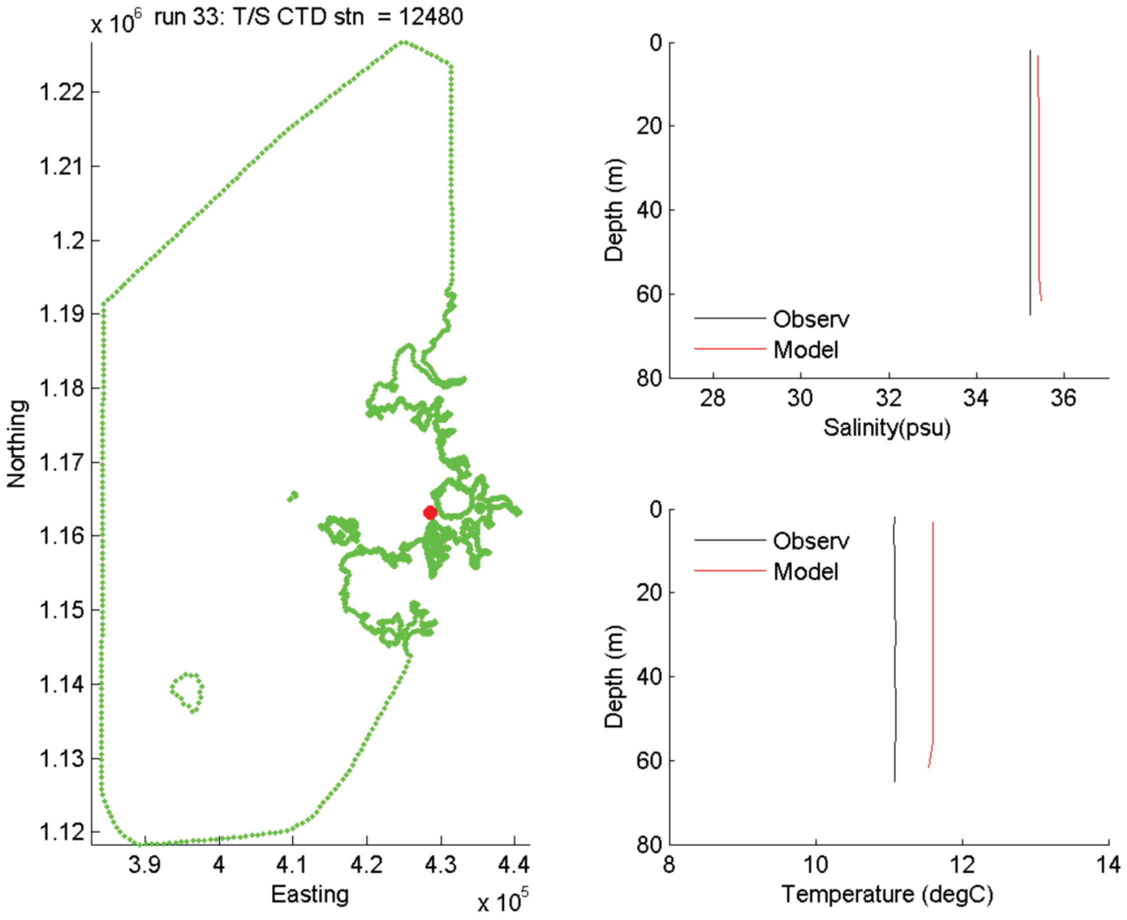

| Client | Consulting Engineer | Project: | Figure Title: | Figure B41 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



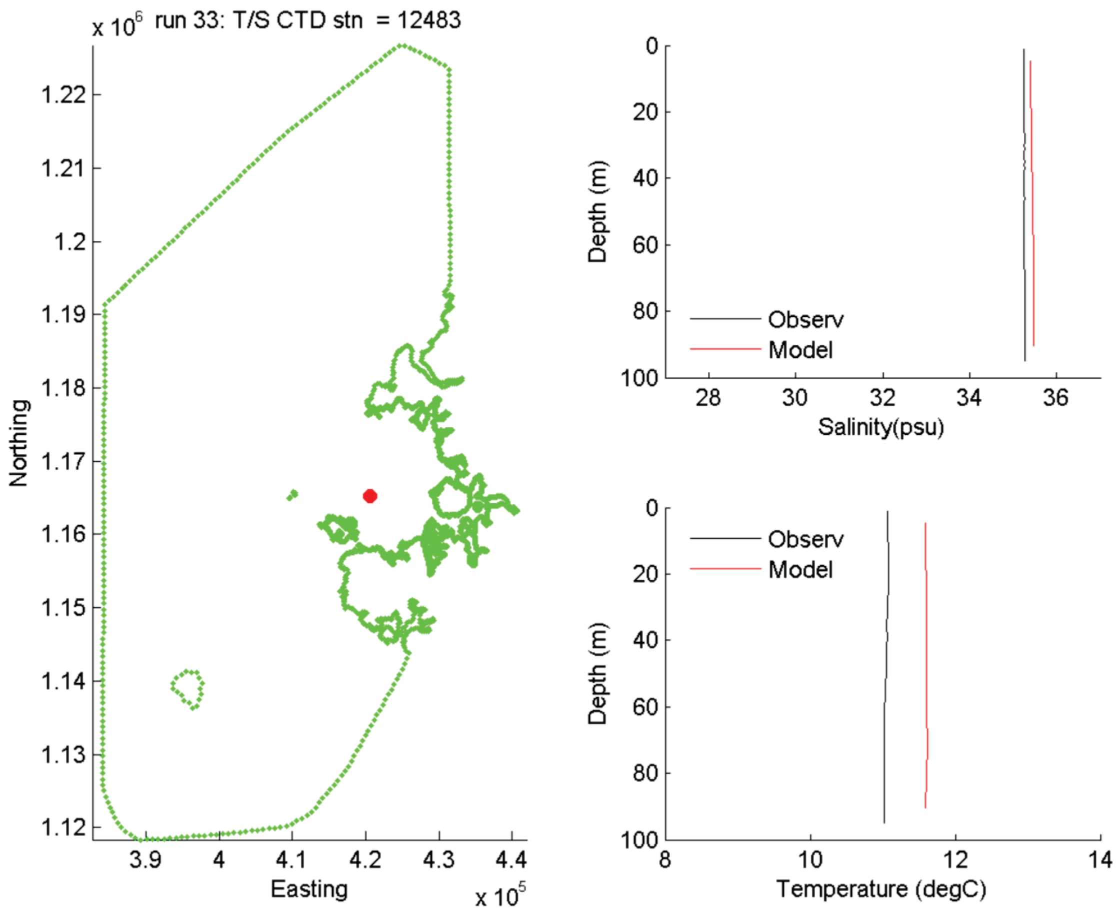

| Client | Consulting Engineer | Project: | Figure Title: | Figure B42 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



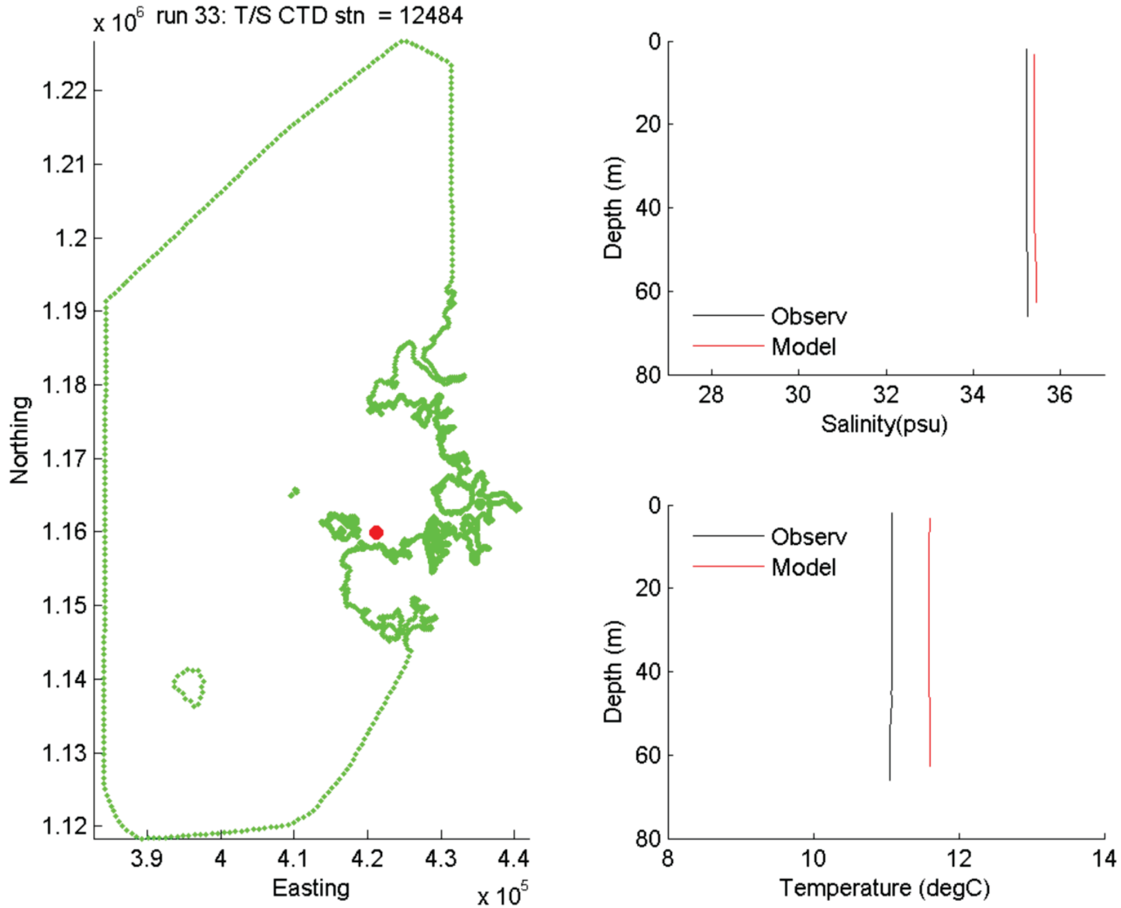

| Client | Consulting Engineer | Project: | Figure Title: | Figure B43 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



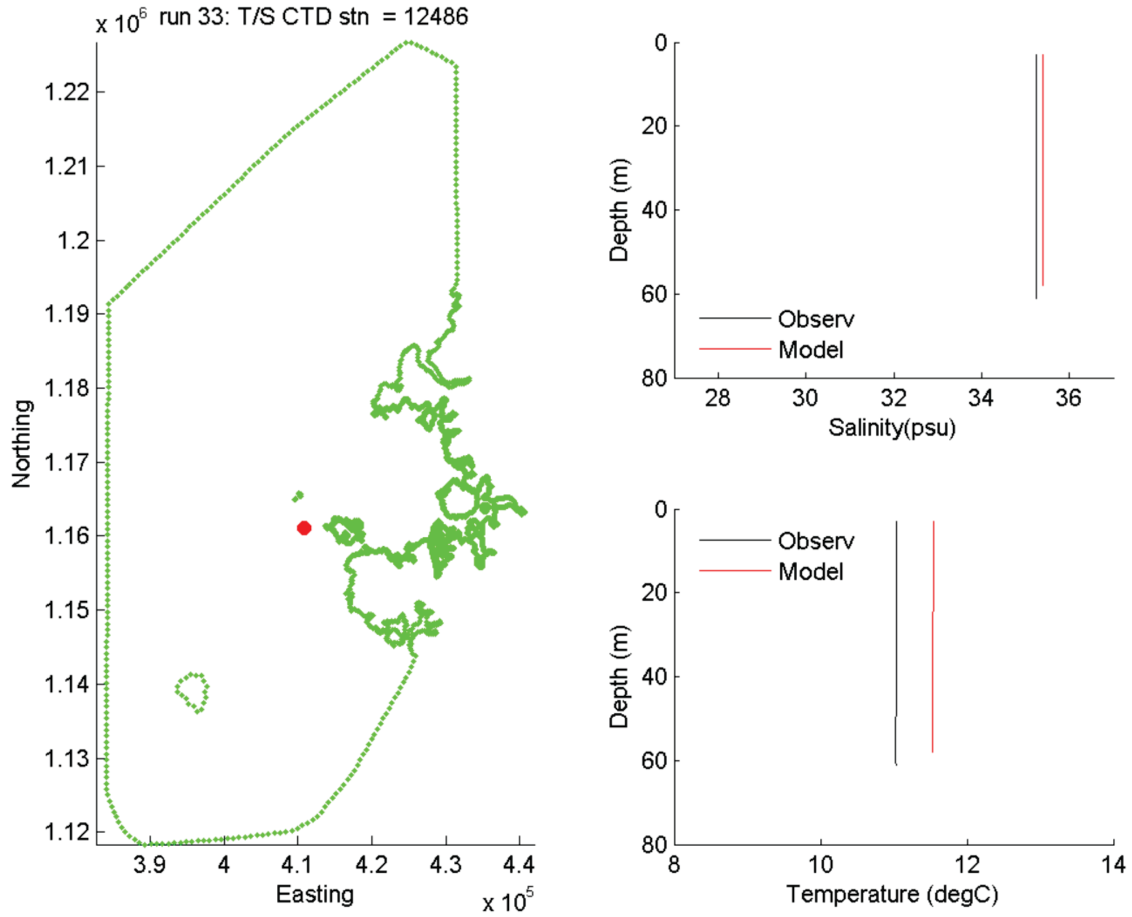

| Client | Consulting Engineer | Project: | Figure Title: | Figure B44 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |



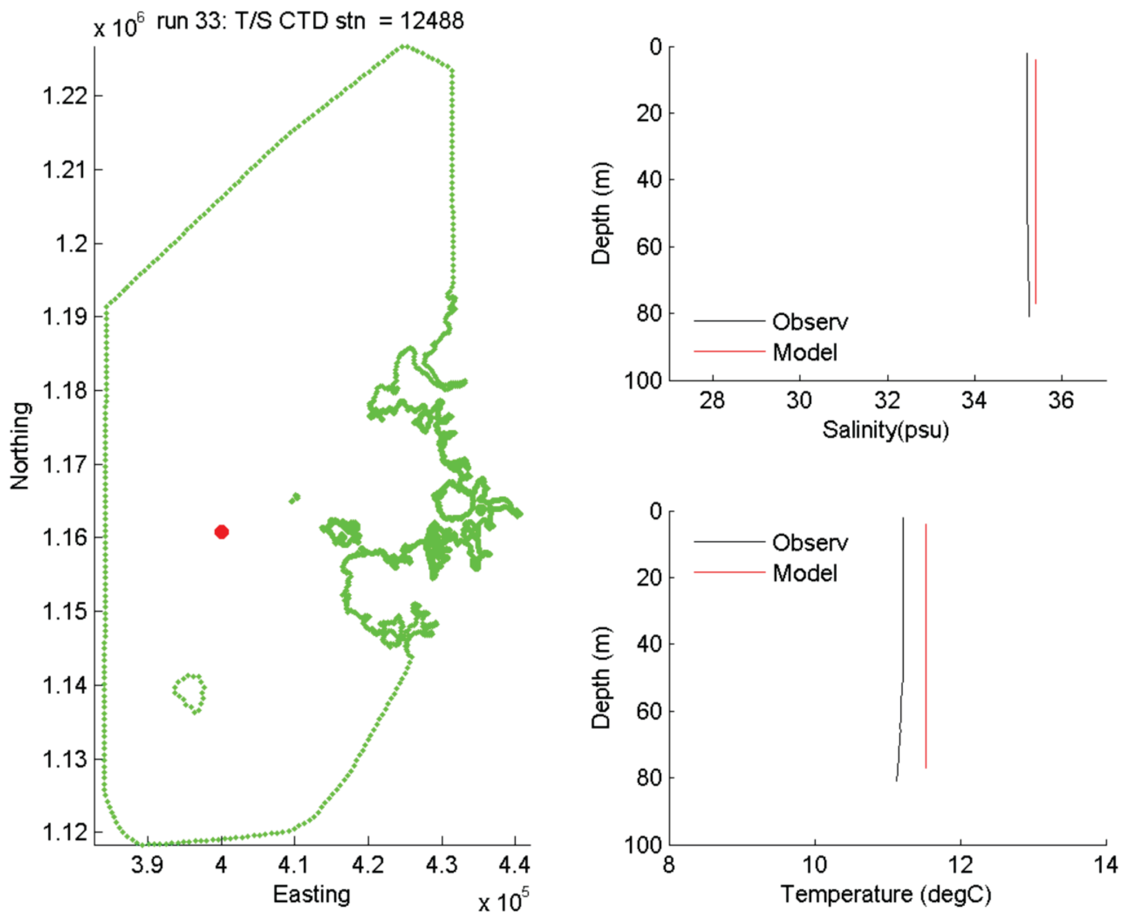

| Client | Consulting Engineer | Project: | Figure Title: | Figure B45 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B46 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B47 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B48 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | St Magnus Bay Model | Comparison between observed temperature and salinity profiles and those predicted by the SMB model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed DMP | Drawn | Date 14/112012 |

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