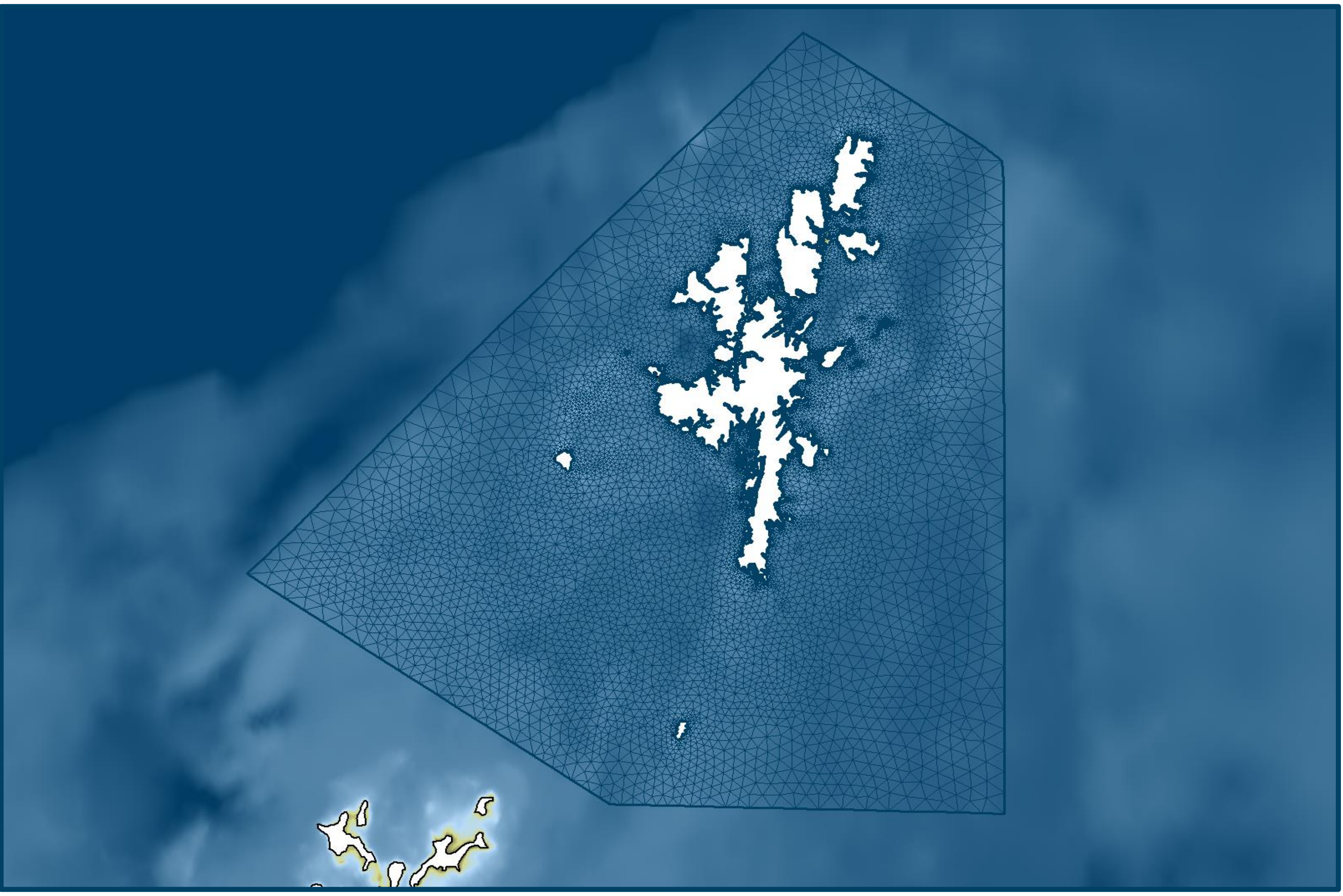
Shetland Aquaculture Modelling

Hydrodynamic Climatology Model

Model Setup Report



Report

May 2021

The expert in **WATER ENVIRONMENTS**

Shetland Aquaculture Modelling

Hydrodynamic Climatology Model

Model Setup Report

Prepared for Scottish Sea Farms Ltd. & Grieg Seafood Shetland Ltd.
Represented by [redacted] (Scottish Sea Farms Ltd.)
[redacted] (Grieg Seafood Shetland Ltd.)

Domain and bathymetry of regional Shetland hydrodynamic model

Project manager	[redacted]
Quality supervisor	[redacted]

Project number	26801650
Approval date	18th May 2021
Revision	Final 1.0
Classification	**Restricted**

DHI WATER ENVIRONMENTS (UK) LTD • Ocean Village Innovation Centre • Ocean Way • SO14 3JZ
Southampton • United Kingdom
Telephone: +44 (0)2380 381961 • www.dhigroup.com
Company Reg. No.: 07890711

CONTENTS

FIGURES

TABLES

APPENDICES

NOMENCLATURE

Abbreviations	
CEH	Centre for Ecology and Hydrology
CD	Chart Datum
DTM	Digital Terrain Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EMODnet	European Marine Observation and Data Network
FM	Flexible Mesh
FVCOM	Finite-Volume Community Ocean Model
GSS	Grieg Seafood Shetland
HD	Hydrodynamic
HWS	High water shoreline
IOS	Institute of Oceanographic Sciences
LAT	Lowest Astronomical Tide
MPFF	Marine Pen Fish Farm
MSL	Mean-Sea-Level
OGL	Open Government License
OS	Ordnance Survey
PSU	Practical Salinity Unit
RANS	Reynolds Averaged Navier-Stokes
SEPA	Scottish Environment Protection Agency
SSF	Scottish Sea Farms
SSM	Scottish Shelf Model
TKE	Turbulent Kinetic Energy
TS	Temperature and Salinity
UKHO	United Kingdom Hydrographic Office
UTM	Universal Transverse Mercator
WGS	World Geodetic System
2D	Two-dimensional
3D	Three-dimensional

Definitions	
Time	Times are relative to UTC
Level	Levels are relative to MSL, CD, or LAT as specified
Co-ordinate system	Horizontal datum are established using World Geodetic System 1984 (WGS 84), UTM zone 30N
Direction	Wind: °N coming from and positive clockwise
	Currents: °N going to and positive clockwise

Abbreviations – Quality Indices	
N	Number of data (synchronized)
MEAN	Mean (average) values
STD	Standard deviation
BIAS	Mean difference
AME	Absolute mean error
RMSE	Root mean square error
SI	Scatter index (unbiased)
EV	Explained variance
CC	Correlation coefficient
QQ	Quantile-Quantile (line slope and intercept)
PR	Peak ratio (of Number of peak highest events)

Tidal Levels	
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
MHWS	Mean High Water Spring
MHWN	Mean High Water Neap
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
Z_0	Mean Water Level

ACKNOWLEDGEMENT

We wish to acknowledge the generous assistance provided by the Marine Scotland Science Oceanography group for providing access to the Scottish Shelf Model.

Executive Summary

Scottish Sea Farms and Greig Seafood Shetland are two of the leading producers of farmed Atlantic salmon throughout Shetland, Scotland. To support ongoing operations, site developments, and regulatory applications, the companies require detailed numerical hydrodynamic models of the islands. A particular focus is on the area around Scalloway (south-west of mainland Shetland) which contains a relatively high density of aquaculture sites.

This report describes the development of a 3-dimensional hydrodynamic climatology model database for Shetland. Climatology models offer a simple technique for predicting the mean status of the atmospheric and oceanographic conditions over an annual period. The Shetland model is a down-scaled version of the Scottish Shelf Model (SSM), developed for and maintained by Marine Scotland Science, to describe the circulation of the Scottish continental shelf waters.

The hydrodynamic climatology models for Shetland have been established using the MIKE 3 modelling suite developed by DHI. This model simulates the water level variations and flows in response to a variety of forcing functions. The models are based on a variable resolution unstructured horizontal mesh with 10 vertical sigma layers. Two models have been developed at different spatial scales. First, a regional model of Shetland with a resolution of between 500m and 250m in the coastal areas. The regional model is forced by offshore boundaries and climatologically averaged meteorological conditions from the SSM. The regional model is verified against the SSM at offshore locations. Second, a local model of the Scalloway area of south-west Shetland with highly refined spatial resolution of around 50m in the area around existing marine pen fish farms. The Scalloway model is a down-scaled version of the regional Shetland model.

The hydrodynamic climatology model database for Shetland is provided alongside this report. This includes the numerical mesh, the model boundaries conditions, meteorological forcing, setup files, and the model output (result) files.

1 Introduction

This report has been prepared for **Scottish Sea Farms Ltd.** (SSF) and **Greig Seafood Shetland Ltd.** (GSS) by DHI in relation to hydrodynamic modelling services for aquaculture sites in Shetland. The project will establish dedicated three-dimensional hydrodynamic numerical models for the waters around Shetland:

- A one-year hydrodynamic climatology model
- A one-year hydrodynamic re-analysis (hindcast) model

This document and its accompanying appendices constitutes the **hydrodynamic climatology model** report.

1.1 Background to the study

Shetland is an archipelago of over 100 islands located approximately 200km north of mainland Scotland. The islands mark the divide between the North Atlantic Ocean (to the west) and the North Sea (to the east). The rugged 2,700km coastline is characterised by numerous inlets (voes) and bays. Shetland has an oceanic climate and the Island’s economy is closely linked to the sea; the main industries being offshore oil and gas, fishing, and aquaculture.

Aquaculture produces Scotland's most valuable food export and Shetland is among the country’s primary aquaculture regions, with over 180 active finfish and shellfish sites. The area is responsible for producing around one third of the Scottish farmed salmon. SSF and GSS are two of the main producers of farmed salmon in Shetland. Between them, the companies currently operate around 25 active fish farms, situated throughout the islands. SSF and GSS are seeking to understand the connectivity between aquaculture sites in Shetland, with a focus on the optimisation of active sites, and the opportunities for the re-opening of the inactive sites. The area around Scalloway (located in a large bay known as *the Deeps,* south-west of Shetland Mainland) is a particular importance, as this region contains a high density of licensed aquaculture sites.

Operational fish farms have the potential to affect the marine environment in several ways via the release of waste materials in the form of dissolved nutrients, medicines, and particulate organic matter. The management of the risks surrounding salmon lice are also of fundamental importance to producers. Consequently, the aquaculture sector is highly regulated by the Scottish Government. There is a requirement for fish farm operators to use modelling tools to demonstrate compliance with the environmental standards relating to the spatial extent and the intensity of impacts, both in the local area around fish pens and in the wider environment. Increasingly, operators are required to use marine hydrodynamic modelling approaches to support of license applications. Hydrodynamic modelling refers to a class of numerical models that simulate the flow of water within a specified geographic area in a physically realistic way. This includes flow due to a range of forcing conditions including tidal variations, density gradients, and meteorological factors (air pressure and wind). Hydrodynamic models provide the physical basis for many other types of numerical environmental modelling such as the transport, dispersion, and decay of dissolved or suspended substances.

1.2 Aims and objectives

The overall aim of the project is to develop a suite of 3-dimensional hydrodynamic models to support aquaculture development in the waters around Shetland.

To achieve this aim, the objectives of this hydrodynamic modelling report are to:

- Develop a regional 3-dimensional hydrodynamic climatology model that predicts the dynamics (marine currents and water properties) and water exchange around Shetland due to tidal and non-tidal forcing.
- Develop a dedicated, high-resolution, 3-dimensional hydrodynamic climatology model of the Scalloway Area (south-west Shetland). This area is of particular interest to both SSF and GSS due to a relatively high density of aquaculture sites.

The models will provide a database for future modelling to support regulatory applications such as: assessing connectivity between fish farms sites around Shetland; site selection and site screening; dispersion modelling of waste solids and bath treatment medicines; and to provide boundary conditions for local scale models.

Climatology Model

The fundamental principle of a climatology model is the assumption that the conditions for a particular day (or month) and at a particular location do not change significantly from one year to the next; hence, the long-term average conditions on a certain day (or month) should be a good approximation to the expected conditions for that day (or month). This offers a simple technique for predicting the *mean status* of the atmospheric and oceanographic conditions within a region (i.e. to understand the seasonal variability, but not to the interannual variability).

The hydrodynamic climatology model thus provides a useful reference for how the expected flow patterns, temperature, and salinity vary over seasonal cycles that are driven by tide, the wind climate, and gradients in water density. However, the climatology model output does not reflect the synoptic scale forcing (e.g. episodic winter storms) which occur at relatively high frequency.

1.3 Layout of this report

The remaining sections of this report are organised as follows:

- Section 2 summarises information on the geographic and environmental setting of Shetland.
- Section 3 provides an overview of the data basis for the modelling study, including coastline, bathymetry, boundary conditions, and meteorological forcing.
- Section 4 describes the setup of the 3D hydrodynamic model of Shetland and the high-resolution local Scalloway model. This includes the mesh and bathymetry development, initial and boundary conditions, model settings, and outputs.
- Section 5 presents the model results and output, including a verification of the regional hydrodynamic climatology.
- Section 6 provides a summary of the hydrodynamic model climatology.

2 Geographic and environmental setting

2.1 Geographic setting

Shetland is an archipelago in the North Sea consisting of approximately 100 islands, of which approximately 16 are inhabited. The islands are located approximately 200km from north coast of mainland Scotland, 280km south-east of the Faroe Islands, and 350km west of Bergen, Norway (Figure 2.1).

Shetland itself spans a distance of almost 160km, from Fair Isle in the south to Muckle Flugga in the north, and represents the northernmost extremity of the United Kingdom. The largest island is called “the Mainland” and is home to around 80% of Shetland’s ~23,000 population. Settlements on the Mainland include Lerwick, the largest town and commercial centre, and the fishing port of Scalloway on the North Atlantic coast.

The coastline of Shetland is approximately 2,700km in length and is characterised by a rugged outer rocky shore and areas of high cliffs (particularly on the western facing shores). The inner part of the coastline comprised of many long open sea lochs (‘voes’), former river and glacial valleys that are now flooded by the sea. The steeply sloping and indented character of these voes has generally hindered the formation of large, sandy beaches around Shetland [1].

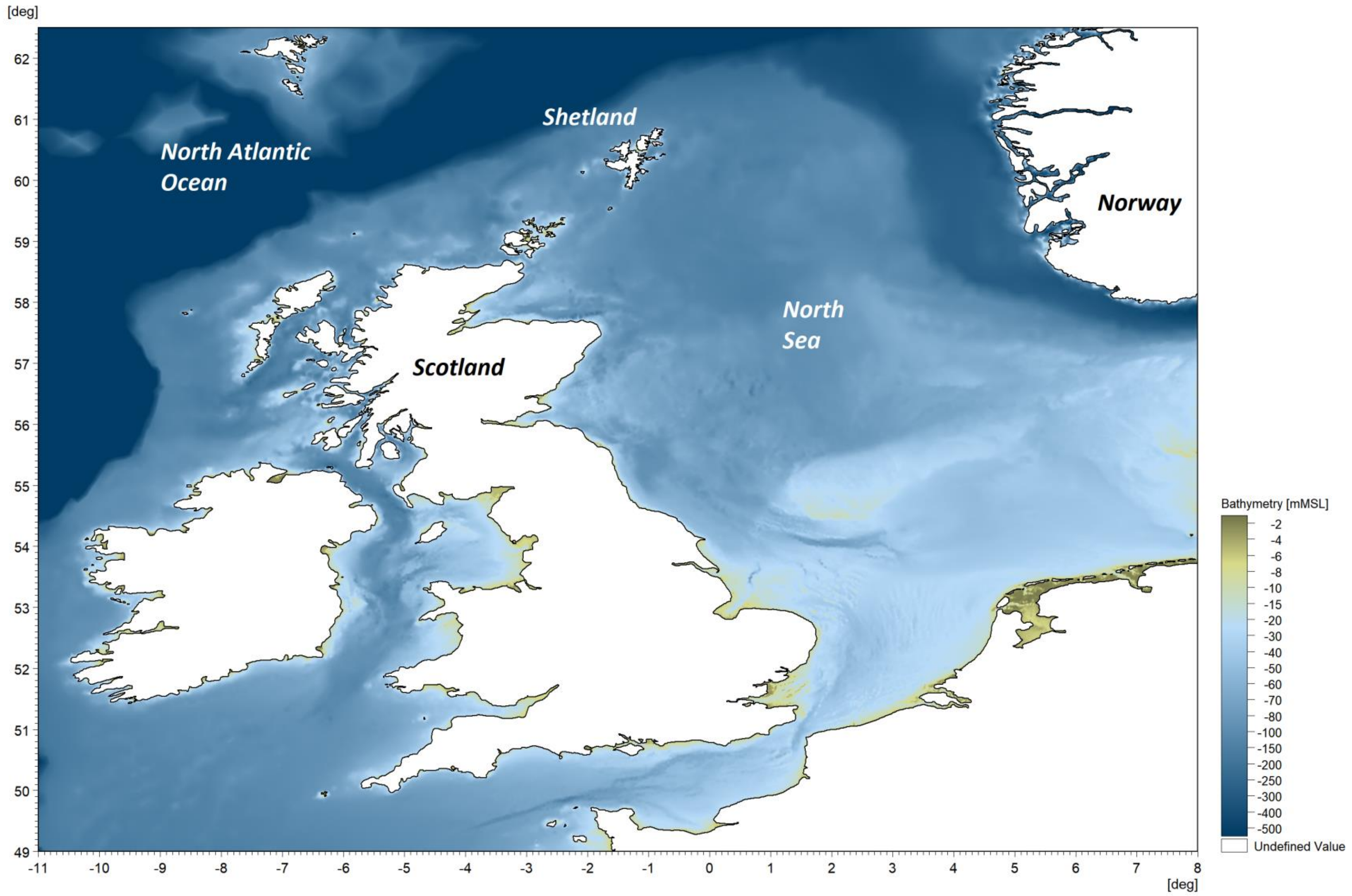


Figure 2.1 Map showing the geographic position of Shetland

2.2 Climatic and oceanographic conditions

Considering its position at around 60°N of the equator, the climate of Shetland is very mild compared to other parts of the world at a comparable latitude. This is explained by the role of the North Atlantic Current (Figure 2.2), a feature that is partly wind driven and partly driven by the density gradients between the warmer sub-tropical water (to the south) and the cooler sub-polar waters (to the north) [2]. The prevailing south-westerly winds pick up heat from the North Atlantic current, resulting in the relatively mild and wet maritime climate that characterises Scotland, and a relatively stable sea temperatures typically ranging from approximately 8°C in March to a peak of 13°C in August [1].

Although the prevailing wind direction is from the south-west, the passage of various low-pressure systems across the North Atlantic accounts for variability in the wind direction around northern and western parts of Scotland. This exposure to the North Atlantic means that Shetland is among the windiest parts of the United Kingdom, and the frequency and depth of these depressions is greatest in the winter months (December through to February). As Atlantic depressions pass the UK the wind typically starts to blow from the south-west, but often later comes from the west or north-west as the depression moves away [3]. The range of directions between south and north-west accounts for the majority of occasions and the strongest winds nearly always blow from these directions (see Figure 2.3). In addition to the North Atlantic Current, a jet-like feature known as the Slope Current, flows along the edge of the continental slope from south-to-north roughly at the 400-500m depth contour (see Figure 2.2). The waters in the Slope Current originate from southern Europe (Iberia) and include North Atlantic Water that reaches the Bay of Biscay [2].

The tides all around Scotland are semi-diurnal with characterised by a high and low water every ~12.5 hours. At Lerwick, the spring and neap tidal range are 1.58m and 0.74m, respectively (see Table 1 of [4]). This is set by the tides in the North Atlantic Ocean which propagate up the west coast of Scotland. Shetland acts as a natural blockage to the northwards sweep of the Atlantic tide, and the tidal wave swings eastwards to the north of the Islands and into the northern North Sea. The result is a difference in the timing of high and low-water between the east and west coast, which sets up strong tidal currents where the flow is constrained around the headlands and in narrow channels that connect the North Atlantic and North Sea [5]. However, in the enclosed and deep water voes tidal currents are generally weak and the circulation is strongly influenced by wind and density-driven current conditions.

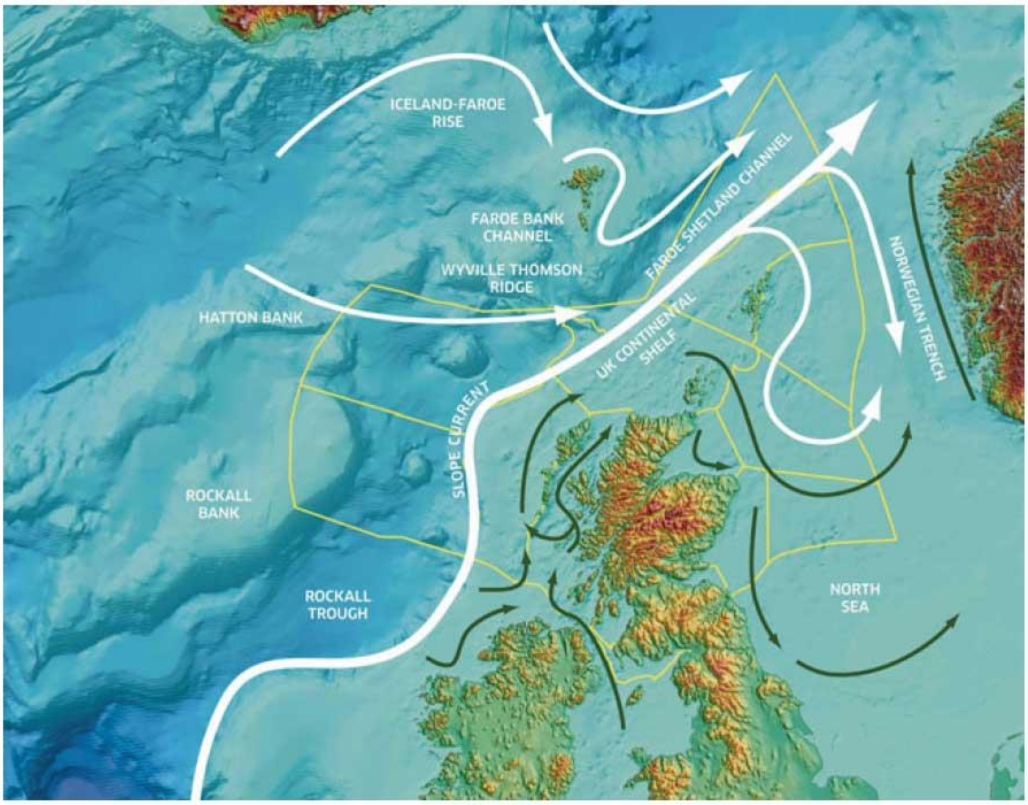


Figure 2.2 Map of the general circulation pattern within the North Atlantic and North Sea around Scotland (reproduced from [2]). The white arrows show the circulation of Atlantic water, while green arrows represent costal circulation

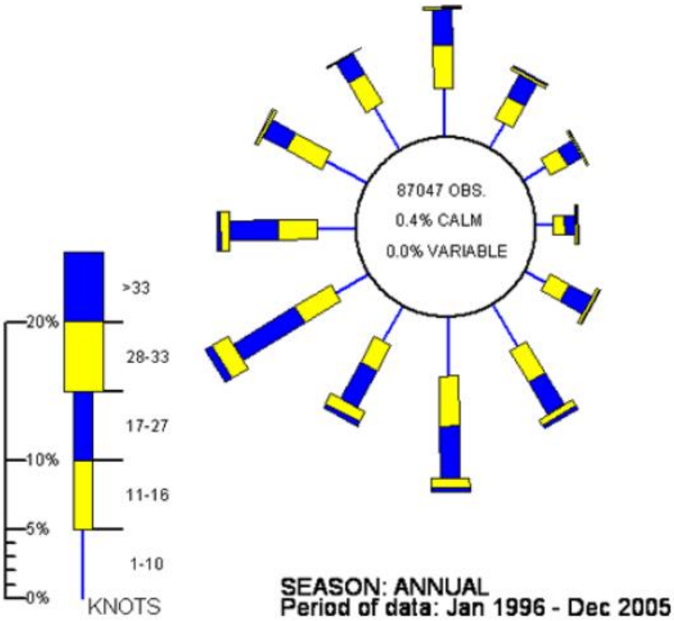


Figure 2.3 Annual (all-year) wind rose for Lerwick for the period 1996-2005 (Shetland), with a prevailing southwest wind direction through the year and frequent strong winds from southerly to north-westerly directional sectors (reproduced from [3])

2.3 Aquaculture in Shetland

Shetland has a greater dependence on aquaculture than other regions of Scotland, accounting for 26% of Scottish fin fish and 80% of shellfish production [1]. Production takes place within the voes and sounds around the coastline, with the highest concentration of sites on the west coast (Figure 2.4).

Fin fish production is dominated by Atlantic salmon (*Salmo salar*). In the decade 2010-2020, the annual Salmon production in the waters around Shetland averaged around 40,000 Tonnes, representing a value of over £200 million. The sector directly employs over 200 full time staff [6], plus supports the wider economy of the islands via fish processing, marine engineering, and transportation [1].

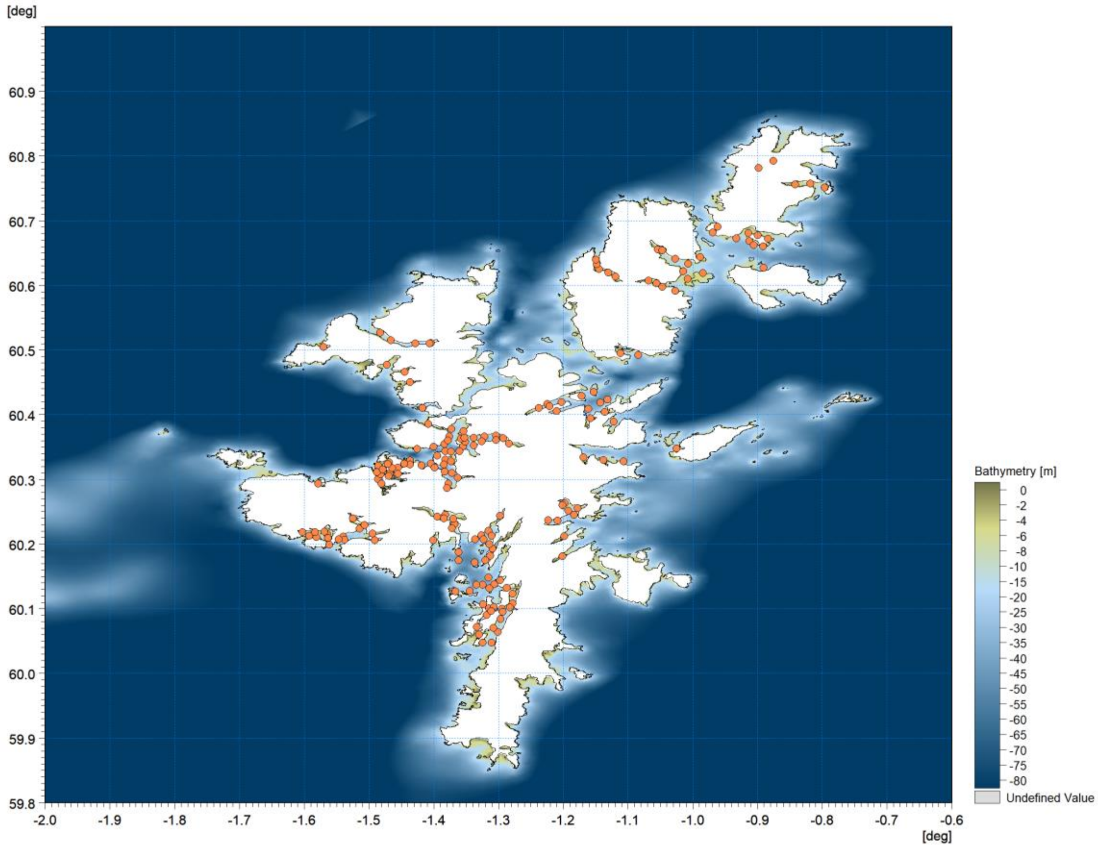


Figure 2.4 Map of Shetland showing the locations of active finfish and shellfish aquaculture sites (orange circles) and bathymetry in meters relative to mean-sea-level

3 Data Basis

In this section, the data sets that are used as input to the modelling study are described. This includes the coastline and bathymetry information (Section 3.1), the model boundary information from the Scottish Shelf Model (Section 3.2), and meteorological forcing (Section 3.3).

3.1 Bathymetry and coastline

3.1.1 Coastline

Ordnance Survey highwater shoreline data (OS HWS) was applied as the governing indicator of the separation between land and water. These data were obtained via OS OpenData[1] licensed under Open Government License[2].

3.1.2 Bathymetry

Various relevant bathymetric datasets were available for use in the setup of the hydrodynamic models. These are summarised in Table 3.1 and briefly described below. The vertical reference datum of the bathymetry datasets were either Chart Datum (CD) or Lowest Astronomical Tide (LAT). All data were converted to a common reference of mean-sea-level (MSL) in the development of the model bathymetry (Section 4.3.2 and Section 4.4.2).

Local site bathymetry data

Bathymetry soundings in and around marine pen fish farms (MPFF's) were provided by SSF and GSS (Figure 3.1 and Figure 3.2). These data are typically recorded using depth sounders installed on board fish farm vessels. Bathymetry information are provided relative to a vertical datum of CD, adjusted by the data provider for the depth of sounder below the surface and the predicted local tidal height.

UKHO Admiralty Data

High-resolution bathymetry data for the waters around Shetland were obtained from the United Kingdom Hydrographic Office (UKHO) Marine Data Portal[3]. The service provides access to the extensive UK bathymetry holdings held within the MEDIN accredited National Data Archive, allowing users to download bathymetry data under an Open Government Licence (OGL). The data are offered at a gridded resolution of <10m vertically referenced to CD. Figure 3.3 shows the high-resolution data-sets in and around Shetland.

C-MAP

An alternative source of bathymetric data was obtained from the Global Electronic Sea Chart Database CM-93 provided by C-MAP. This provides digitised bathymetric chart data vertically referenced to CD. C-MAP data was used in the coastal areas and voes where high-resolution bathymetric data or local soundings are not available.

EMODnet

For offshore areas that are not covered by the multibeam bathymetric datasets, bathymetric data from the Digital Terrain Model (DTM) data products have been adopted from the

[1] OpenData - Free GIS Data Download - Geospatial Data Sources for Mapping (ordnancesurvey.co.uk)

[2] Contains OS data © Crown copyright [and database right] (2021)

[3] Admiralty Marine Data Solution, Marine Data Portal (UKHO) accessed May 2021

EMODnet Bathymetry portal (version, 24 September 2018). This portal was initiated by the European Commission as part of developing the European Marine Observation and Data Network (EMODnet). The EMODnet digital bathymetry has been produced from bathymetric survey data and aggregated bathymetry data sets collated from public and private organisations. The data are provided processed, and quality controlled at a grid resolution of 1/16 x 1/16 arc minutes (approximately 115m latitude x 57m longitude). The average water depth in LAT for each cell is provided.

Table 3.1 Summary of $HD_{Shetland,Clima}$ model settings

Source	Resolution	Vertical Reference	Date
Local soundings at fish farm sites	Variable (~100m between soundings)	Chart Datum (CD)	Various (2000 – 2020)
UKHO Admiralty Data	2m to 8m	Chart Datum (CD)	Various
EMODnet	1/16 x 1/16 arc minutes (115m lat. x 57m lon.)	Lowest Astronomical Tide (LAT)	2018 version
C-MAP	Variable	Lowest Astronomical Tide (LAT)	Variable

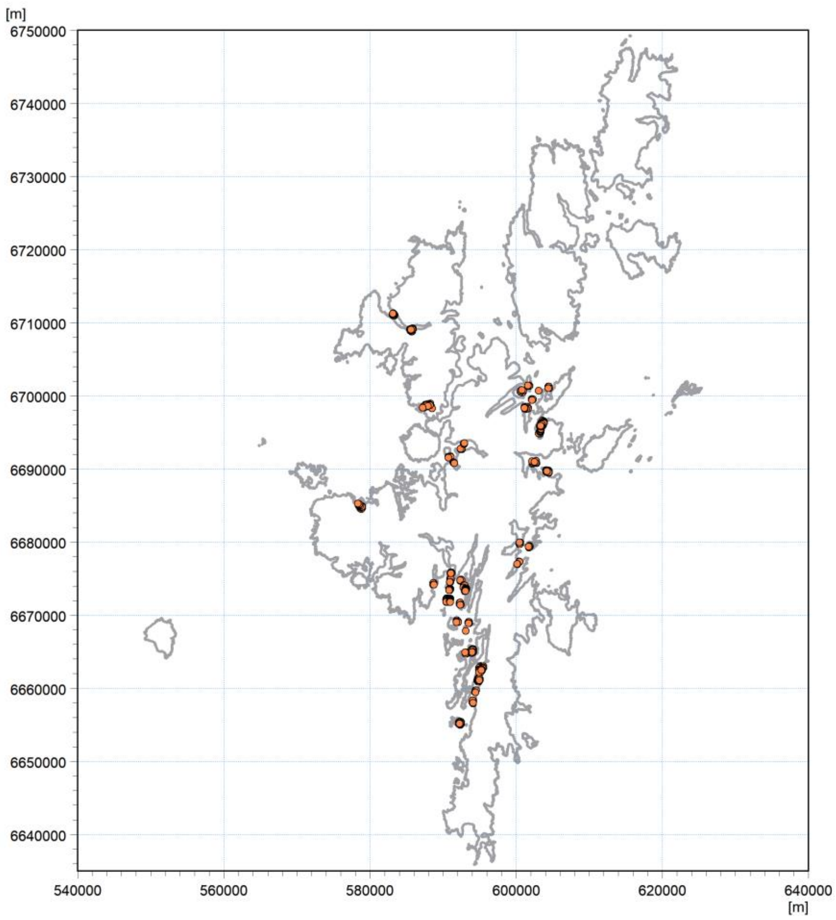


Figure 3.1 Map showing locations of bathymetry soundings at MPFF sites around Shetland (orange markers)

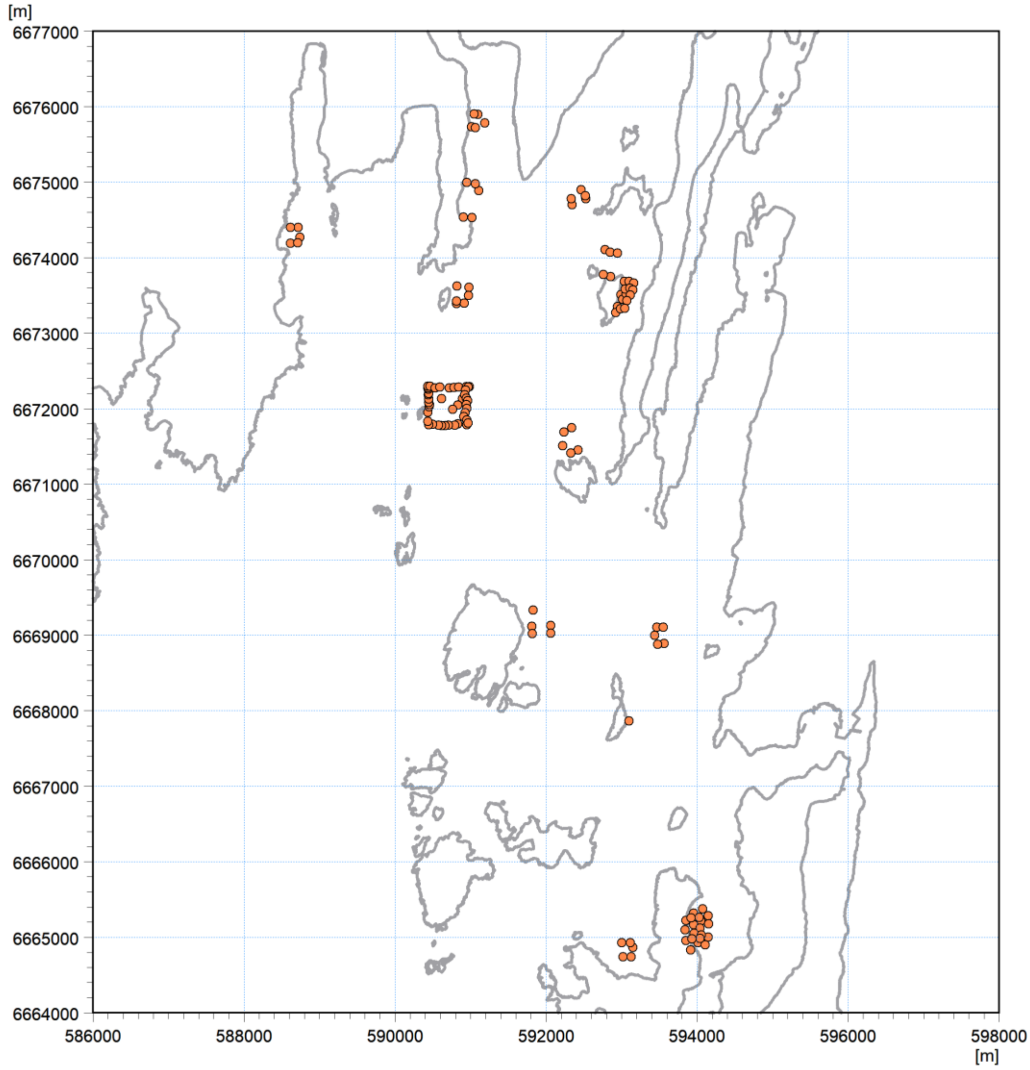


Figure 3.2 Map showing locations of bathymetry soundings at MPFF sites in the Scalloway area of south-west Shetland (orange markers)

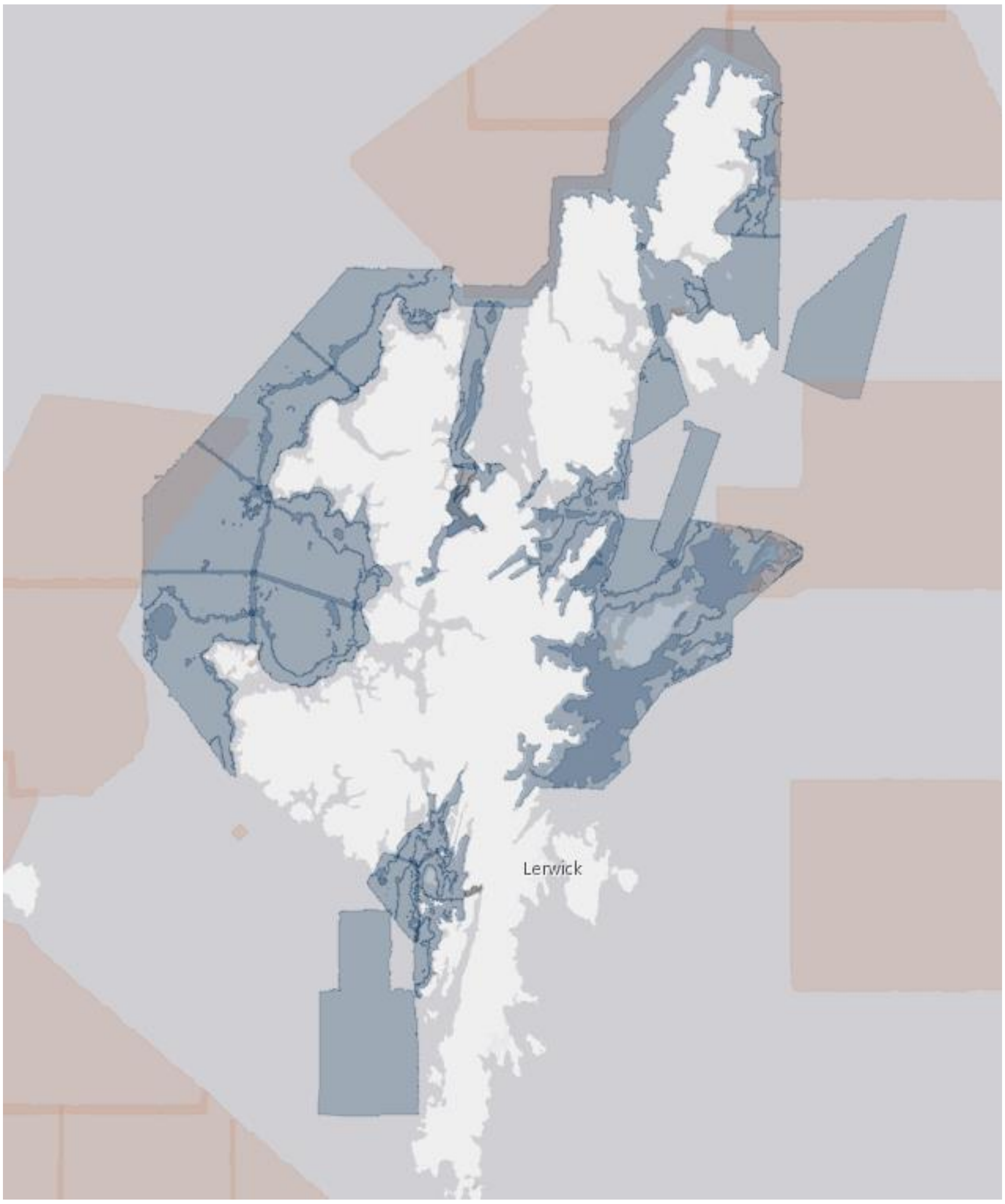


Figure 3.3 Map showing areas of high resolution bathymetry around Shetland (shaded blue polygons), from UKHO Marine Data Portal

3.2 The Scottish Shelf Model

The Scottish Shelf Model (SSM) is a suite of hydrodynamic numerical models of Scottish continental shelf waters, developed for and maintained by Marine Scotland Science, to describe the circulation of the Scottish continental shelf waters [7]. The SSM has been designed to support a varied range of marine science and policy applications, including for rapidly developing marine renewable energy and aquaculture sectors.

The wider domain SSM encompasses the majority of UK waters and the entire Scottish Continental shelf area (Figure 3.4). The horizontal resolution varies from approximately 10km in the outer domain to around 1km around the Scottish Coast (Figure 3.5). For the vertical discretization a σ coordinate system (terrain following coordinates) based on 20 uniform layers is used. The SSM suite of models also includes several smaller domain sub-models, with higher resolution, covering specific areas of interest including the Firth of Clyde, Pentland Firth and Orkney Waters, Loch Linnhe, and the east Coast of Lewis and Harris (see [7]). A specific sub-domain of the Northwest Shetland mainland at St Magnus Bay has also been developed [8], there are currently no long-term models of the whole of Shetland. In this report we shall only be using the wider domain Scottish Shelf Model (version 2.01), and shall henceforth use the abbreviation SSM when referring to this model.

Full details of the SSM climatology are provided in [9, 10], and a brief summary of the model setup is provided below.

The SSM is a one-year climatology model that represents average conditions with a 1993 tidal component. The model was implemented using an unstructured grid coastal ocean model, FVCOM (Finite-Volume Community Ocean Model) [11]. The model forcing includes:

- Offshore boundary conditions (temperature, salinity, currents, and sea-surface elevation) from monthly mean over the 25-year period (1990-2014) provided by the Atlantic Margin Model 7km (AMM7) [12, 13]
- Climatology atmospheric forcing is also included based on monthly 1990–2014 data set derived from ERA-Interim data [14] (further discussed in Section 3.3)
- Freshwater inputs from river runoff volume flux climatology were obtained from the Centre for Ecology and Hydrology (CEH) Grid-to-Grid (G2G) model [15, 16], covering the period from 1962 to 2011 and including 577 rivers in Scottish Waters.

As the conditions of the SSM encompass an averaging period of 25-years (1990-2014), the climatology seeks to smooth the natural variability of the climate and achieve an approximately stationary characterisation that averages out the interannual variability.

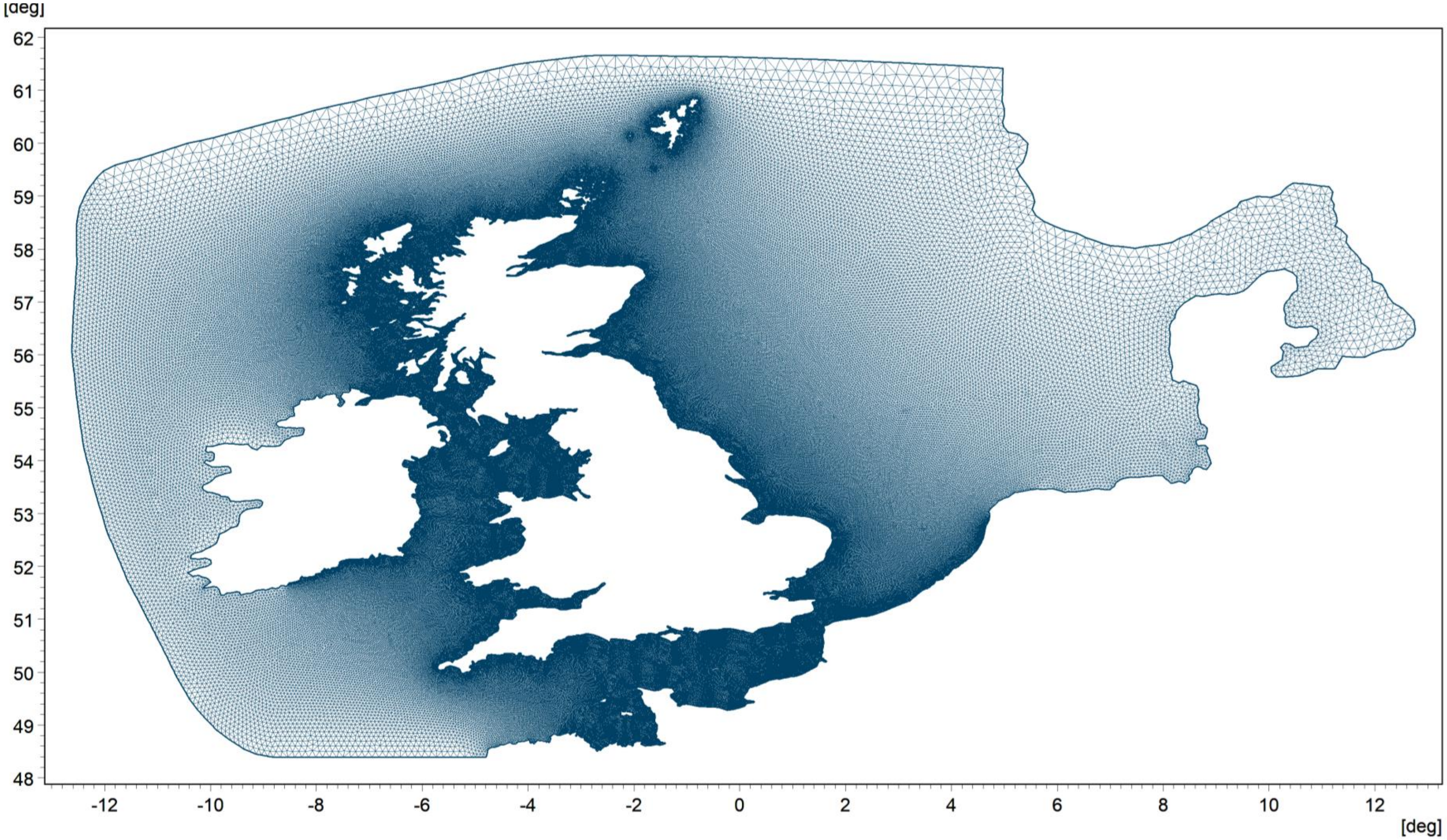


Figure 3.4 Scottish Shelf Model (SSM) numerical mesh showing the entire model domain

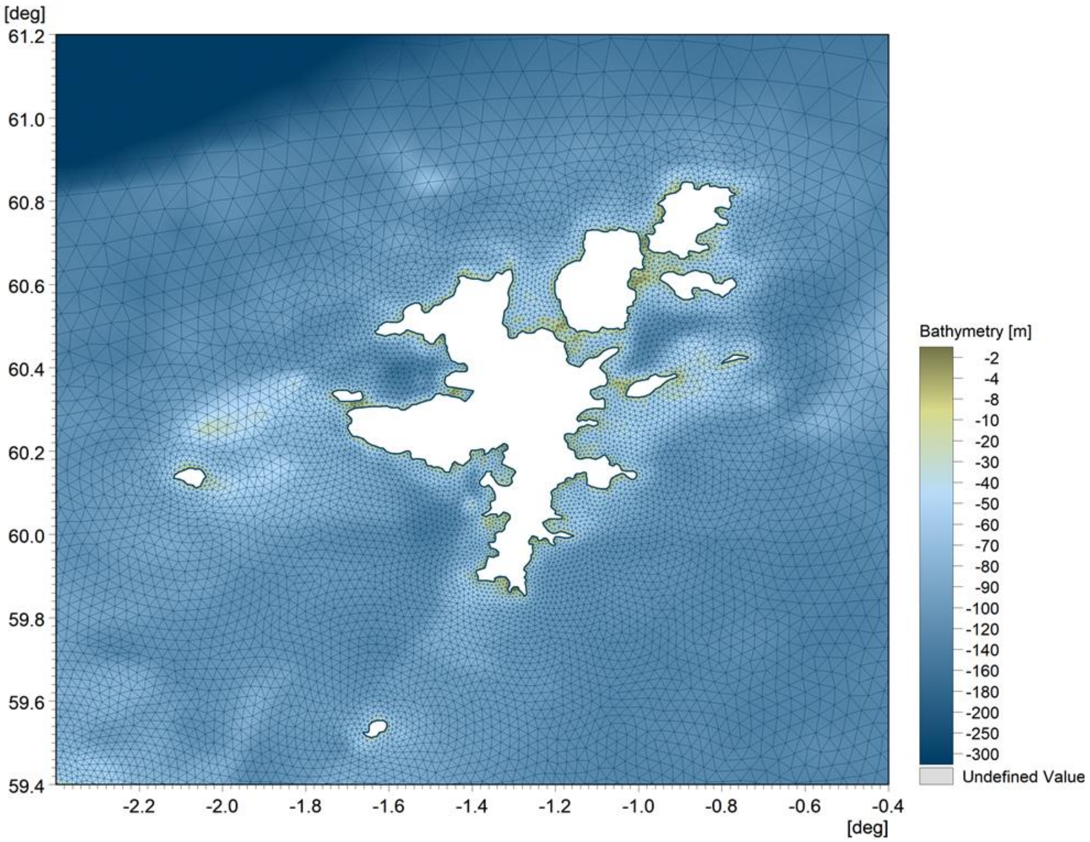


Figure 3.5 Scottish Shelf Model (SSM) numerical mesh showing the area around Shetland

3.3 Meteorological conditions

Climatologically averaged meteorological conditions used to force the SSM are derived from the ERA-40 and ERA-Interim re-analysis products produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [14]. A monthly mean wind climatology was derived from these data (Figure 3.6). The met forcing was derived as monthly means, which were then linearly interpolated to 6-hourly smoothed forcing data for each grid-point, i.e. mean February data were applied at the middle of February; then mean March data were applied mid-March etc., with time-interpolation between (see Section 5.3 of [9]).

The atmospheric conditions include wind conditions (wind speed and direction), atmospheric pressure, surface heat flux, precipitation, evaporation, relative humidity, air temperature, thermal/solar radiation. For wind, the 6-hourly data were used to construct a monthly mean wind stress, which was then converted back into an equivalent wind field [10]. It should be noted that the AMM7 model, that was used to derive the offshore boundary conditions for the SSM climatology, were also forced by ERA-Interim reanalysis; hence, providing some consistency in the boundary forcing of the SSM.

Figure 3.7 shows a time-series plot of the climatologically averaged meteorology for selected parameters for a location offshore of Scalloway, south-west Shetland. As expected for a climatology model there is a low temporal variability at shorter temporal scales (hours and days), but the seasonal pattern is quite clear. For example, the largest wind speeds occur during the winter months (December to February) with lowest tine speeds in the summer (June to August). Conversely, air temperatures are lowest in the winter and largest during the summer.

The time-series of wind direction (second panel in Figure 3.7) shows only very slight variation throughout the year. This can also be observed in Figure 3.8, which shows a rose plot of the distribution of wind speed and wind direction (coming from) extracted the climatologically averaged meteorology for the same location offshore of Scalloway. The wind direction is dominated by south-westerly conditions; directional sectors from 210°N to 240°N accounting for approximately 80% of the total. This is consistent with the prevailing wind direction for Shetland. However, this does not reflect the full range of wind directions that may occur on Shetland during the passage of low-pressure systems (as mentioned in Section 2.2), which are averaged out in the model climatology.

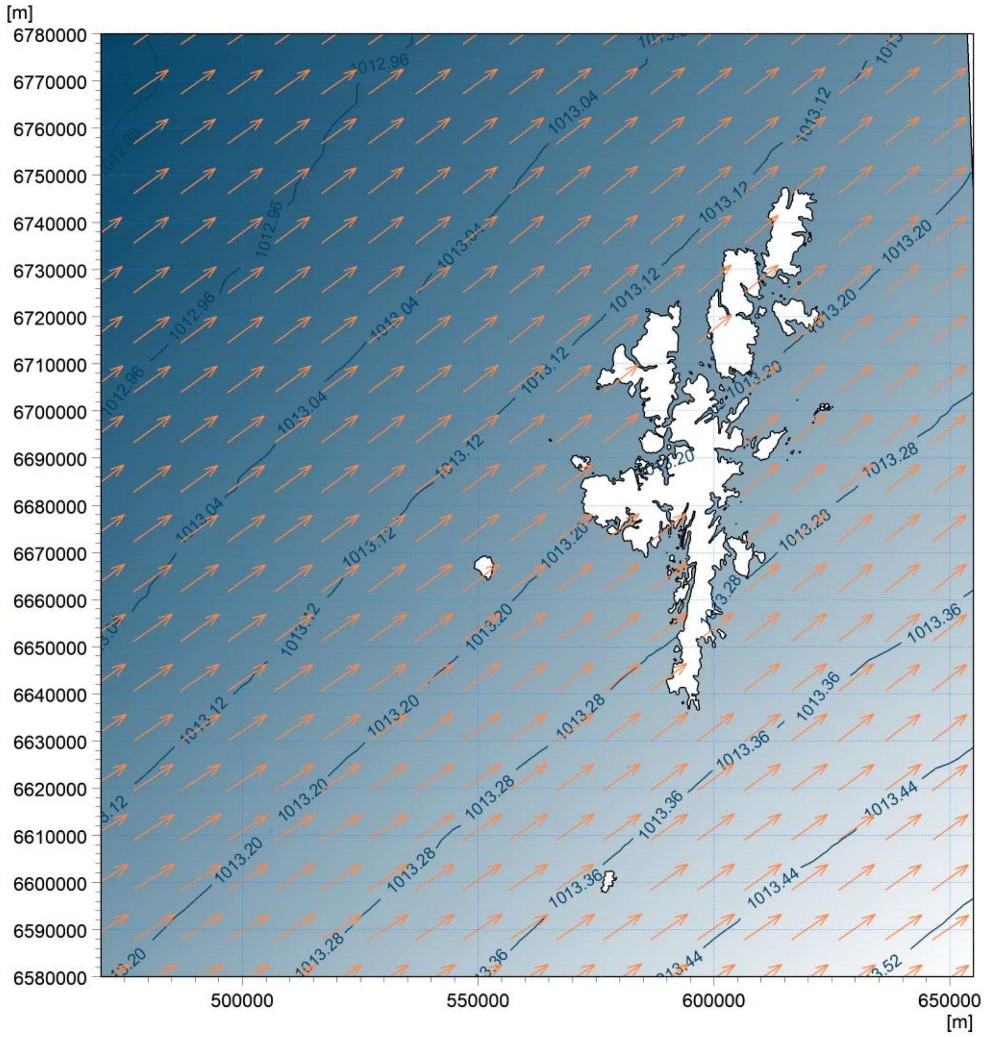


Figure 3.6 Snapshot of climatology atmospheric forcing used as input to the SSM over Shetland during May. The blue shading and contours show the air pressures [hPa], and the orange vectors designate the wind conditions (coming from).

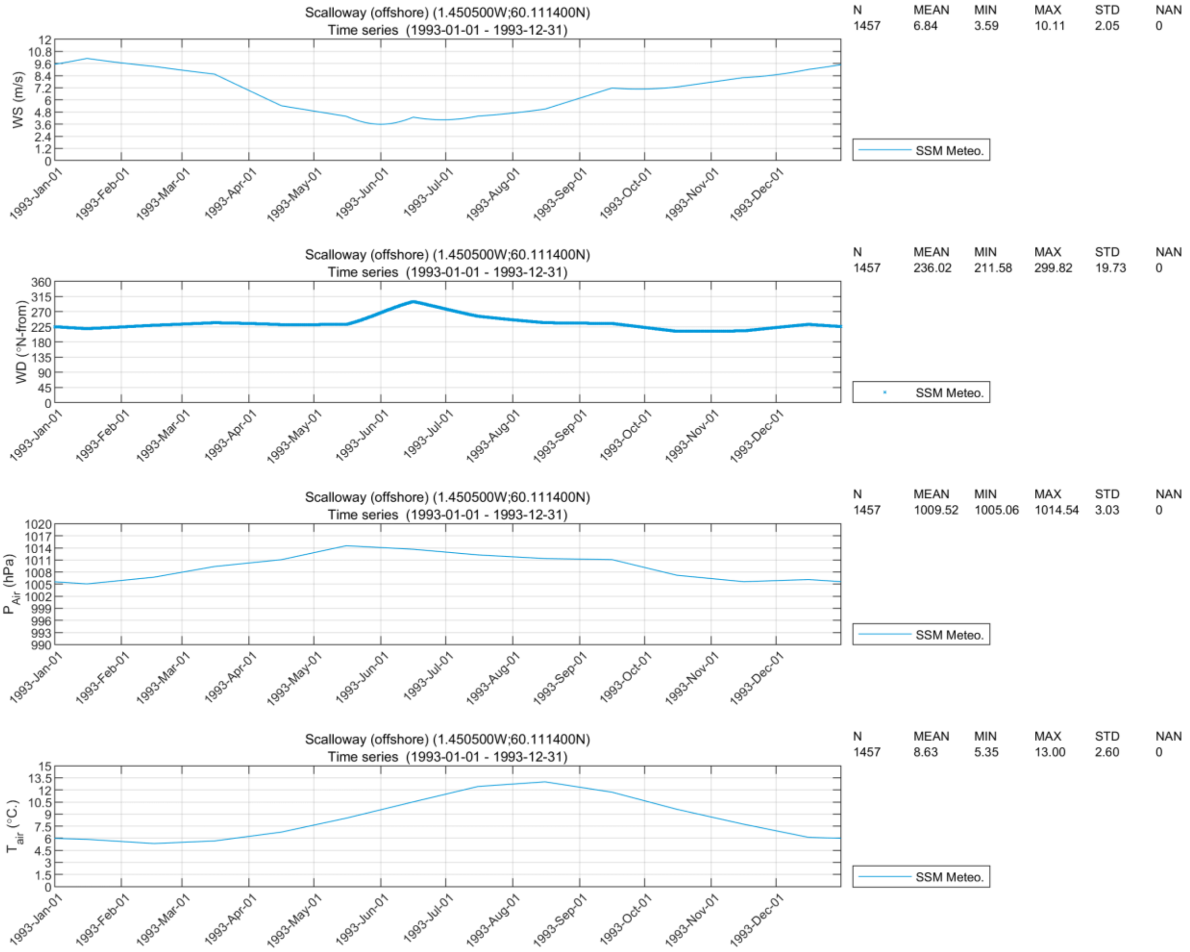


Figure 3.7 Time-series and annual statistics of climatologically averaged meteorological conditions for a location offshore of Scalloway (south-west Shetland). From top to bottom: wind speed, wind direction, atmospheric pressure, and air temperature.

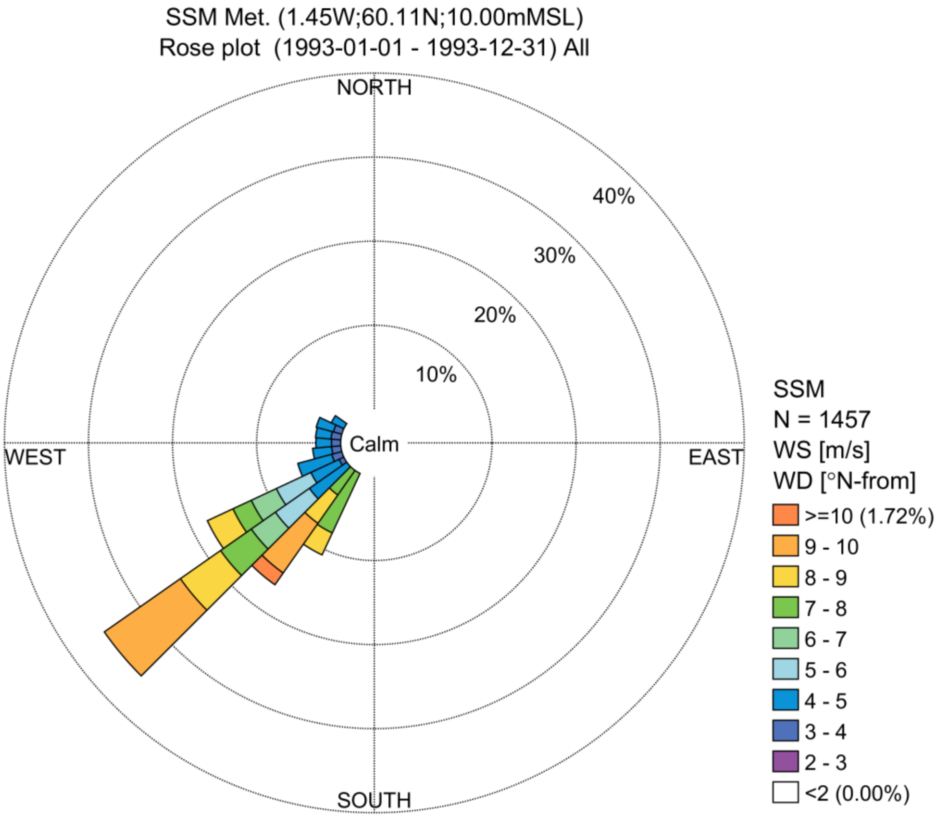


Figure 3.8 Annual wind rose for a location offshore of Scalloway (south-west Shetland) from climatology atmospheric forcing used as input to the SSM

4 Model Development

This section describes the development of the 3-dimensional hydrodynamic climatology models that were established during the project: regional Shetland model, and the local Scalloway model.

4.1 Model selection

4.1.1 Three-dimensional model

Many of the aquaculture sites in the waters around Shetland are located within the relatively long and deep voes. These areas have the potential to be exhibit vertical stratification due to density gradients (due to difference in water temperature and salinity), which may have important implications for vertical mixing and flow velocities. In such environments, a three-dimensional (3D) model may be necessary to capture the important processes [17]. Temperature and salinity are also important factors in biological modelling (e.g., for sea-lice development). Finally, wind forcing will also play an important role in driving local flow patterns, which is important for surface dispersion (e.g. for modelling bath-treatment) so this must also be included in the model setup.

As such, a modelling package which computes conditions throughout the water column was used to represent the hydrodynamic conditions in and around Shetland. The MIKE 3 FM modelling system was chosen as this allowed changes throughout the water column to be considered (see Section 4.1.2).

4.1.2 MIKE 3 hydrodynamic model

The Shetland hydrodynamic modelling has been performed using the MIKE 3 modelling package developed by DHI. MIKE 3 includes the simulation tools to model 3D free surface flows and associated sediment or water quality processes. The following modules available within MIKE 3 were used during this study:

- HD – Hydrodynamics: This module simulates the water level variations and flows in response to a variety of forcing functions. It includes a wide range of hydraulic phenomena in the simulations and it can be used for any 3D free surface flow. The Flexible Mesh version, which uses a depth and surface adaptive vertical grid, is particularly suitable in areas with a high tidal range.

The MIKE 3 Model used for the present study was version 2021 [18].

The Hydrodynamic Module is the basic computational component of the entire MIKE 3 Flow Model FM, and has been developed for applications within oceanographic, coastal, and estuarine environments [18]. The hydrodynamic module provides the basis for the other modules such as sand transport, mud transport, particle tracking, and ECO Lab.

The computational mesh is based on the unstructured grid in the horizontal direction, an approach which gives maximum degree of flexibility when handling problems in complex domains (such as in the voes and narrow straits around Shetland). In the vertical direction a sigma (σ) discretisation is used meaning that model elements are represented as 3-sided prisms (Figure 4.1)

The MIKE3 modelling system is based on the numerical solution of the three-dimensional incompressible Reynolds Averaged Navier-Stokes (RANS) equations, invoking the assumptions of Boussinesq, and of hydrostatic pressure. Thus, the MIKE 3 flow model consists of continuity, momentum, temperature, salinity, and density equations and is closed by a turbulent closure scheme. In the horizontal domain both Cartesian and spherical coordinates can be used. The free surface is taken into account using a sigma-coordinate transformation approach.

The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping element/cells. In the horizontal plane an unstructured grid is used while in the vertical domain a structured discretisation is used. The elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively. An approximative Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.

For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly, and the vertical terms are treated implicitly.

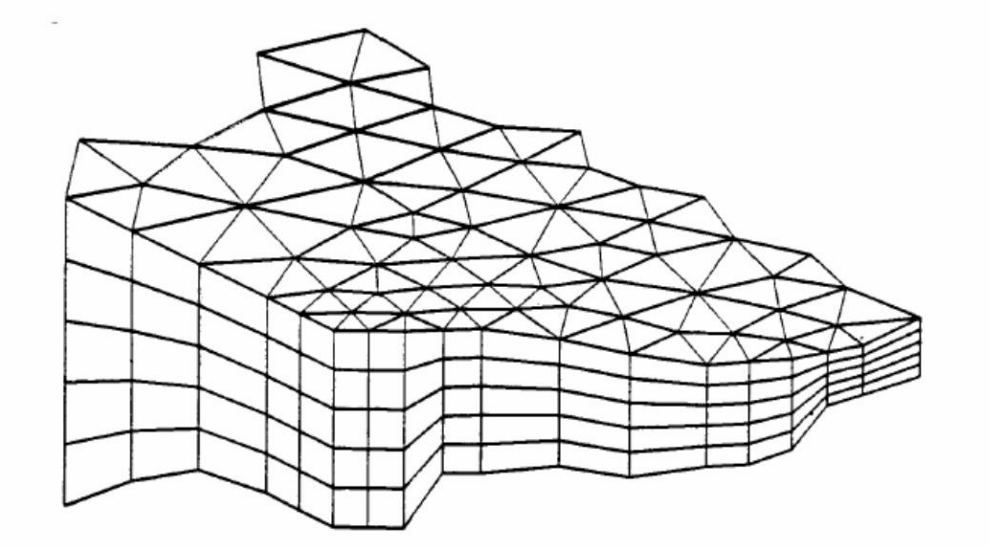


Figure 4.1 Example of an unstructured mesh in MIKE3 with 5 sigma (σ) layers.

4.2 Datums

Unless explicitly stated otherwise, the following reference datums were adopted for the models developed during this project.

- Horizontal datum is established using World Geodetic System 1984 (WGS 84), UTM zone 30N
- Vertical datum is referenced to mean-sea-level (MSL)

4.3 Shetland hydrodynamic climatology model

A dedicated regional 3D hydrodynamic climatology model of Shetland ($HD_{Shetland,Clima}$) was established. The $HD_{Shetland,Clima}$ model is a dynamically downscaled version of the SSM (see Section 3.2). In other words, $HD_{Shetland,Clima}$ is a high-resolution regional model that dynamically extrapolates the effects of the large-scale processes of the SSM to regional scales of interest around the waters of Shetland.

The following sections describe the establishment of the $HD_{Shetland,Clima}$ model, including the model mesh and bathymetry, the specification, and model outputs.

4.3.1 Model domain

The computational domain of the regional model encompasses the entire area of Shetland including the outlying islands of Foula and Fair Isle (Figure 4.2). The model has five open (sea) boundaries to the North Atlantic Ocean and North Sea, and land boundaries defined according to OS HWS (see Section 3.1.1). In total the model area encloses an area of slightly over 19,600 km^2.

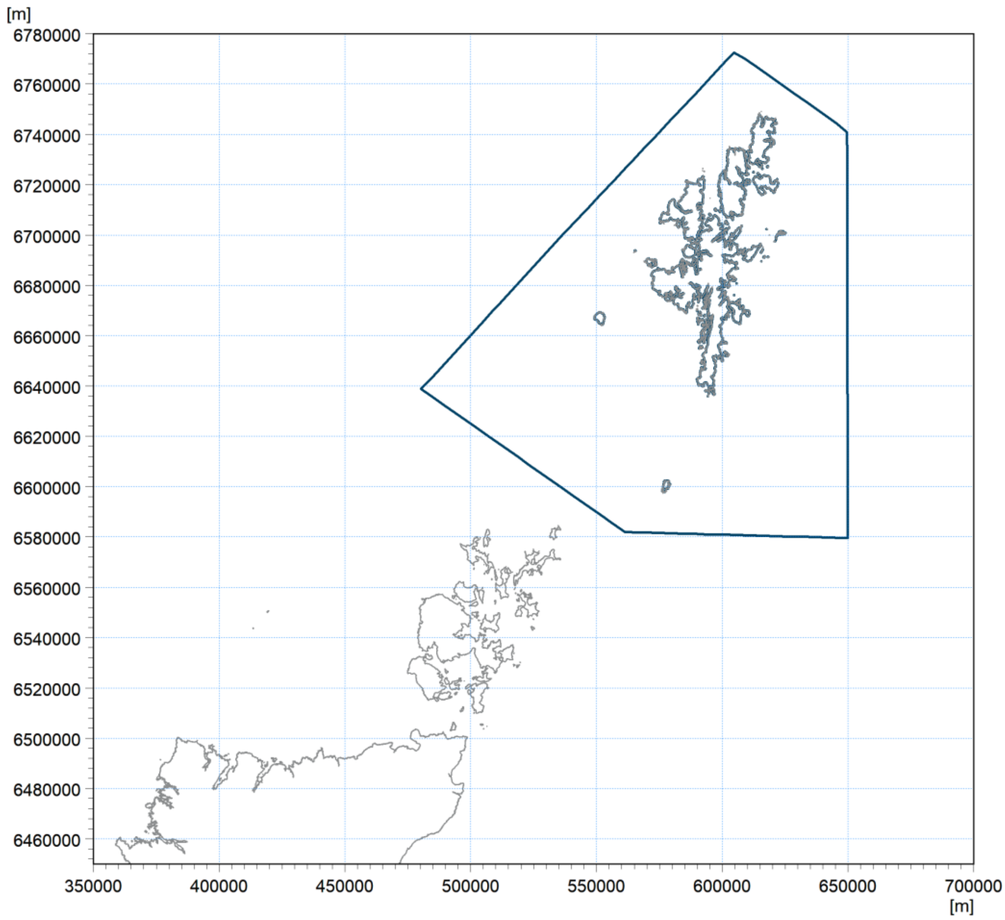


Figure 4.2 Computational domain (dark blue outline) of the regional 3-dimensional Shetland climatology model ($HD_{Shetland,Clima}$)

4.3.2 Mesh and bathymetry

The computational mesh is based on the variable resolution unstructured grid in the horizontal direction, while a variable discretisation is specified in the vertical direction. The mesh resolution was chosen to capture the important hydrodynamic processes in the waters around Shetland within reasonable and practical computational run times. This was also informed by similar regional scale models (such as the SSM sub-domain for the East coast of Lewis and Harris "ECLH" model), and recommendations provided by SEPA and MSS.

The computational mesh of $HD_{Shetland,Clima}$ is shown in Figure 4.3. In the outer domain, close to the model boundaries, the horizontal mesh element length is set at around 3.5km. The mesh element length gradually reduces to between 500m and 250m in the coastal areas around Shetland (see left-hand of Figure 4.4). The highest resolution is specified near the shoreline, in the narrow straits between islands, and within voes. In these areas the mesh element length was between 250m and 125m (see right hand plot of Figure 3.5). In total the horizontal mesh consists of 22,202 nodes defining 38,133 mesh elements.

A comparison between the domain and resolution of the SSM and $HD_{Shetland,Clima}$ in the area around Scalloway is provided in Figure 4.6. The down-scaled regional $HD_{Shetland,Clima}$ model offers significant improvement in the resolution around the coastline and includes details of features (e.g. smaller islands and voes) that are absent in the shelf-sea scale SSM model.

The vertical mesh was specified with 10 σ layers, with variable thickness such that resolution is increased near the surface (Figure 4.5).

The bathymetry datasets described in Section 3.1.2 were interpolated to the computational mesh as shown in Figure 4.7. Careful attention was given to smoothing of bathymetry to alleviate large bathymetric gradients between adjacent computational cells that can introduce errors due to the sigma coordinate vertical scheme (known as stair-casing).

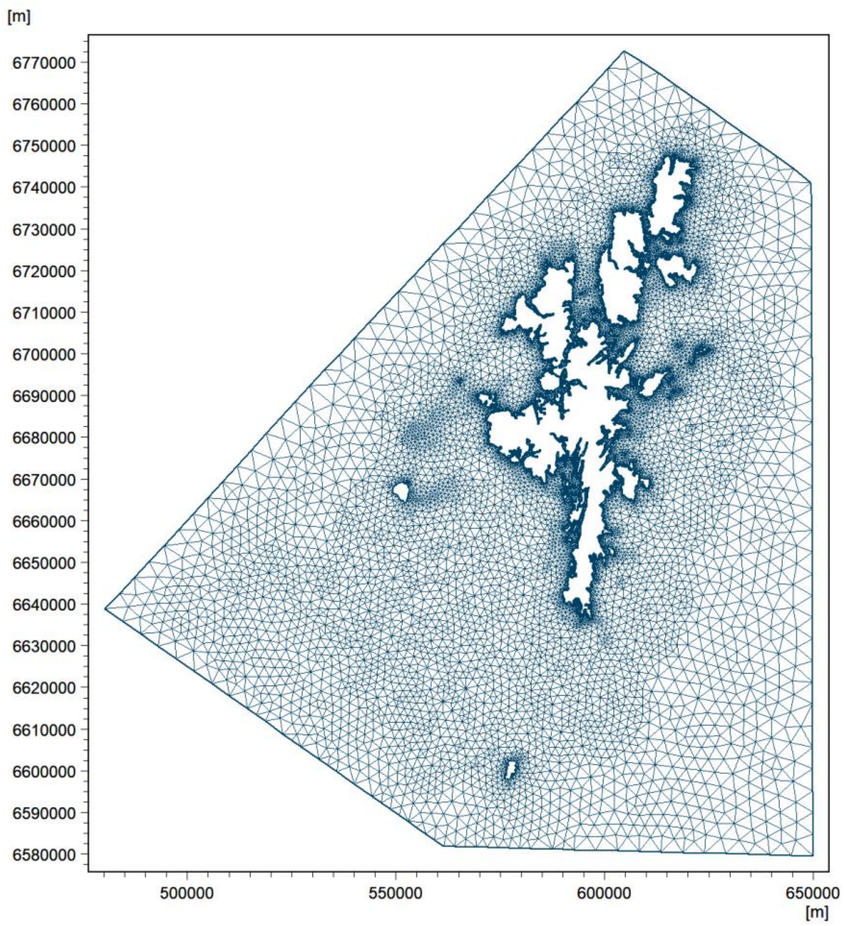


Figure 4.3 Computational mesh of the regional Shetland hydrodynamic climatology model ($HD_{Shetland,Clima}$)

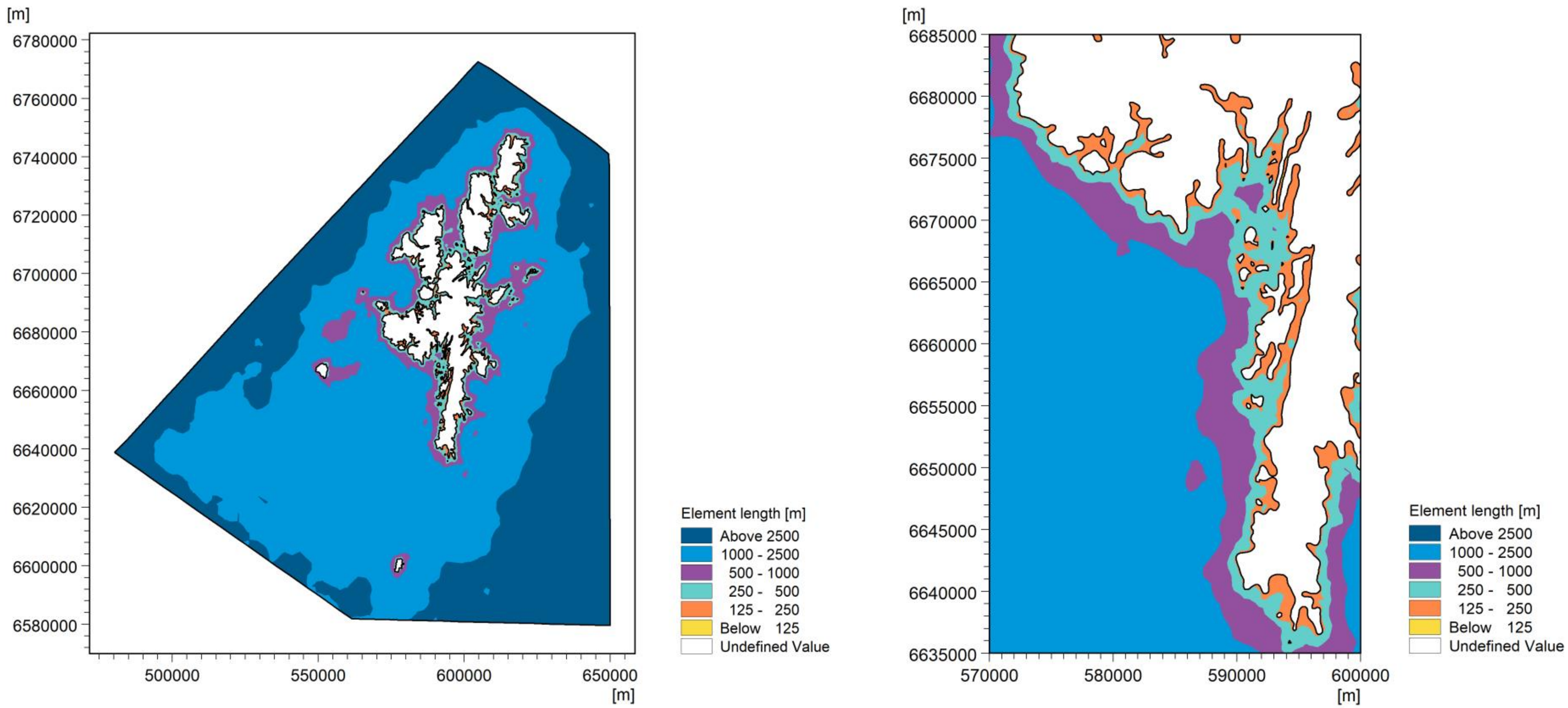


Figure 4.4 The approximate mesh element length [m] of the regional Shetland hydrodynamic climatology model $HD_{Shetland,Clima}$ showing the entire model domain (left) and detail around Scalloway, south-west Shetland (right)

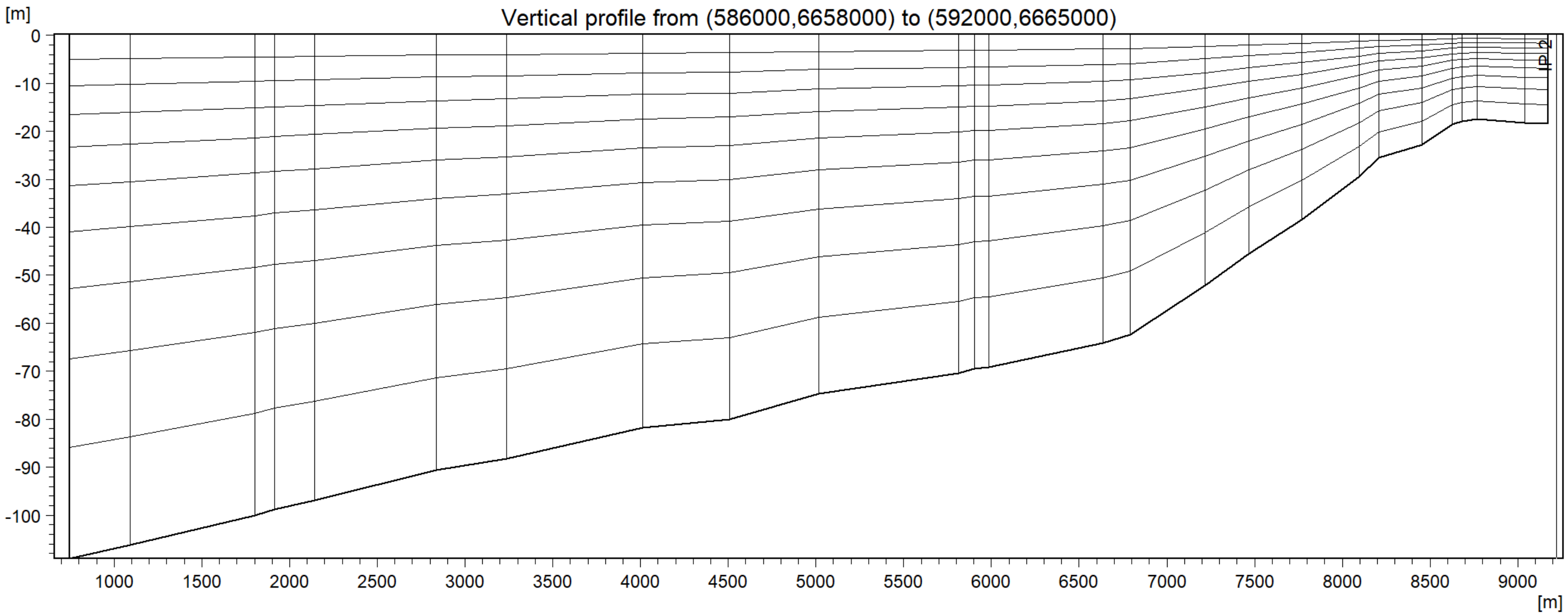


Figure 4.5 Vertical model mesh for a c. 9.2km transect in south-west Shetland showing the variable resolution vertical discretisation of $HD_{Shetland,Clima}$

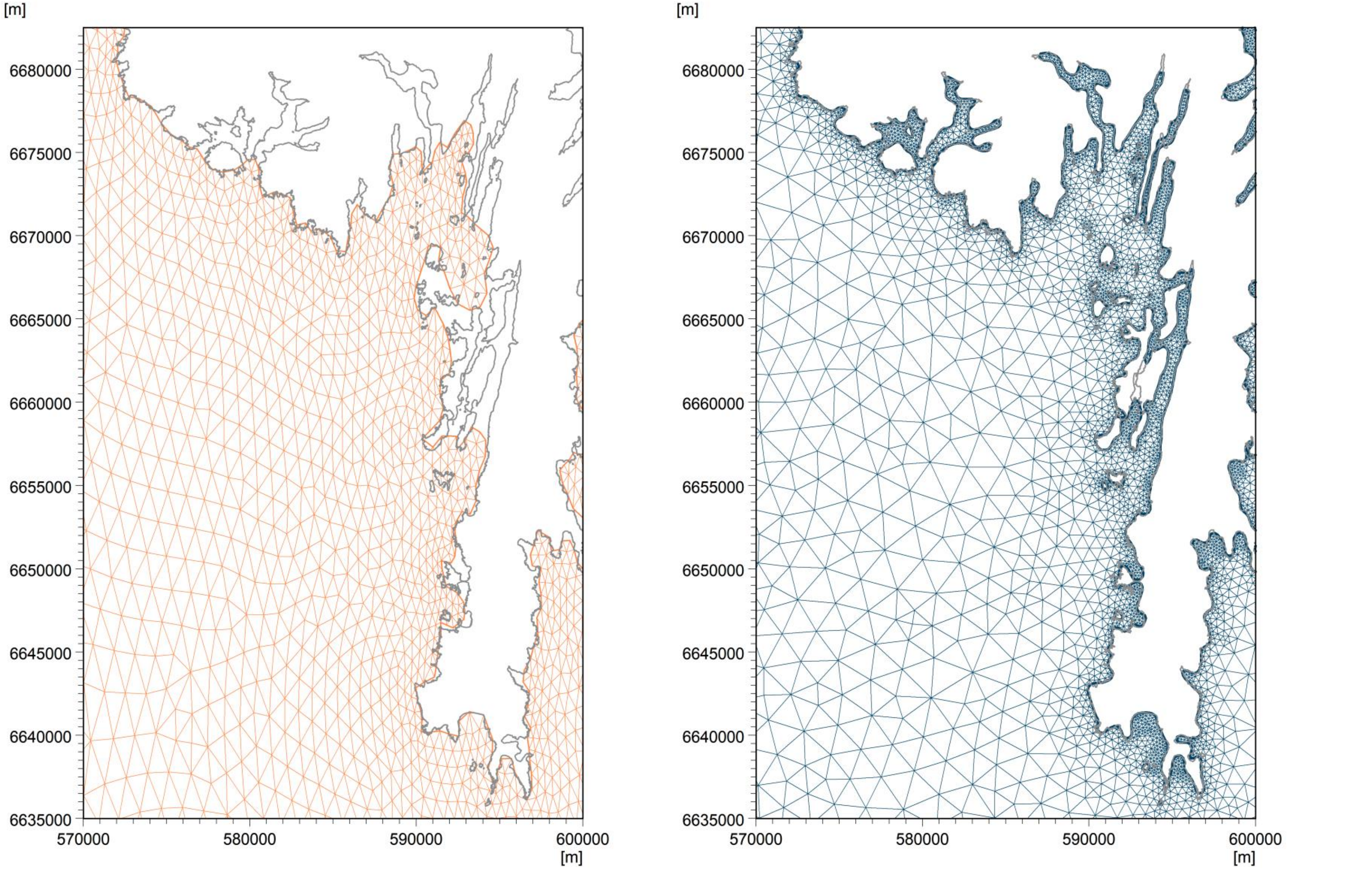


Figure 4.6 Computational mesh of area around Scalloway, south-west Shetland from SSM (left) and the hydrodynamic climatology $HD_{Shetland,Clima}$ (right)

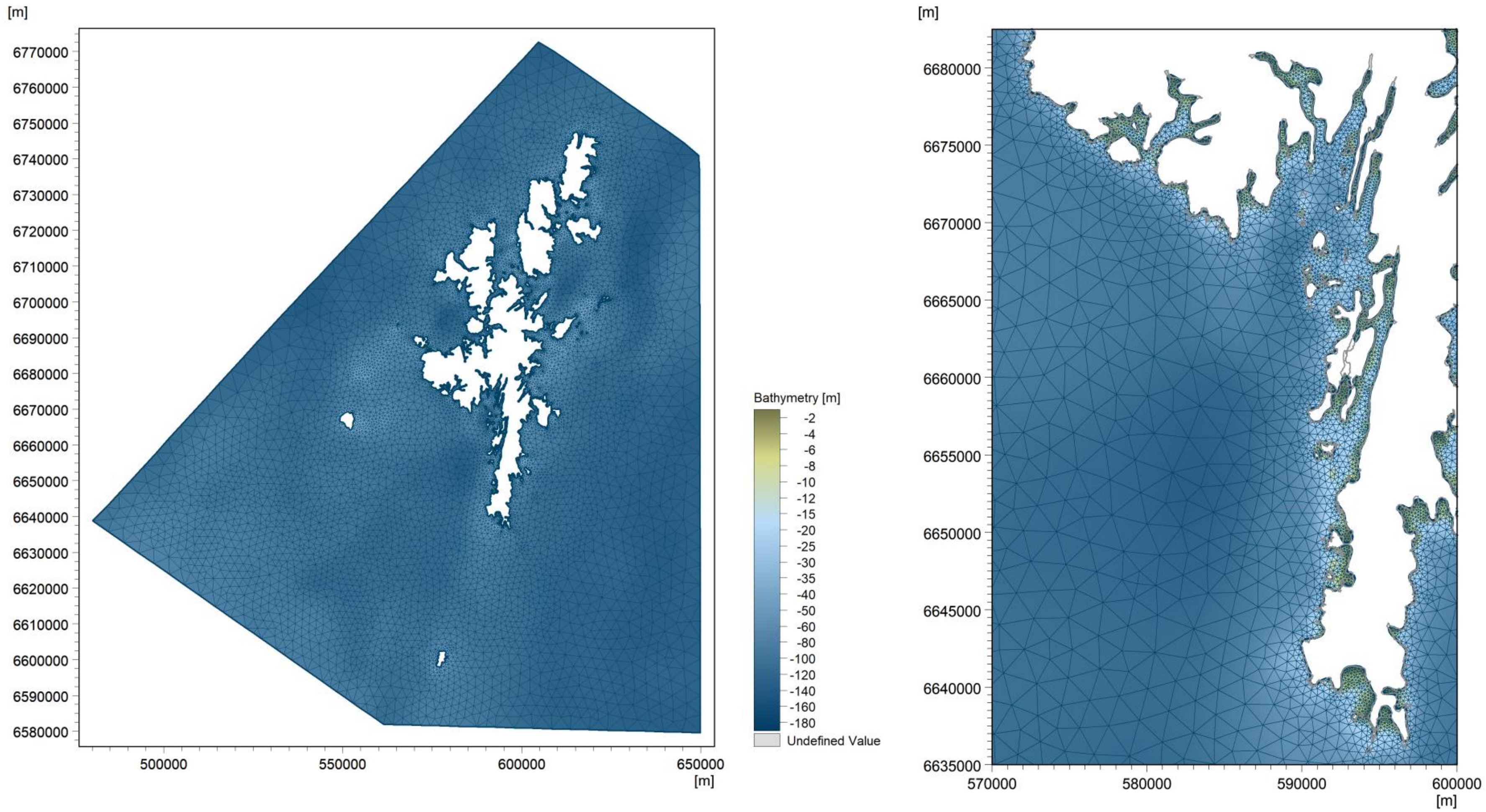


Figure 4.7 Interpolated model bathymetry relative to MSL of the Shetland hydrodynamic climatology model ($HD_{Shetland,Clima}$) showing the entire model domain (left) and detail around Scalloway, south-west Shetland (right)

4.3.3 Initial and boundary conditions

Initial and boundary conditions were derived from the SSM one-year climatology (see Section 3.2). This included temporally and spatially varying water surface elevation (1D, horizontal), and current velocities, temperature, and salinity (2D, horizontal and vertical).

Hydrodynamic boundaries (water levels and current velocities) were specified as Flather boundary conditions [19]. This is an efficient open boundary condition method for downscaling coarse model simulations to local areas, and can generally avoid model instabilities when imposing stratified density at a water level boundary.

Initial conditions were set for the spatially varying distribution of water levels (2D), and the temperature and salinity (3D) throughout the computational domain at the beginning of the simulation. These were derived from the SSM starting conditions (interpolated onto the $HD_{Shetland,Clima}$ computational mesh).

The $HD_{Shetland,Clima}$ model was optimised using data assimilation of temperature and salinity. This was technique blends the computed solution with data provided from a reference file (in this case the SSM) to maintain a stable long term solution.

4.3.4 Meteorological forcing

Meteorological forcing applied in $HD_{Shetland,Clima}$ model include the wind speed and wind direction at 10mMSL, atmospheric pressure at mean-sea-level, total precipitation, and evaporation. This forcing was adopted climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis product (see Section 3.3). This is the same meteorological forcing as used in the wider domain SSM model; hence, achieving consistency with the model boundary forcing.

Other meteorological inputs specified in $HD_{Shetland,Clima}$ include items related to heat exchange between the sea and the atmosphere. The temperature variations are used in the MIKE3 temperature/salinity (TS) module which sets up additional transport equations in the model. The calculated temperature and salinity are fed-back to the hydrodynamic equations through buoyancy forcing induced by density gradients. The inputs to the heat exchange include air temperature, short-wave radiation, and long-wave radiation. Once again, these data were adopted climatologically averaged meteorological conditions used in the SSM (see Section 3.3).

4.3.5 Model configuration

The configuration of the $HD_{Shetland,Clima}$ model is summarised in Table 4.1. For more information on the scientific background of the model settings or the governing equations of the model, please refer to [18, 20].

Table 4.1 Summary of $HD_{Shetland,Clima}$ model settings

Setting	Description/Value
Basic equations	3D incompressible Reynolds averaged Navier-Stokes (RANS) equations
Numerical scheme	Higher order scheme (time integration and space discretisation)
Horizontal mesh	Variable resolution unstructured grid (see Section 4.3.2)
Vertical mesh	10 variable thickness σ layers (see Section 4.3.2)
Simulation period	A one-year climatological run, which represents average conditions with a 1993 tidal component.
Model time step (adaptive)	0.01 to 120 seconds
Flooding and drying	Drying depth 0.005m, wetting depth 0.1m
Density	Function of temperature and salinity (see temperature and salinity module below)
Horizontal Eddy viscosity	Smagorinsky formulation with constant = 0.5
Vertical Eddy viscosity	K-epsilon formulation with eddy viscosity values min:1.8e-06/max:0.4 [m2/s]
Bed resistance	Roughness height 0.05m
Coriolis Forcing	Varying in domain
Wind forcing	Varying in time and domain specified from the climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis products (see Section 3.3)
Wind friction	Varying with wind speed (Linear variation Speed): • 7 [m/s] Friction: 0.00185 • 25 [m/s], Friction: 0.002825
Ice coverage	Not included
Tidal potential	Not included
Precipitation/Evaporation	Varying in time and domain specified from the climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis products (see Section 3.3)
Initial conditions	Spatially varying surface elevation derived from SSM (interpolated to the $HD_{Shetland,Clima}$ mesh)
Boundary conditions	Flather boundary conditions, temporally and spatially varying water levels and 3D current velocities from the SSM (see Section 3.2)
Temperature and salinity module	Temporally and spatially varying boundaries from the SSM (see Section 3.2), plus data assimilation.

4.4 Scalloway hydrodynamic climatology model

4.4.1 Model domain

The computational domain of the Scalloway hydrodynamic model encompasses the south-west of Shetland (Figure 4.8). The model has two open (sea) boundaries: the north-west boundary extends from the west of Shetland Mainland to the island of Foula, and the south-west boundary crosses from Foula to the south of Shetland Mainland. The land boundaries are defined according to the OS HWS (see Section 3.1.1). In total the model area encloses a total area of around 940 km².

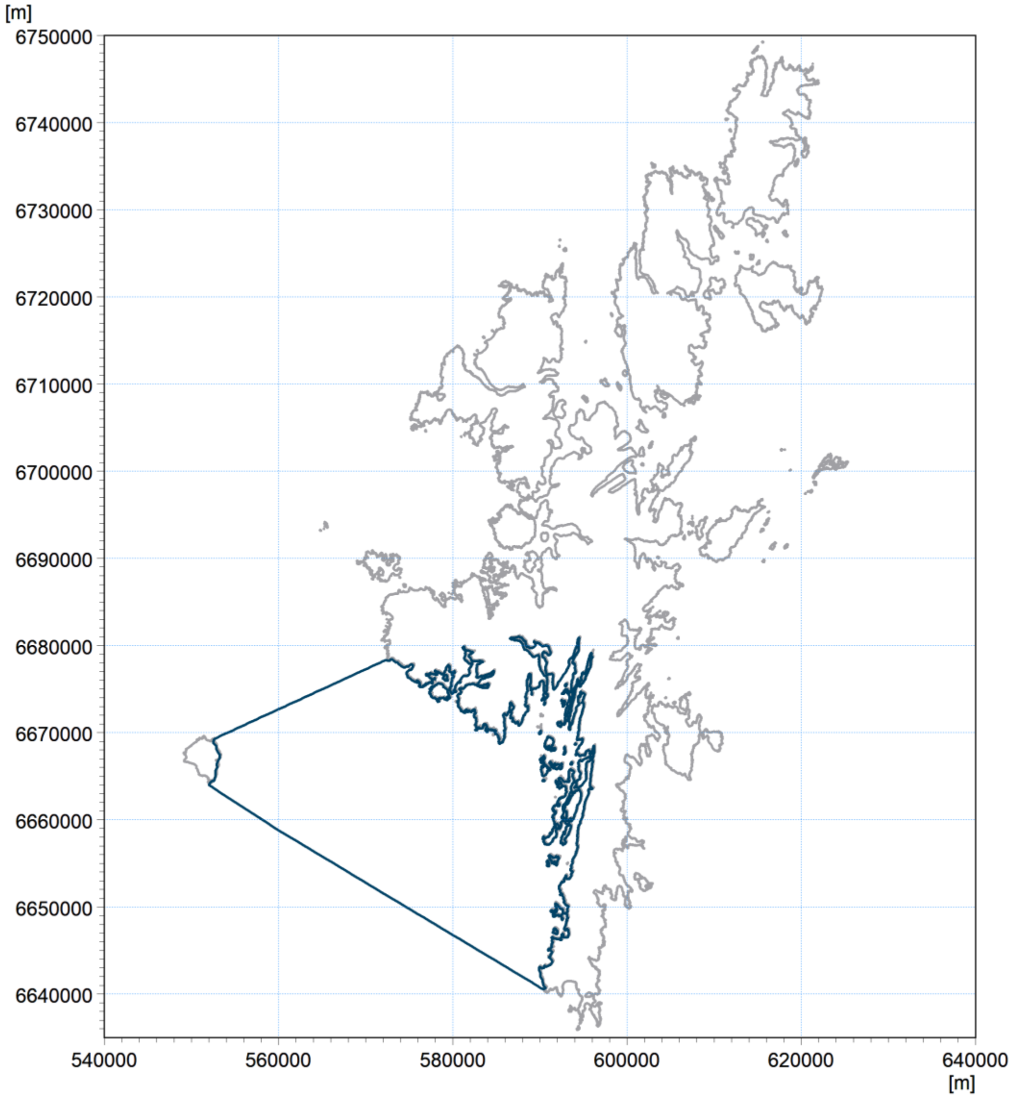


Figure 4.8 Computational domain (dark blue outline) of the local 3-Dimensional Scalloway hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

4.4.2 Mesh and bathymetry

Similar to the regional Shetland model (see Section 4.3.2), the computational mesh for the Scalloway model was based on the variable resolution unstructured grid in the horizontal direction, with a variable discretisation in the vertical direction.

The computational mesh of $HD_{Scalloway,Clima}$ is shown in Figure 4.9. In the outer domain, close to the model boundaries, the horizontal mesh element length is set at around 750m. The mesh element length gradually reduces to between 75m to 100m near the shoreline, in narrow channel and in the voes. The highest resolution is specified in the area around MPFF's. In these areas the mesh element length was generally 50m or lower (Figure 4.11), which is comparable to the typical mesh resolution of the St Magnus Bay sub domain of the SSM [8]. In total the horizontal mesh consists of 17,479 nodes defining 29,758 mesh elements.

A comparison between the horizontal mesh of the regional model ($HD_{Shetland,Clima}$, as described in Section 4.3) and the local Scalloway model ($HD_{Scalloay,Clima}$) is provided in Figure 4.10. This reveals the significant increased resolution in narrow channels, entrances to voes, and around MPFF's. This is to provide the requisite level of spatial detail for use of the local hydrodynamic climatology model as input to dispersion modelling at fish farms sites.

The local Scalloway model was run with a vertical mesh specified with 10 σ layers, with variable thickness such that resolution is increased near the surface.

The bathymetry datasets described in Section 3.1.2 were interpolated to the computational mesh as shown in Figure 4.12. Careful application was given to smoothing of bathymetry to alleviate large bathymetric gradients between adjacent computational cells that can introduce errors due to the sigma coordinate vertical scheme

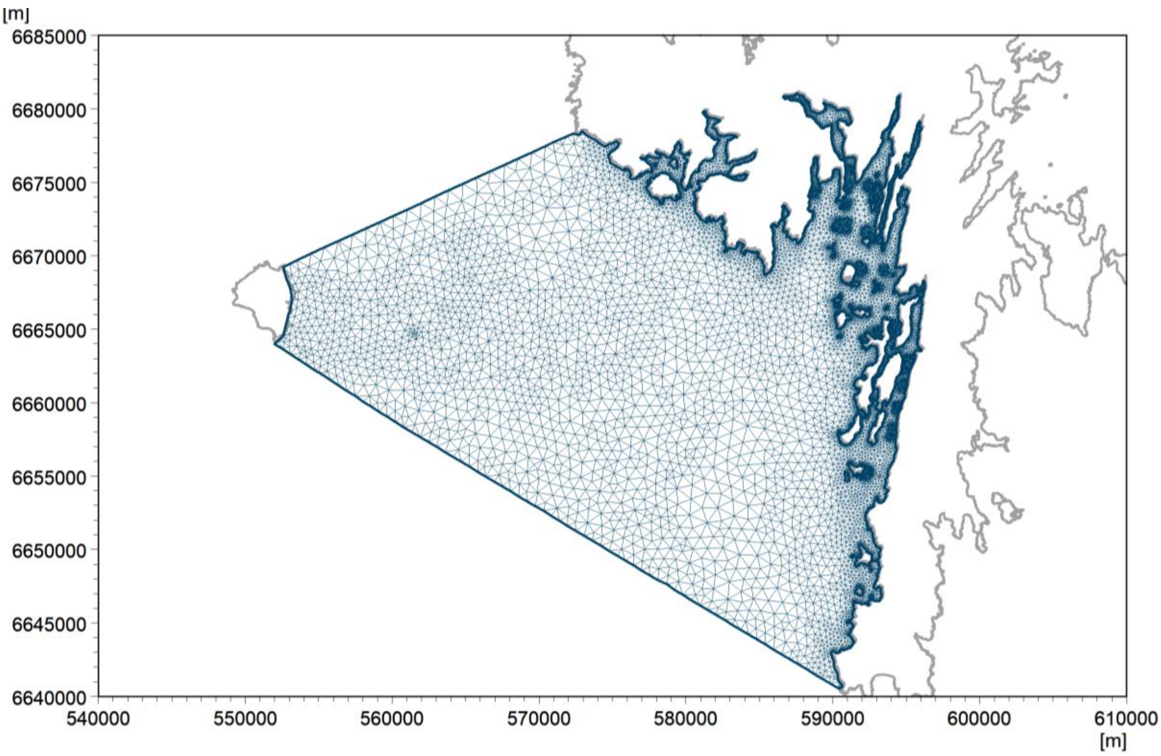


Figure 4.9 Computational mesh of the local Scalloway hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

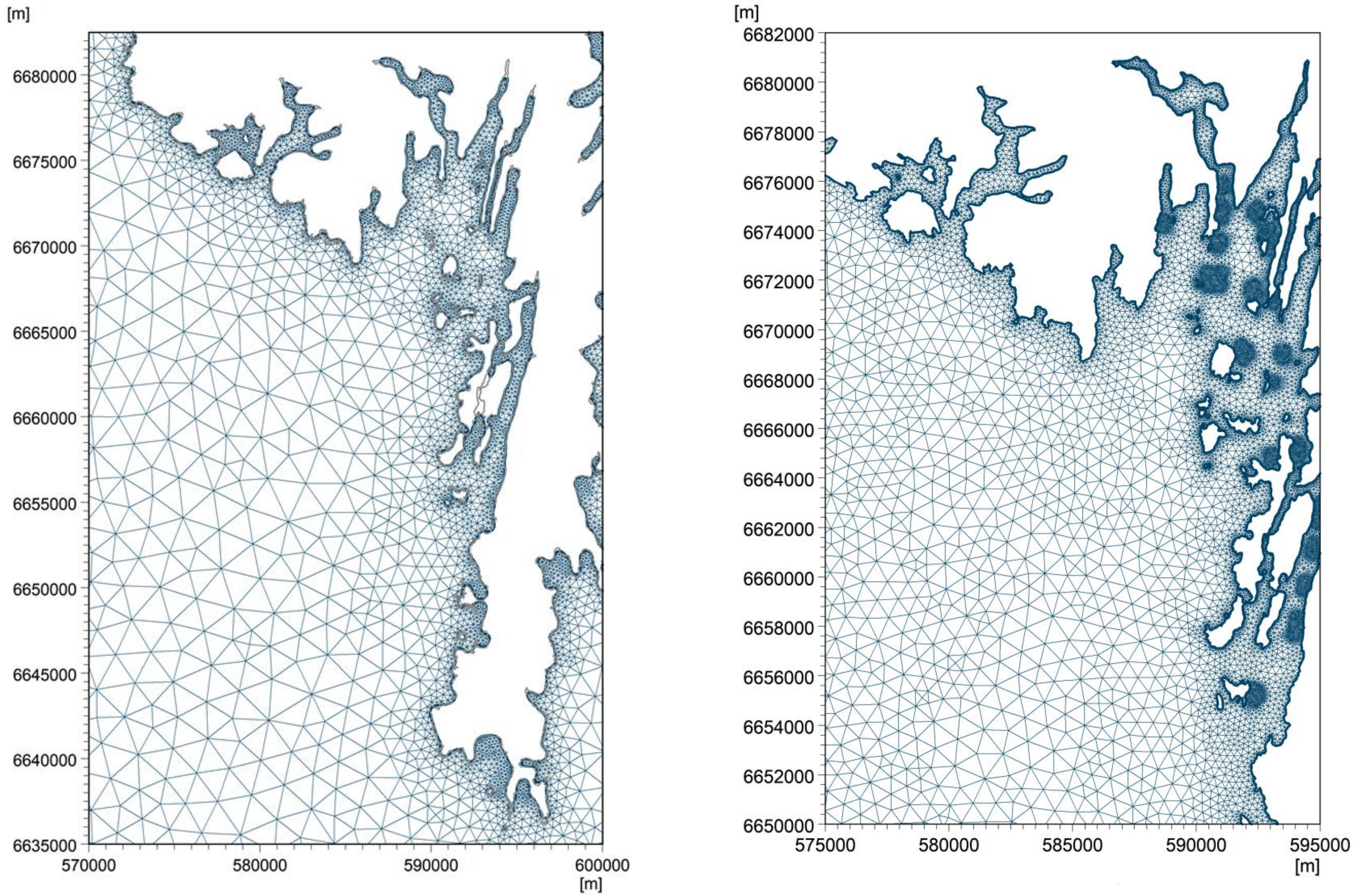


Figure 4.10 Computational mesh of area around Scalloway, south-west Shetland from $HD_{Shetland,Clima}$ (left) and the hydrodynamic climatology $HD_{Scalloway,Clima}$ (right)

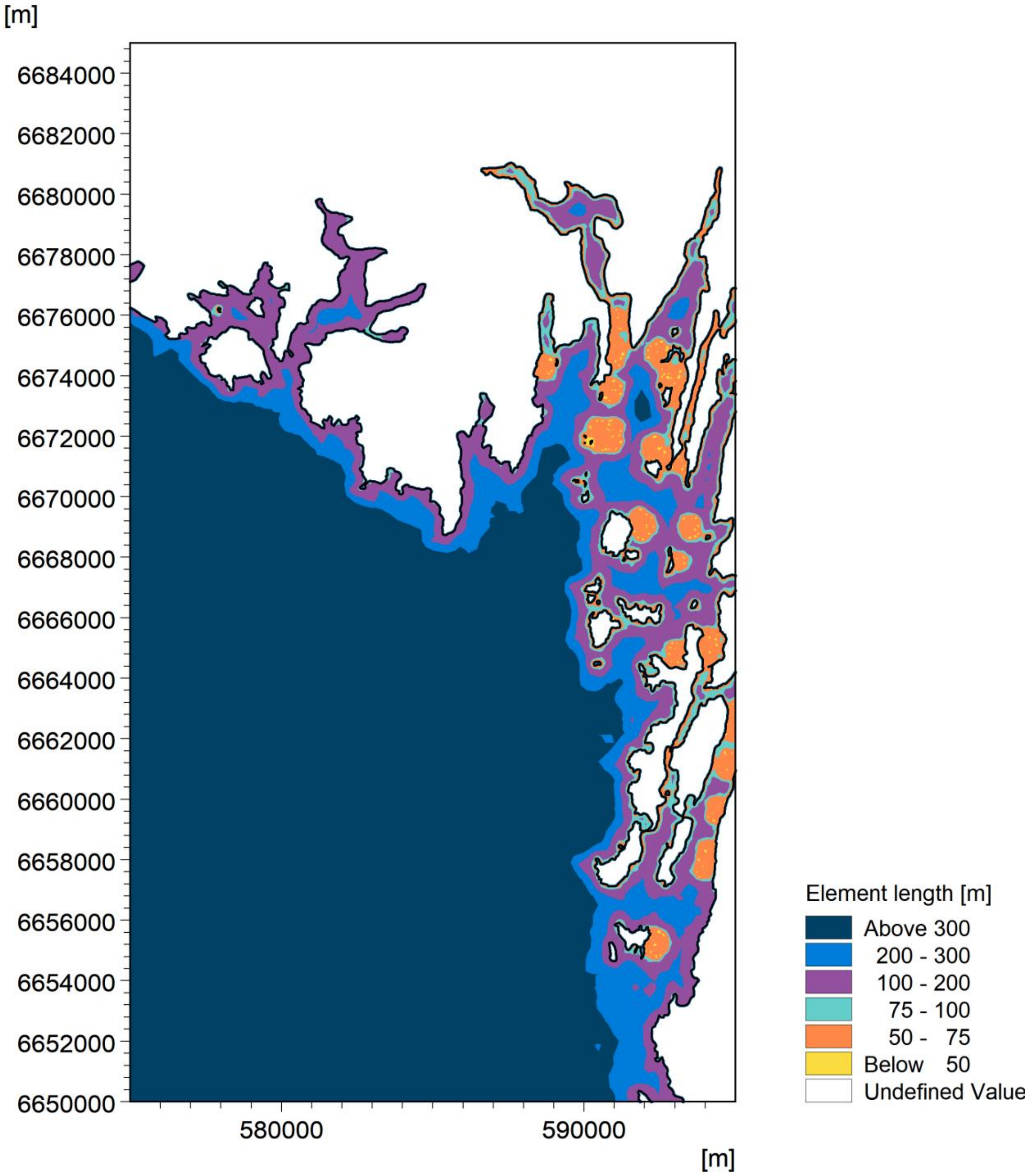


Figure 4.11 The approximate mesh element length [m] of the local Scalloway hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

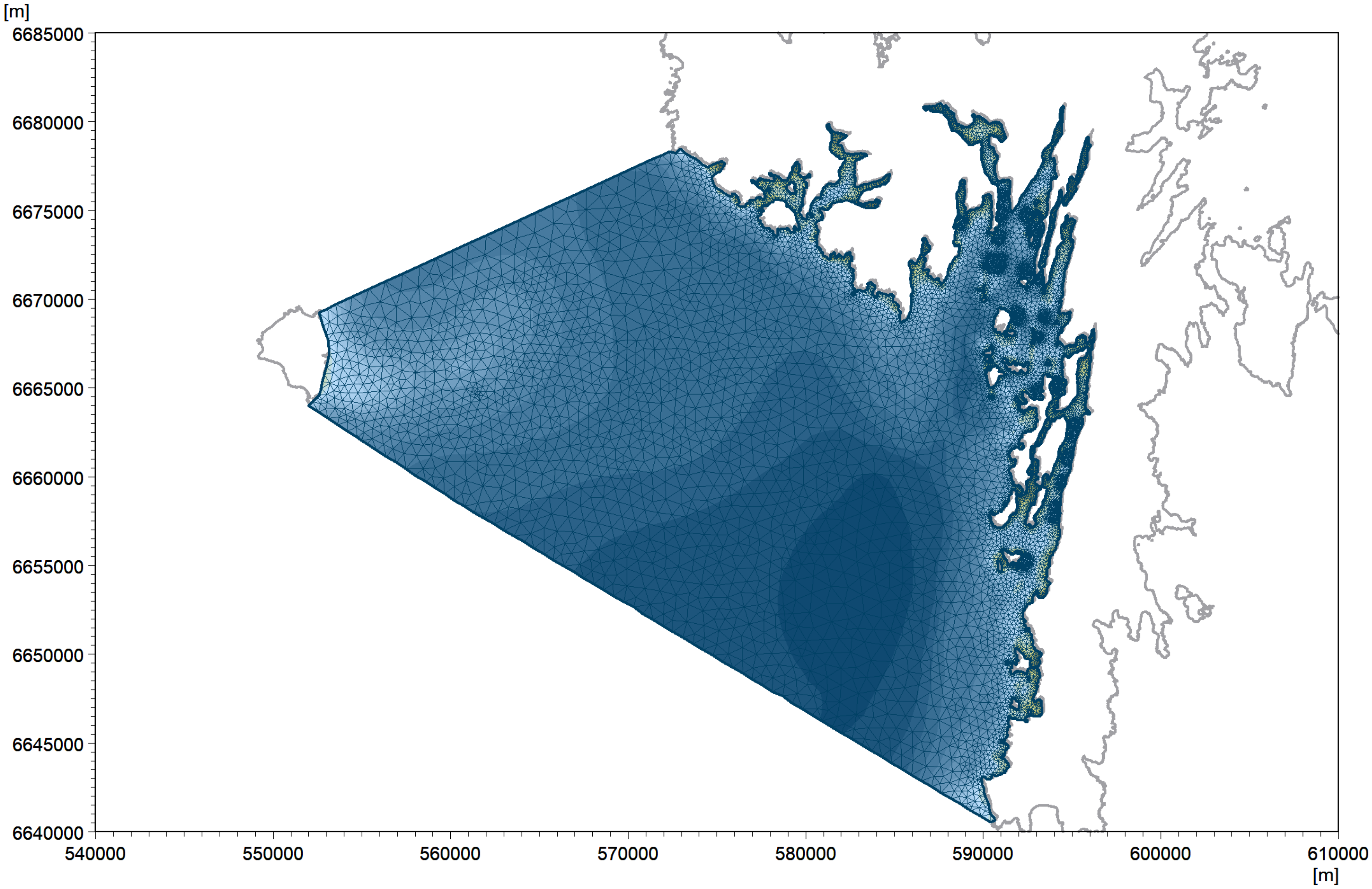


Figure 4.12 Interpolated model bathymetry relative to MSL of the local Scalloway hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

4.4.3 Initial and boundary conditions

Initial and boundary conditions for $HD_{Scalloway,Clima}$ were extracted from the results of the one-year regional Shetland hydrodynamic climatology model ($HD_{Shetland,Clima}$) as described in Section 4.3. This included temporally and spatially varying water surface elevation (1D, horizontal), and current velocities, temperature, and salinity (2D, horizontal and vertical) across the two open boundaries.

Hydrodynamic boundaries (water levels and current velocities) were specified as Flather boundary conditions [19]. This is an efficient open boundary condition method for downscaling coarse model simulations to local areas, and can generally avoid model instabilities when imposing stratified density at a water level boundary.

The $HD_{Scalloway,Clima}$ model was optimised using data assimilation of temperature and salinity. This was technique blends the computed solution with data provided from a reference file (in this case the SSM) to maintain a stable long term solution.

4.4.4 Meteorological forcing

Meteorological forcing applied in $HD_{Scalloway,Clima}$ was consistent with that of the regional Shetland climatology model ($HD_{Shetland,Clima}$) as described in Section 4.3.4.

4.4.5 Model configuration

The configuration of the $HD_{Scalloway,Clima}$ model is summarised in Table 4.2. For more information on the scientific background of the model settings or the governing equations of the model, please refer to [18, 20].

Table 4.2 Summary of $HD_{Scalloway,Clima}$ model settings

Setting	Description/Value
Basic equations	3D incompressible Reynolds averaged Navier-Stokes (RANS) equations
Numerical scheme	Higher order scheme (time integration and space discretisation)
Horizontal mesh	Variable resolution unstructured grid (see Section 4.4.2)
Vertical mesh	10 variable thickness σ layers (see Section 4.4.2)
Simulation period	A one-year climatological run, which represents average conditions with a 1993 tidal component.
Model time step (adaptive)	0.01 to 120 seconds
Flooding and drying	Drying depth 0.005m, wetting depth 0.1m
Density	Function of temperature and salinity (see temperature and salinity module below)
Horizontal Eddy viscosity	Smagorinsky formulation with constant = 0.5
Vertical Eddy viscosity	K-epsilon formulation with eddy viscosity values min:1.8e-06/max:0.4 [m2/s]
Bed resistance	Roughness height 0.05m
Coriolis Forcing	Varying in domain
Wind forcing	Varying in time and domain specified from the climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis products (see Section 3.3)
Wind friction	Varying with wind speed (Linear variation Speed): • 7 [m/s] Friction: 0.00185 • 25 [m/s], Friction: 0.002825
Ice coverage	Not included
Tidal potential	Not included
Precipitation/Evaporation	Varying in time and domain specified from the climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis products (see Section 3.3)
Initial conditions	Spatially varying surface elevation derived from regional Shetland hydrodynamic climatology model ($HD_{Shetland,Clima}$).
Boundary conditions	Flather boundary conditions, Temporally and spatially water levels and 3D current velocities from Shetland hydrodynamic climatology model ($HD_{Shetland,Clima}$)
Temperature and salinity module	Temporally and spatially boundaries from the SSM (see Section 3.2), plus data assimilation.

4.5 Model outputs

The 2-dimensional and 3-dimenaional outputs from the hydrodynamic climatology models ($HD_{Shetland,Clima}$ and $HD_{Scalloway,Clima}$) are summarised in Table 4.3 and Table 4.4, respectively. All parameters were saved in all model mesh elements (grid cells) at 1-hourly time intervals.

Table 4.3 2D model outputs from $HD_{Shetland,Clima}$ and $HD_{Scalloway,Clima}$

Parameter	Unit	Description
Surface elevation	m	Still water level relative to MSL
Total water depth	m	Depth from still water level to seafloor
u-velocity component	ms^{-1}	Depth-averaged velocity speed in the west-to-east direction
v-velocity component	ms^{-1}	Depth-averaged velocity in the south-to-north direction
P Flux	$m^3s^{-1}m^{-1}$	Flow flux per metre in west-to-east direction
Q Flux	$m^3s^{-1}m^{-1}$	Flow flux per metre in south-to-north direction

Table 4.4 3D model outputs from $HD_{Shetland,Clima}$ and $HD_{Scalloway,Clima}$

Parameter	Unit	Description
u-velocity component	ms^{-1}	Current velocity in the west-to-east direction
v-velocity component	ms^{-1}	Current velocity in the south-to-north direction
w-velocity component	ms^{-1}	Current velocity in the vertical direction
Density	kgm^{-3}	-
Temperature	°C	-
Salinity	PSU	Practical Salinity Unit
Horizontal eddy viscosity	m^2s^{-1}	-
Vertical eddy viscosity	m^2s^{-1}	-

4.6 Model files

The hydrodynamic climatology model is supplied to SSF and GSS as part of the project deliverables. This includes the mesh files, offshore boundary conditions, meteorological climatology, and the model results files. The data are provided in DHI MIKE format, and can be used to generate boundary conditions for local climatology modelling or as input for scenario modelling.

Appendix A includes a description of the model files that are provided alongside this report.

5 Model Results

In this section, the results of the 3D hydrodynamic climatology models are presented. This includes a verification of the regional model against measurements water levels at Lerwick (Section 5.1.1), and a comparison of 3D currents, temperature, and salinity at selected offshore locations compared to the wider domain Scottish Shelf Model (Section 5.1.2). Finally, some examples of outputs from the regional Shetland and local Scalloway models are presented (Section 5.2).

5.1 Verification of the climatology

As mentioned previously, the underlying concept of a climatology model is the assumption that the conditions at a particular location for a particular day do not change significantly from one year to the next. Unfortunately, no long-term (multi-year) records of currents or water properties are available to assess model performance, and it is unreasonable to compare model predictions against short-term measurement data, which reflect a specific set of conditions during which the measurements were made. Instead, an assessment of the regional Shetland hydrodynamic climatology is performed in the following ways:

- Deriving tidal constituents at Lerwick from the regional climatological model ($HD_{Shetland,Clima}$) and comparing against those derived from long-term tide gauge observations
- Comparing model prediction of water level, currents speed, current direction, water temperate, and water salinity at offshore locations. Here we are verifying the model down-scaling from shelf scale to local domain (SSM→$HD_{Shetland,Clima}$→$HD_{Shetland,Clima}$)

5.1.1 Tidal constituents at Lerwick

Long-term water level observations of the water level at Lerwick were obtained from the UK National Tide Gauge Network[4] for the period 1994-2014. Modelled water levels at Lerwick (-1.1403°E; 601541°N) were also extracted from $HD_{Shetland,Clima}$. Astronomical water levels (tidal levels) were then calculated using harmonic tidal analysis to separate the tidal and non-tidal (residual) components of the total water level time series. The harmonic analysis was conducted using the U-tide toolbox, see [21], which is based on the IOS tidal analysis method defined by the Institute of Oceanographic Sciences as described by [22], and integrates the approaches defined in [23] and [24]. The residual water level was calculated by subtracting the predicted tidal level from the total water level.

Figure 5.1 shows the derived tidal constituents from $HD_{Shetland,Clima}$ and their amplitude, period, and phase at Lerwick. The largest constituent is the principal lunar semi-diurnal *M2* component (0.60m amplitude), followed by the principal solar semi-diurnal *S2* component (0.21m amplitude). Table 4.1 compares the largest tidal constituents derived from $HD_{Shetland,Clima}$ with those derived from the Lerwick tide gauge. There is an overall good agreement in the prediction of tidal amplitude and phase.

Figure 5.2 shows a time series plot of modelled water levels (total, tidal, and residual) at Lerwick. The semidiurnal and spring-neap tidal cycle is prominent in the total and tidal signal. One can also clearly see the seasonal variability in the residual water levels, but low variability on shorter time-scales which reflects the climatologically averaged

[4] UK Tide Gauge Network accessed May 2021

meteorological conditions (see Section 3.3). Also shown in the legend of Figure 5.2 are the astronomical water levels which are defined as follows:

- HAT Maximum predicted WL
- MHWS: Average of the two successive high waters reached during the 24 hours when the tidal range is at its greatest (spring tide)
- MHWN: Average of the two successive high waters reached during the 24 hours when the tidal range is at its lowest (neap tide)
- MSL: Mean predicted WL
- MLWN: Average of the two successive low waters reached during the 24 hours when the tidal range is at its lowest (neap tide)
- MLWS: Average of the two successive low waters reached during the 24 hours when the tidal range is at its greatest (spring tide)
- LAT: Minimum predicted WL

Table 5.1 Comparison of the amplitude [m] and phase [°] of selected tidal constituents at Lerwick based on tide gauge measurements (1994-2014) and $HD_{Shetland,Clima}$ model

Consituent	Lerwick tide gauge (1994-2014)		Lerwick, $HD_{Shetland,Clima}$	
	Amplitde [m]	Phase [°]	Amplitde [m]	Phase [°]
M2	0.58	311.8	0.60	308.9
S2	0.21	347.1	0.21	346.1
N2	0.12	290.7	0.13	289.5
K1	0.08	163.7	0.08	175.0
O1	0.08	33.1	0.06	45.3
K2	0.06	344.7	0.06	342.4

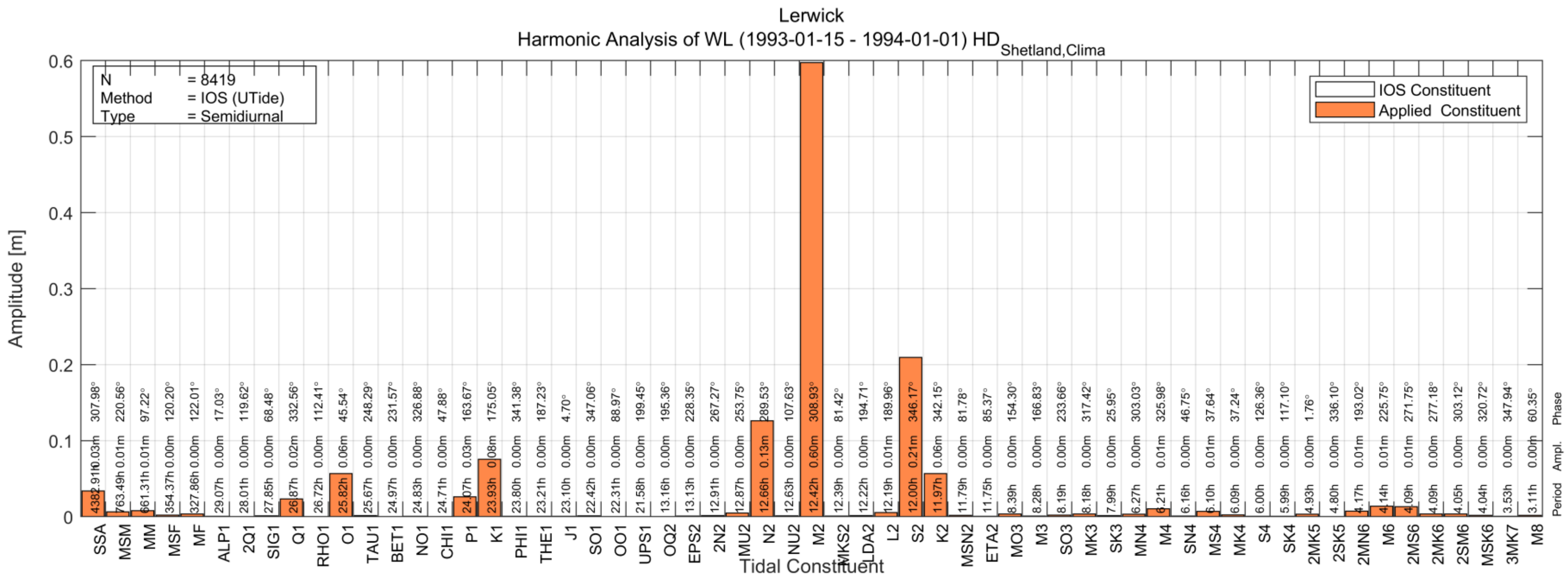


Figure 5.1 Amplitude, period, and phase of tidal constituents at Lerwick derived from $HD_{Shetland,Clima}$

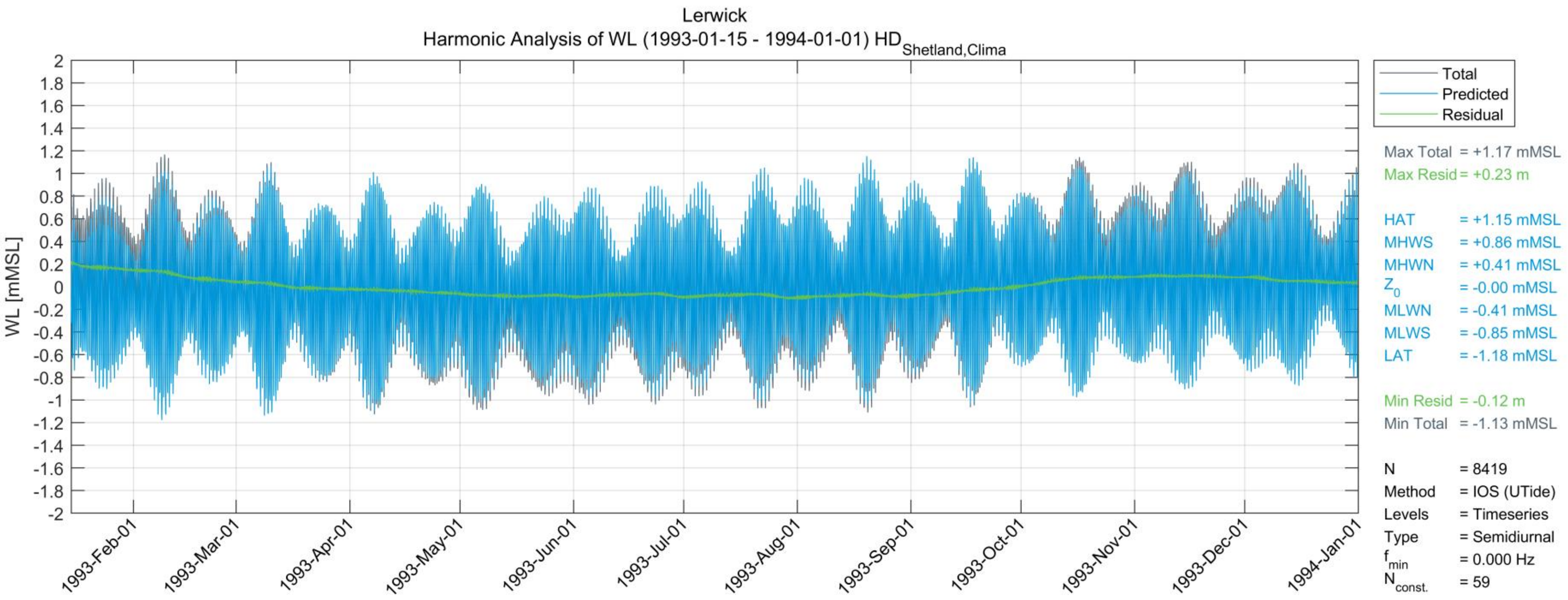


Figure 5.2 Time-series of modelled water levels at Lerwick (total, tidal, and residual) and astronomical water levels derived from $HD_{Shetland,Clima}$

5.1.2 Offshore comparisons to SSM

The regional Shetland hydrodynamic climatology model is a down-scaled version of the SSM shelf-wide domain model; it is forced by SSM derived boundary conditions with consistent meteorological inputs, but with higher spatial resolution in and around Shetland. To verify the model down-scaling (SSM → $HD_{Shetland,Clima}$) comparisons of model predictions have been performed at five offshore locations (P1, P2, P3, P4, and P5 in Figure 5.3). These locations are approximately equidistant between the model boundariesand Shetland itself and in relatively deep water (100mMSL to 120mMSL). These five offshore points should not be influenced by the changes in model resolution and bathymetry in and around the islands from $HD_{Shetland,Clima}$.

Model parameters including current speed, current direction, sea water temperature, and salinity were extracted from both the SSM and $HD_{Shetland,Clima}$ at location P1 to P5 for depths of 5m, 10m, 20m, 40m, and 80m below SWL. Water levels relative to MSL were also extracted at each location. A comparison of the two model time-series was then performed, consisting of time-series, scatter plot, histogram, and rose plot comparisons. Statistical model quality indices (QI's) were also determined. For more information on model QI's please see Appendix B (note that these indices are more commonly used to compare measurement, but we herein use the SSM model as the baseline reference).

Verification plots of water levels at location P1 are shown in Figure 5.4, while comparison of current speed, current direction, sea water temperature, and salinity at 5m below SWL at P1 are shown in Figure 5.5 to Figure 5.8. A very good replication of the SSM modelled conditions is predicted by $HD_{Shetland,Clima}$ at location P1, however it is noted that the current speeds show a small negative bias (average underprediction by $HD_{Shetland,Clima}$). Equivalent plots showing the verification at all locations (P1 to P5) and water depths are provided in digital format accompanying this report (see Appendix C).

Table 5.2 to Table 5.4 summarise the performance of $HD_{Shetland,Clima}$ in terms of water levels, current speeds, and sea water temperatures by giving an overview of model QI's achieved in comparison to the SSM domain wide model.

An additional point was selected to the south-west of Shetland Mainland at the entrance to the Scalloway area (P6 in Figure 5.3). This analysis point is also in the domain of the Scalloway hydrodynamic model ($HD_{Scalloway,Clima}$) and the water depth at this location is around 70mMSL. Figure 5.9 shows a comparison of the three models at locaiton P6 which Illustrates the appropriate downscaling of models from shelf scale to local domains (SSM → $HD_{Shetland,Clima}$ → $HD_{Scalloway,Clima}$).

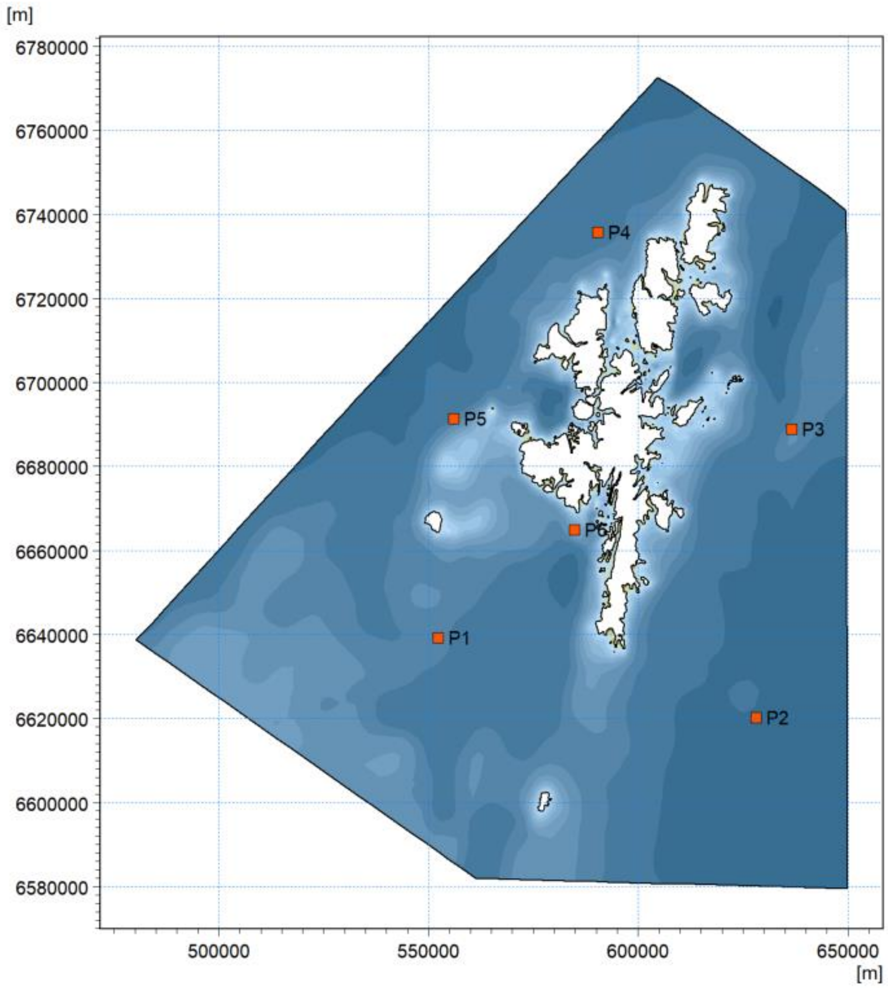


Figure 5.3 HD$_{Shetland,Clima}$ model domain showing locations of verification points including offshore locations (P1 to P5), and location in the outer Scalloway area (P6)

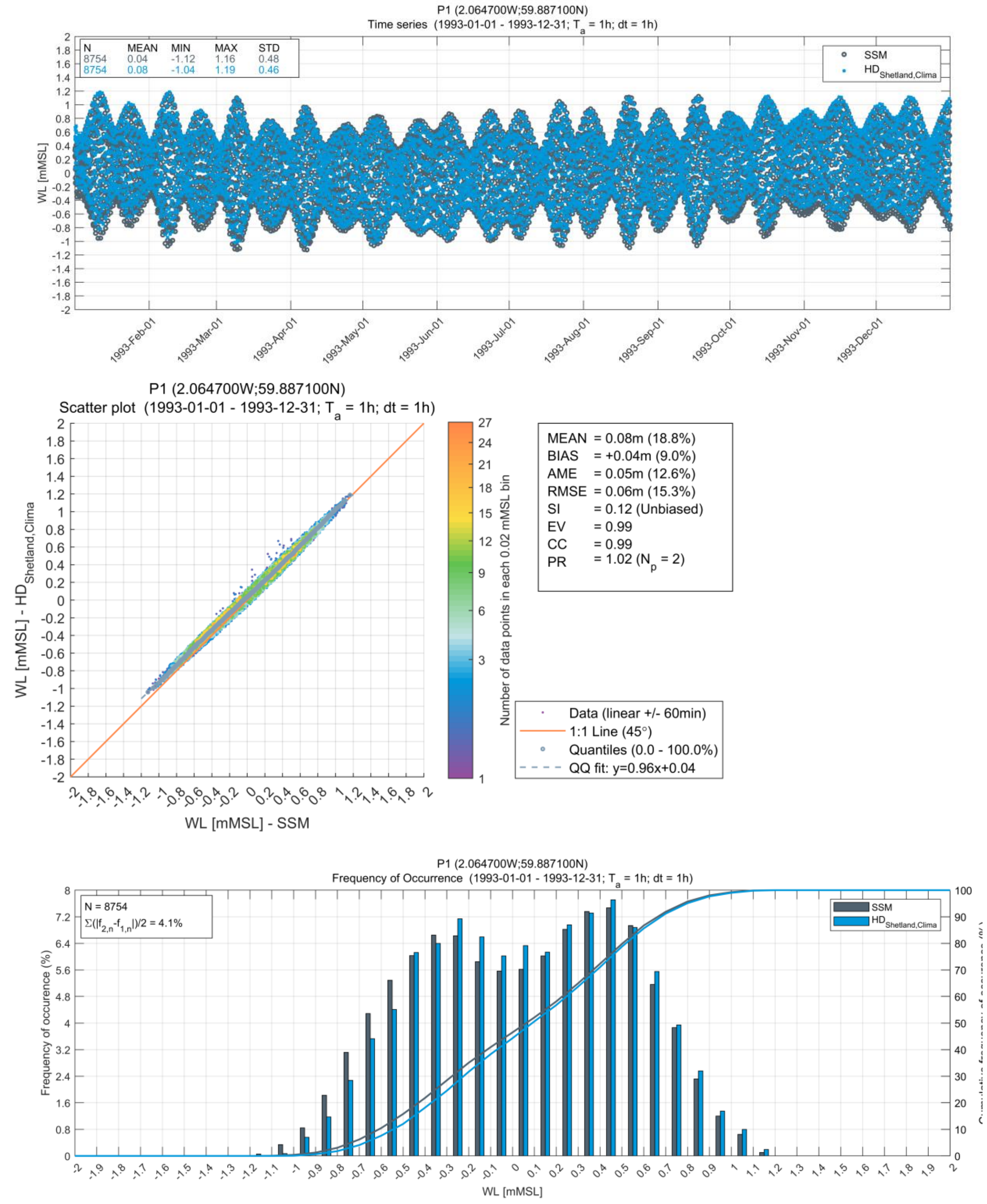


Figure 5.4 Time-series (upper panel), scatter plot (central panel), and histogram plot (lower panel) comparison of SSM and $HD_{Shetland,Clima}$ modelled water levels (*WL*) at point P1

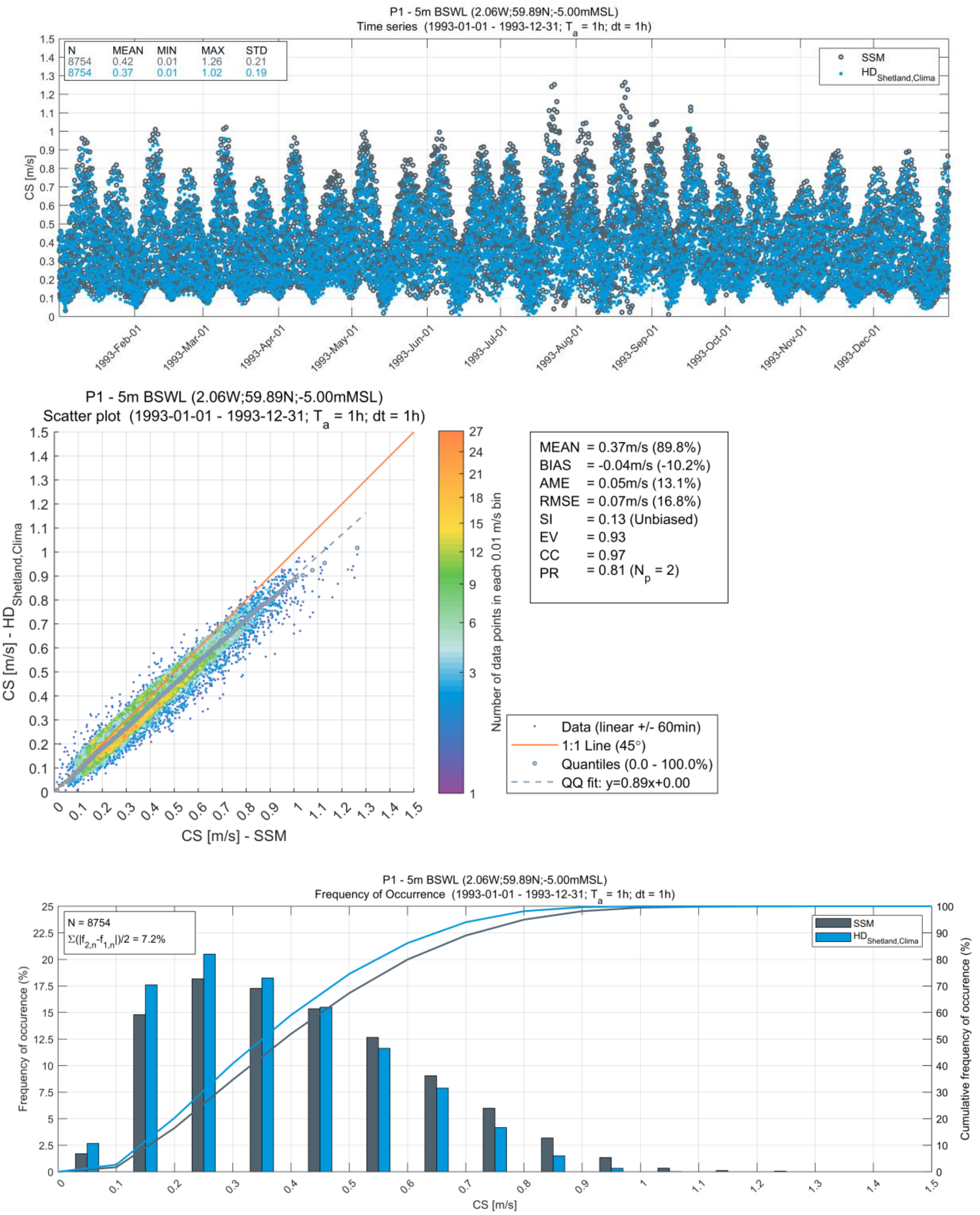


Figure 5.5 Time-series (upper panel), scatter plot (central panel), and histogram plot (lower panel) comparison of SSM and $HD_{Shetland,Clima}$ modelled current speed (*CS*) at 5m below SWL at point P1

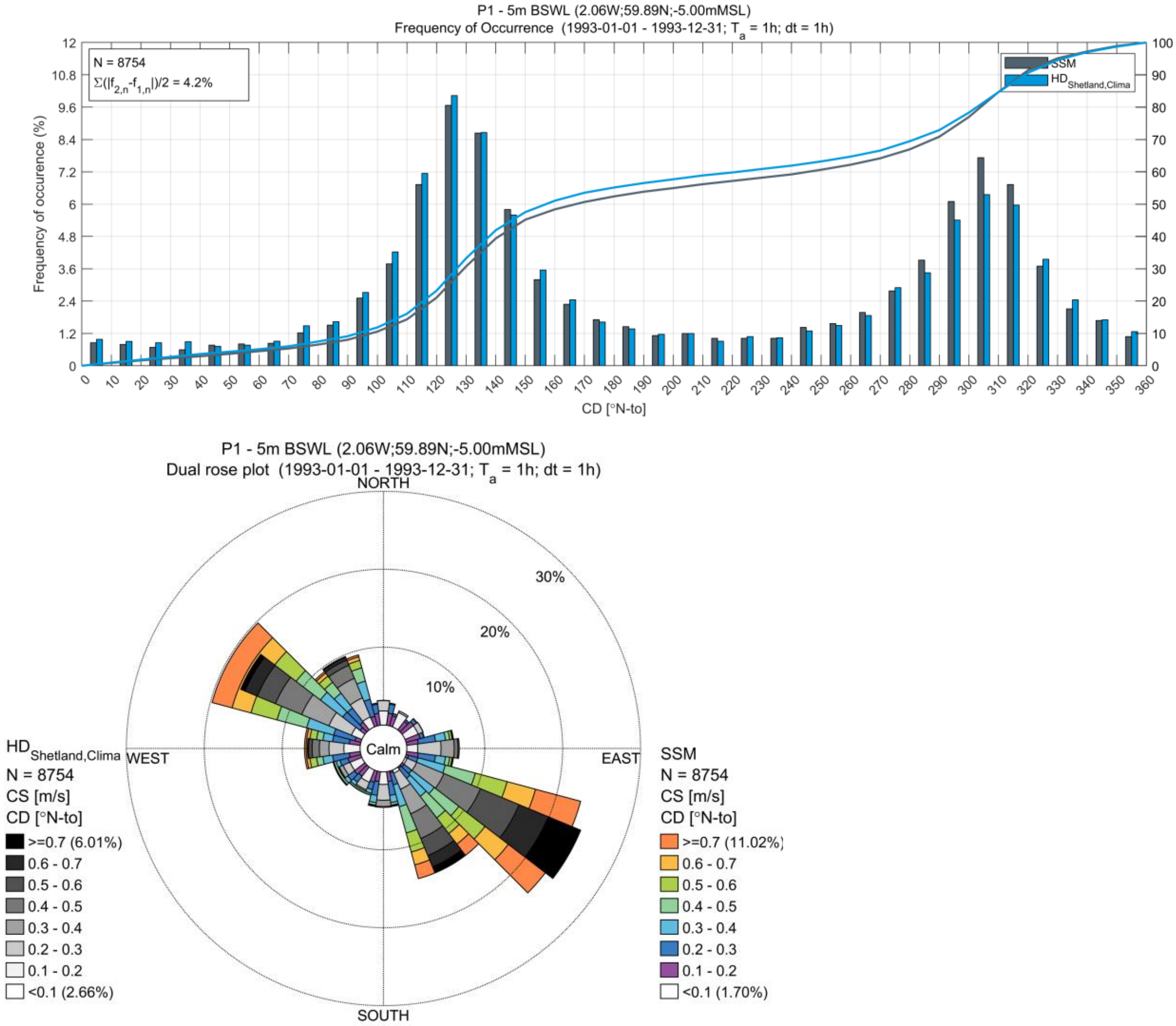


Figure 5.6 Histogram (upper panel) and rose plot (lower panel) comparison of SSM and $HD_{Shetland,Clima}$ modelled current direction (*CD*) at 5m below SWL at point P1

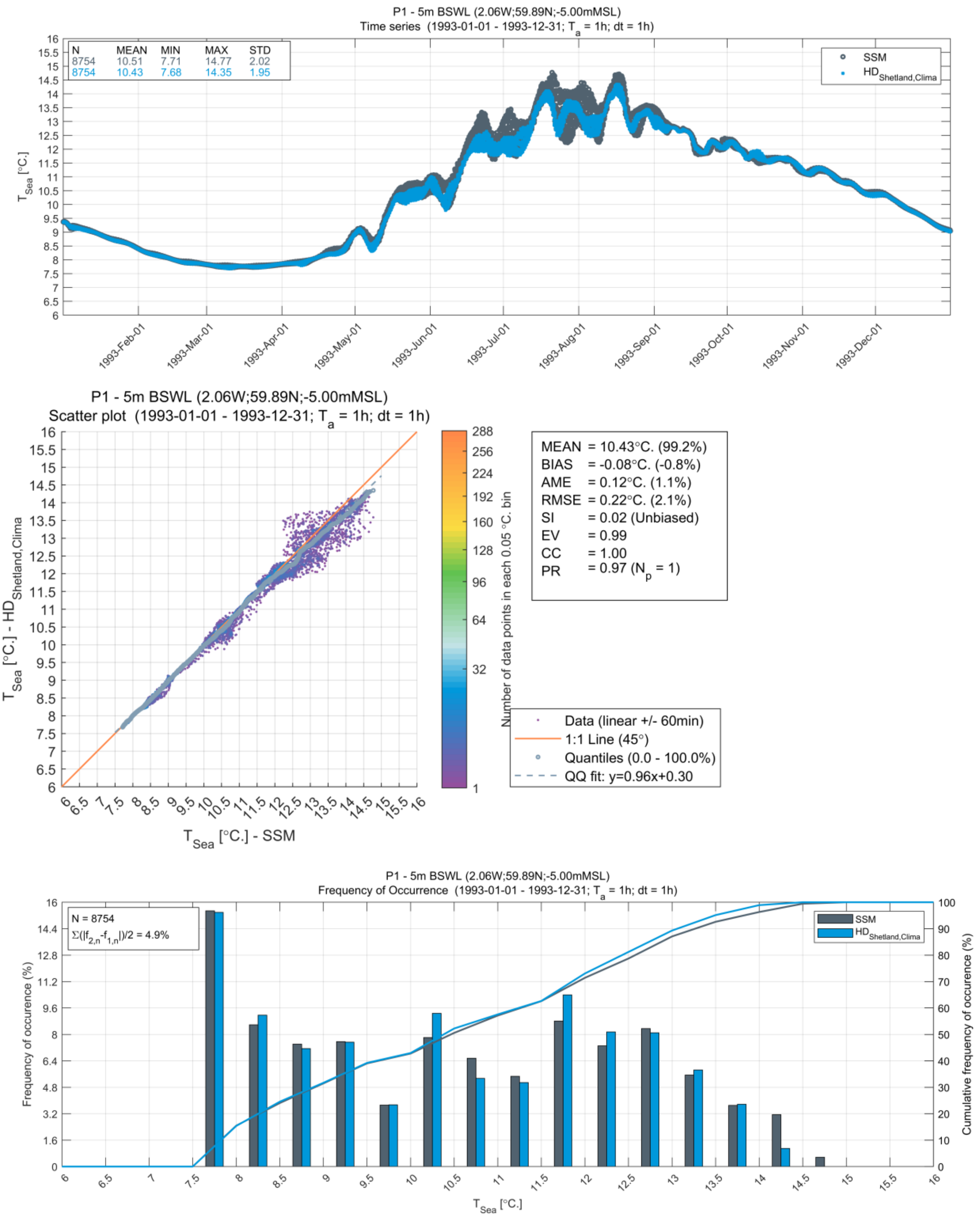


Figure 5.7 Time-series (upper panel), scatter plot (central panel), and histogram plot (lower panel) comparison of SSM and $HD_{Shetland,Clima}$ modelled sea water temperature (T_{Sea}) at 5m below SWL at point P1

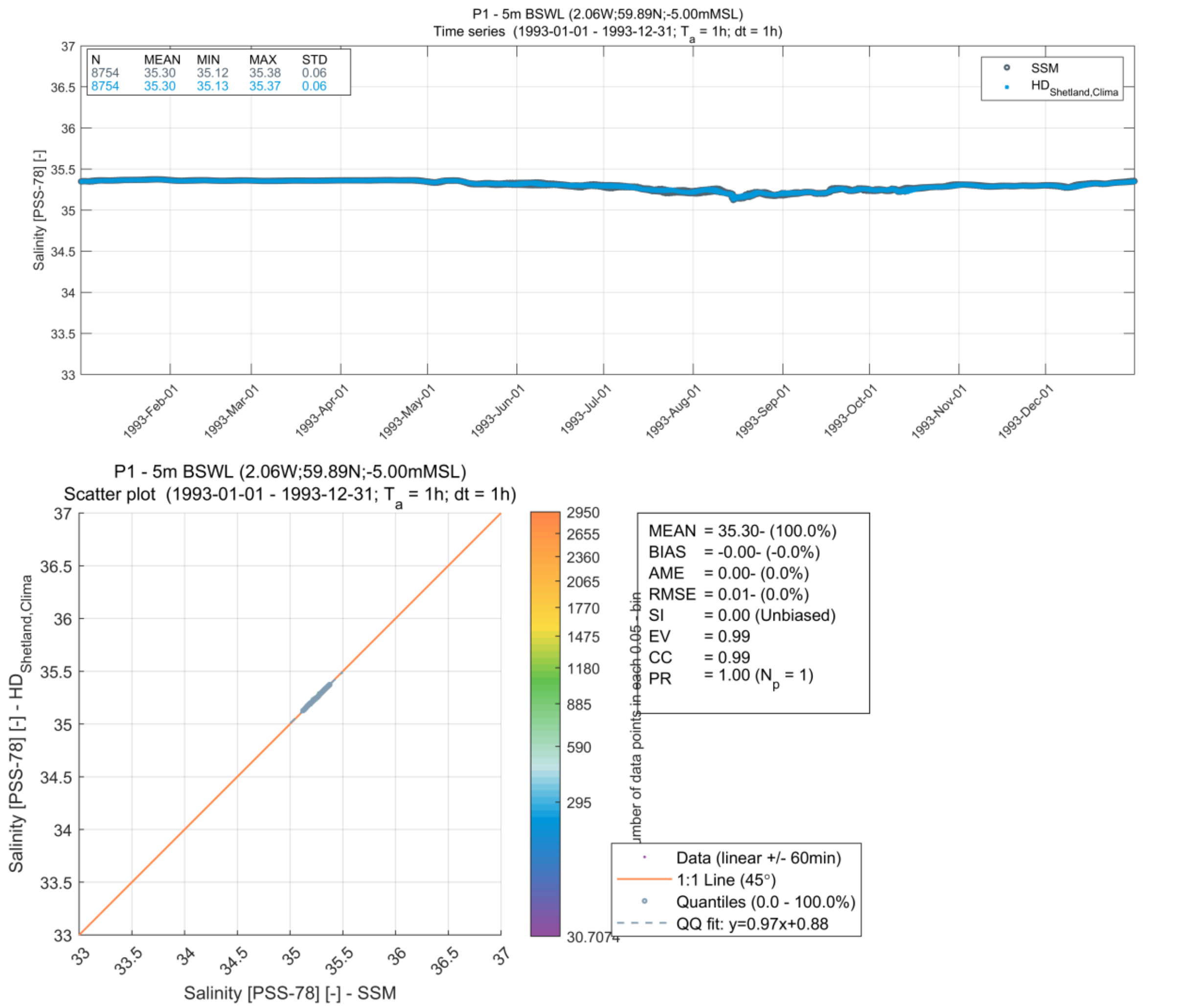


Figure 5.8 Time-series (upper panel) and scatter plot (lower panel) comparison of SSM and $HD_{Shetland,Clima}$ modelled salinity 5m below SWL at point P1

Table 5.2 Summary of verification of modelled total water level (*WL*) at offshore locations

Location	MEAN [m]	BIAS [m]	AME [m]	RMSE [m]	SI	EV	CC	PR
P1	0.08	+0.04	0.05	0.06	0.12	0.99	0.99	1.02
P2	0.04	+0.04	0.04	0.05	0.09	0.99	1.00	1.08
P3	0.06	+0.04	0.04	0.05	0.08	0.99	1.00	1.04
P4	0.08	+0.04	0.04	0.05	0.08	1.00	1.00	1.05
P5	0.08	+0.04	0.05	0.06	0.12	0.99	1.00	1.00
P6	0.07	+0.03	0.04	0.05	0.13	0.99	0.99	1.00

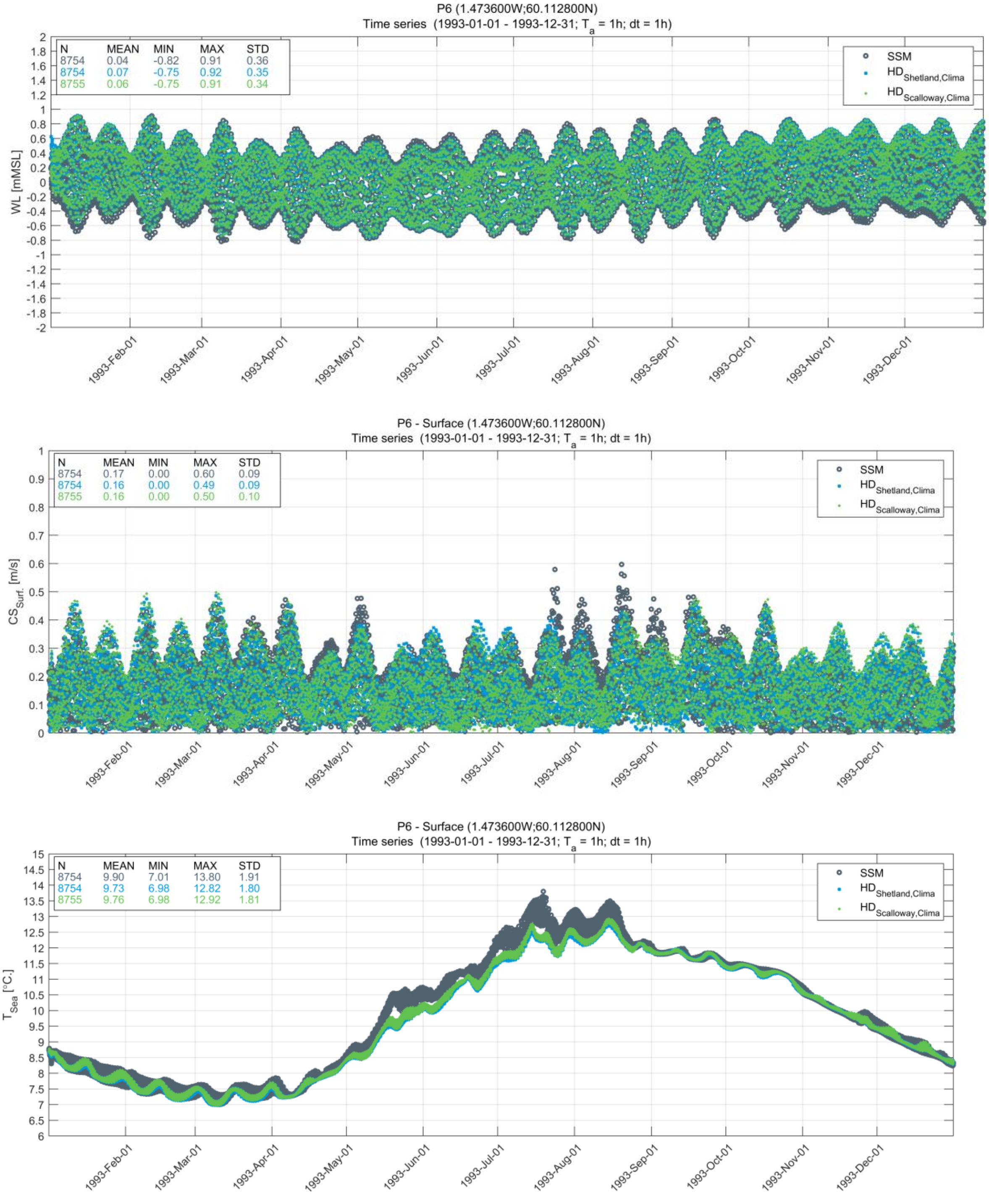


Figure 5.9 Time-series comparison of SSM (grey), $HD_{Shetland,Clima}$ (blue) and $HD_{Scalloway,Clim}$ (green) water levels upper panel), current speed at 5m below SWL (central panel), and sea water temperature (lower panel) at point P6

Table 5.3 Summary the $HD_{Shetland,Clima}$ model verification against SSM at offshore locations, total current speed (*CS*)

Location	Depth [m]	MEAN [m/s]	BIAS [m/s]	AME [m/s]	RMSE [m/s]	SI	EV	CC	PR
P1	5	0.37	-0.04	0.05	0.07	0.13	0.93	0.97	0.81
	10	0.37	-0.04	0.05	0.06	0.11	0.95	0.98	0.87
	20	0.36	-0.04	0.04	0.05	0.08	0.98	0.99	0.88
	40	0.34	-0.03	0.03	0.04	0.06	0.98	1.00	0.90
	80	0.29	-0.01	0.01	0.02	0.05	0.99	1.00	0.98
P2	5	0.18	+0.01	0.03	0.04	0.23	0.61	0.81	1.04
	10	0.18	+0.01	0.02	0.03	0.19	0.73	0.86	1.02
	20	0.18	0.00	0.01	0.02	0.10	0.91	0.95	0.97
	40	0.19	0.00	0.01	0.01	0.07	0.96	0.98	0.97
	80	0.18	-0.01	0.01	0.01	0.06	0.95	0.98	0.92
P3	5	0.19	-0.01	0.03	0.04	0.20	0.85	0.92	0.85
	10	0.19	-0.01	0.03	0.04	0.19	0.85	0.92	0.89
	20	0.19	0.00	0.02	0.03	0.16	0.89	0.95	1.03
	40	0.18	0.00	0.02	0.02	0.13	0.92	0.97	1.06
	80	0.16	+0.04	0.04	0.05	0.28	0.66	0.96	1.45
P4	5	0.14	-0.02	0.03	0.04	0.21	0.90	0.95	0.83
	10	0.14	-0.03	0.03	0.04	0.20	0.91	0.96	0.76
	20	0.14	-0.03	0.04	0.05	0.21	0.91	0.96	0.77
	40	0.13	-0.03	0.03	0.04	0.18	0.93	0.98	0.82
	80	0.12	-0.02	0.02	0.02	0.13	0.95	0.98	0.87
P5	5	0.21	-0.06	0.06	0.07	0.18	0.85	0.93	0.72
	10	0.21	-0.07	0.07	0.09	0.19	0.83	0.93	0.67
	20	0.22	-0.06	0.06	0.07	0.13	0.91	0.97	0.77
	40	0.21	-0.04	0.04	0.05	0.10	0.94	0.98	0.90
	80	0.17	+0.02	0.02	0.03	0.12	0.90	0.96	1.11
P6	5	0.16	-0.02	0.03	0.04	0.21	0.85	0.92	0.88
	10	0.16	-0.02	0.03	0.04	0.18	0.89	0.95	0.91
	20	0.16	-0.01	0.02	0.02	0.13	0.94	0.97	0.95
	40	0.15	0.00	0.01	0.02	0.11	0.97	0.98	0.96

Table 5.4 Summary the $HD_{Shetland,Clima}$ model verification against SSM at offshore locations, sea water temperature (T_{Sea})

Location	Depth [m]	MEAN [°C]	BIAS [°C]	AME [°C]	RMSE [°C]	SI	EV	CC	PR
P1	5	10.43	-0.08	0.12	0.22	0.02	0.99	1.00	0.97
	10	10.20	+0.12	0.16	0.28	0.03	0.98	0.99	0.99
	20	9.81	+0.01	0.05	0.08	0.01	1.00	1.00	0.98
	40	9.23	+0.16	0.17	0.28	0.02	0.98	0.99	1.01
	80	9.72	0.00	0.03	0.04	0.00	1.00	1.00	1.00
P2	5	10.38	-0.24	0.24	0.39	0.03	0.99	1.00	0.96
	10	10.12	+0.04	0.09	0.16	0.01	1.00	1.00	1.00
	20	9.23	+0.16	0.17	0.28	0.02	0.98	0.99	1.01
	40	9.45	+0.06	0.08	0.13	0.01	0.99	1.00	1.02
	80	7.98	0.00	0.02	0.04	0.00	1.00	1.00	1.00
P3	5	10.54	-0.14	0.14	0.25	0.02	0.99	1.00	0.99
	10	10.28	+0.09	0.12	0.22	0.02	0.99	1.00	1.01
	20	9.45	+0.06	0.08	0.13	0.01	0.99	1.00	1.02
	40	9.72	+0.07	0.09	0.16	0.01	0.99	1.00	1.02
	80	8.88	+0.01	0.01	0.02	0.00	1.00	1.00	1.00
P4	5	10.46	-0.15	0.15	0.27	0.02	0.99	1.00	0.97
	10	10.25	+0.10	0.13	0.25	0.02	0.98	0.99	1.02
	20	9.72	+0.07	0.09	0.16	0.01	0.99	1.00	1.02
	40	9.72	+0.06	0.08	0.14	0.01	0.99	1.00	1.00
	80	9.31	+0.01	0.02	0.03	0.00	1.00	1.00	1.00
P5	5	10.48	-0.09	0.10	0.18	0.01	0.99	1.00	0.99
	10	10.25	+0.15	0.17	0.31	0.03	0.97	0.99	1.03
	20	9.72	+0.06	0.08	0.14	0.01	0.99	1.00	1.00
	40	9.31	0.00	0.06	0.09	0.01	1.00	1.00	1.00
	80	9.50	+0.01	0.03	0.06	0.01	1.00	1.00	1.01
P6	5	9.73	-0.08	0.11	0.16	0.01	0.99	1.00	0.98
	10	9.58	+0.02	0.10	0.14	0.01	0.99	1.00	0.99
	20	9.31	0.00	0.06	0.09	0.01	1.00	1.00	1.00
	40	9.73	-0.01	0.03	0.05	0.01	1.00	1.00	0.99

5.2 Model outputs

The statistical mean and maximum current speed in the surface layer of $HD_{Shetland,Clima}$ are shown in Figure 5.10 and Figure 5.11, respectively. As expected, the strong currents are to be found where the flow is constrained around the headlands and in narrow channels that connect the North Atlantic and North Sea.

The statistical mean and maximum current speed in the surface layer from $HD_{Scalloway,Clima}$ are shown in Figure 5.12 and Figure 5.13, respectively. The largest current speeds are found close to the open boundaries between Shetland and Foula and towards Sumburgh Head. In the area of *the Deeps*, the large inlet that includes Scalloway, the surface currents speeds are lower with mean values generally of less than 0.1m/s and with slightly larger speeds in areas of flow construction (Figure 5.14). The net current vectors reveals a complex flow pattern at the surface.

To highlight the differences in the predicted flow field at various spatial scales, the annual average surface current speed and net surface current direction at the entrance to Weisdale Voe in the Scalloway area (see Figure 5.14 for reference to this location) are shown for the SSM (Figure 5.15), $HD_{Shetland,Clima}$ (Figure 5.16), and $HD_{Scalloway,Clima}$ (Figure 5.17). The SSM model only captures the vague shape of the coastline in this area and does not resolve individual islands (e.g. Hoy, Flotta, or Greena) or the neighbouring inlet of Sandsoud Voe. The regional climatology model ($HD_{Shetland,Clima}$) resolves the islands in the area with simple geometries, capturing their influence on the flow field, and shows faster mean current speeds that the SSM. The net current direction from $HD_{Shetland,Clima}$ is similar to that of the local Scalloway climatology model ($HD_{Scalloway,Clima}$); however, the high resolution coastline and mesh in the latter provides additional insight into the spatial distribution of surface current in the area.

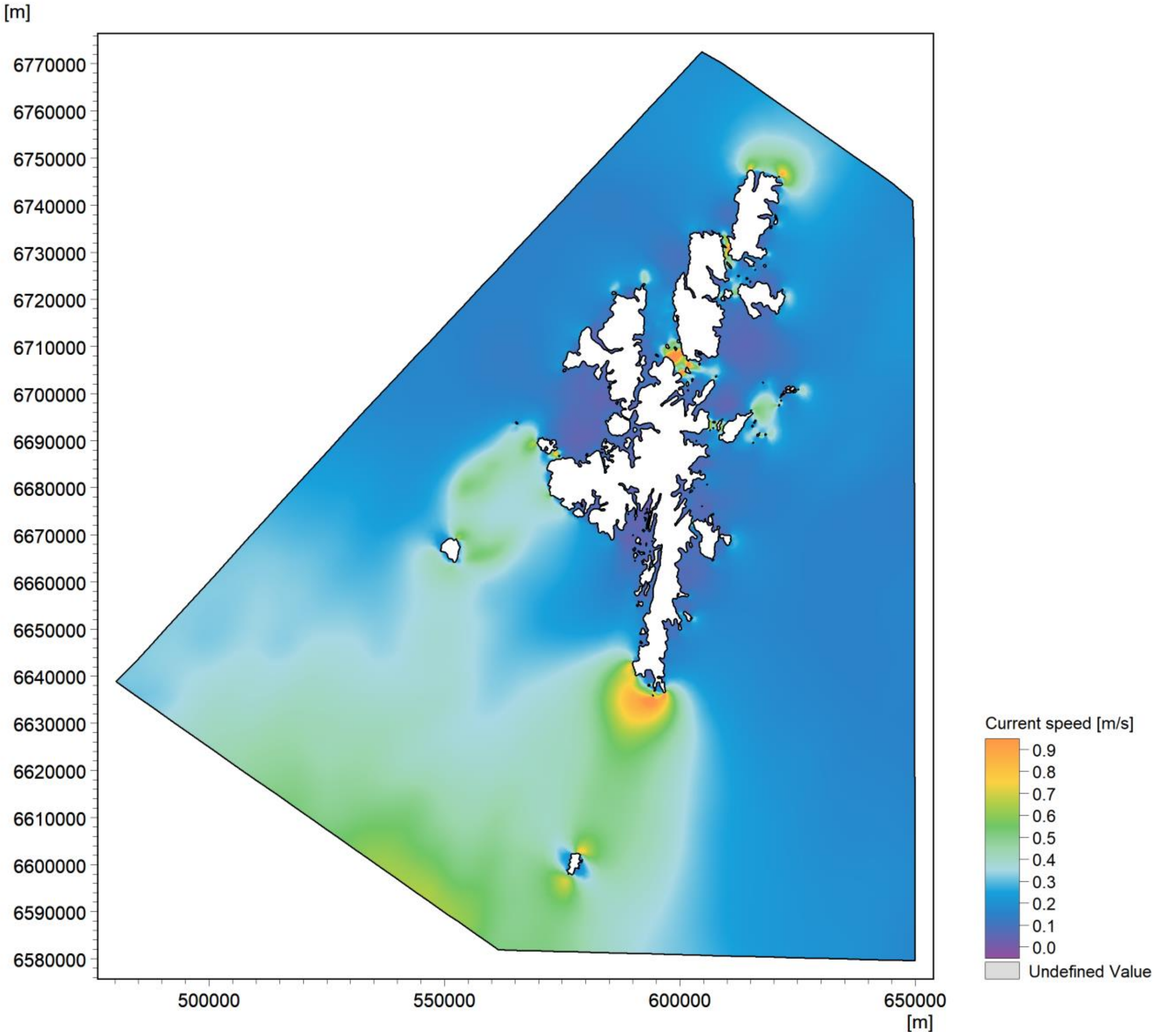


Figure 5.10 Mean annual surface current speed around Shetland based on regional hydrodynamic climatology model ($HD_{Shetland,Clima}$)

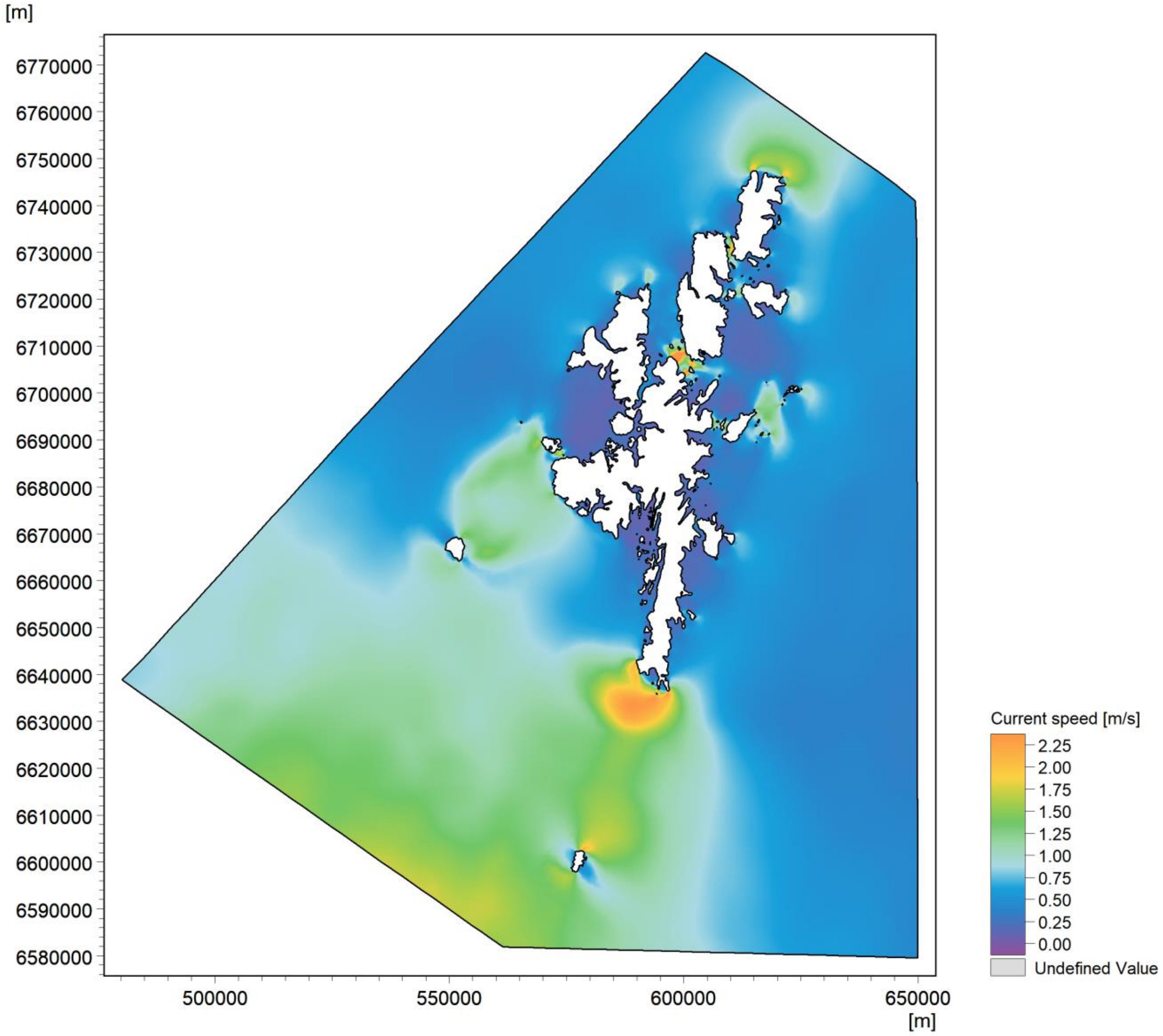


Figure 5.11 Statical maximum surface current speed around Shetland based on regional hydrodynamic climatology model ($HD_{Shetland,Clima}$)

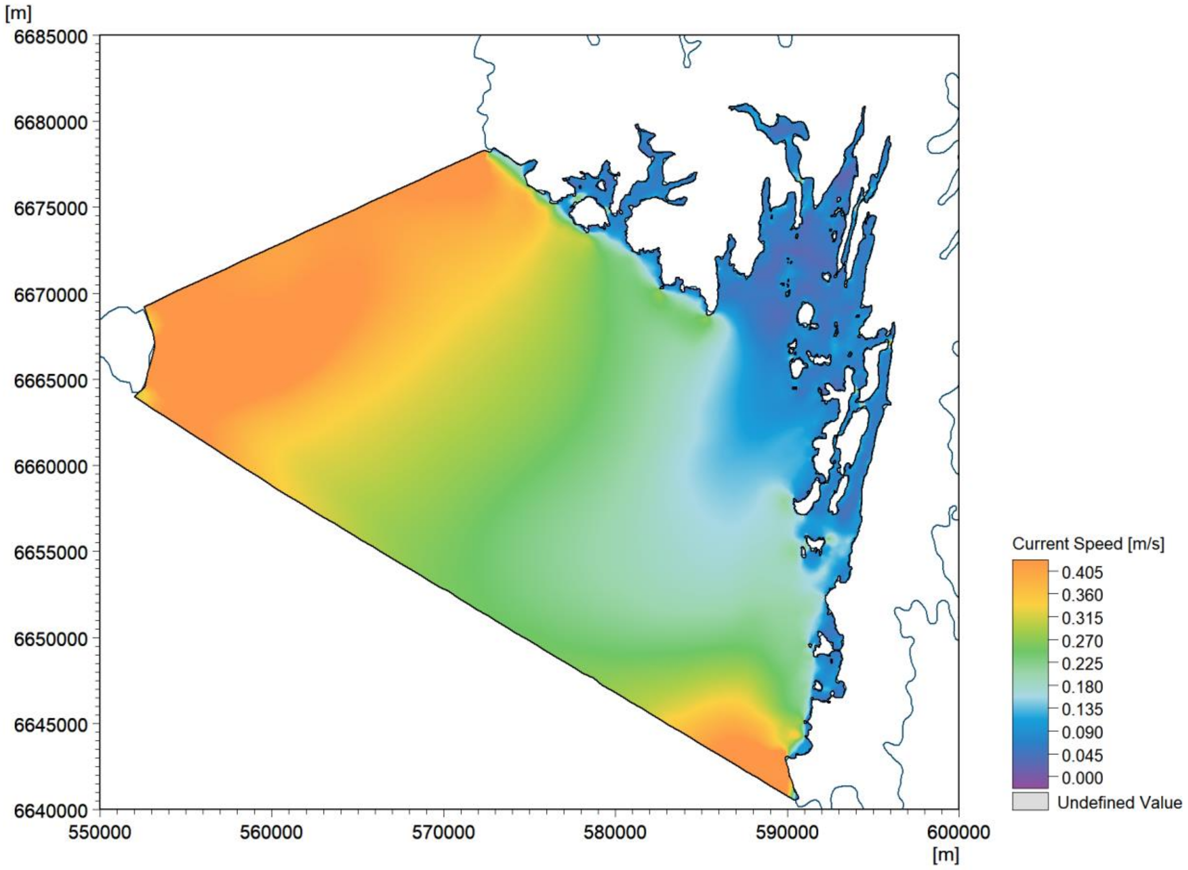


Figure 5.12 Mean annual surface current speed in area around Scalloway based on local hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

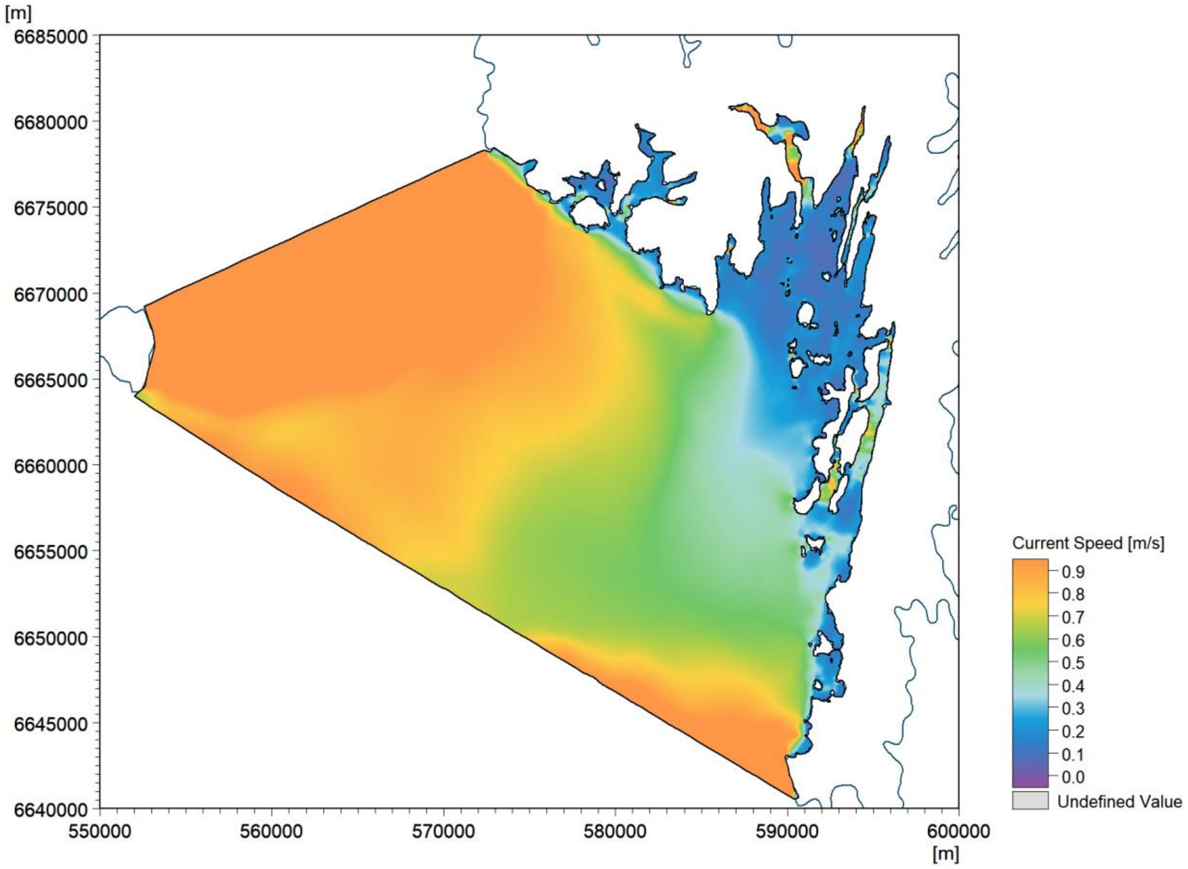


Figure 5.13 Statical maximum surface current speed in area around Scalloway based on local hydrodynamic climatology model ($HD_{Scalloway,Clima}$)

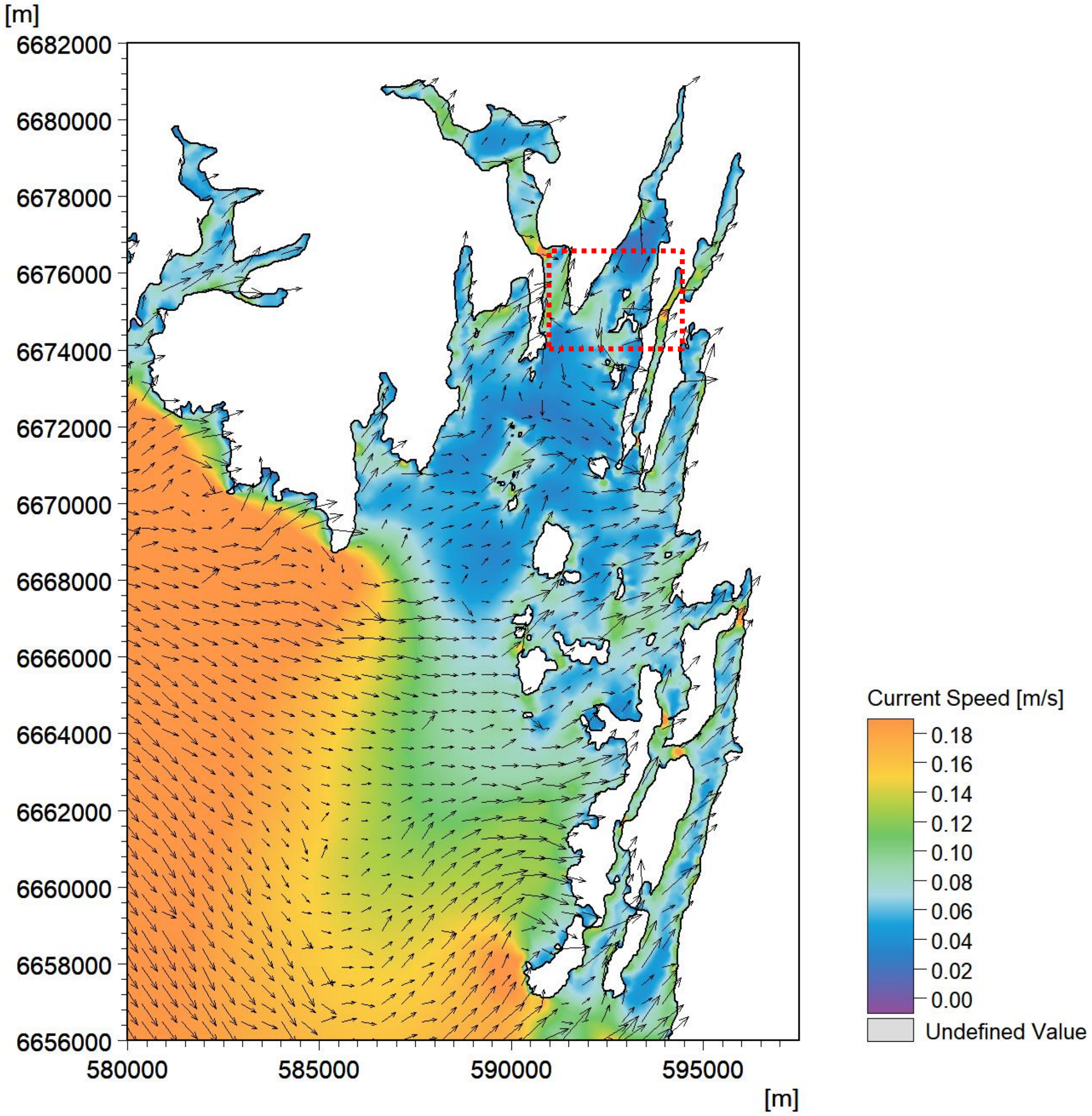


Figure 5.14 Contour plot showing the annual average surface current speed and net current direction (black arrows) in area around Scalloway based on local hydrodynamic climatology model ($HD_{Scalloway,Clima}$). For clarity, the vectors are plotted onto a structured grid. The area at the entrance Weisdale Voe is highlighted by the dashed red rectangle (shown in more detail in Figure 5.17 to Figure 5.17)

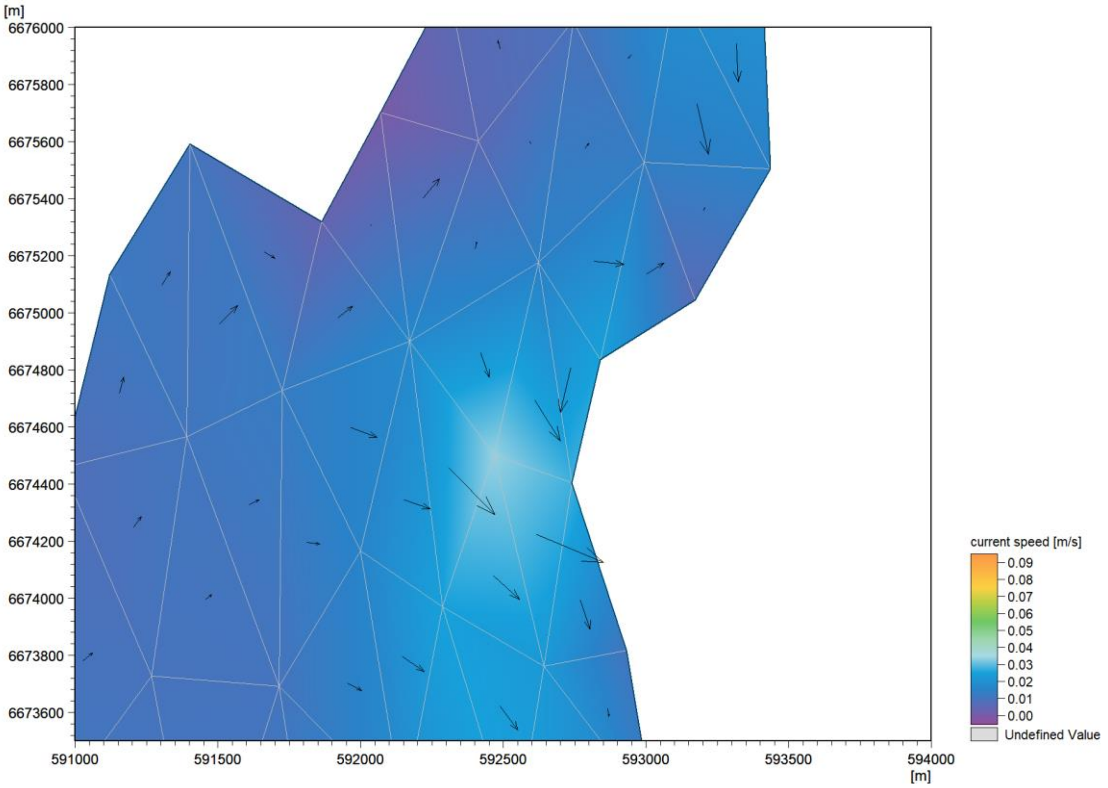


Figure 5.15 Contour plots showing the SSM annual average surface current speed with net surface current directional vectors (arrows at cell centres) at the entrance the of Weisdale Voe

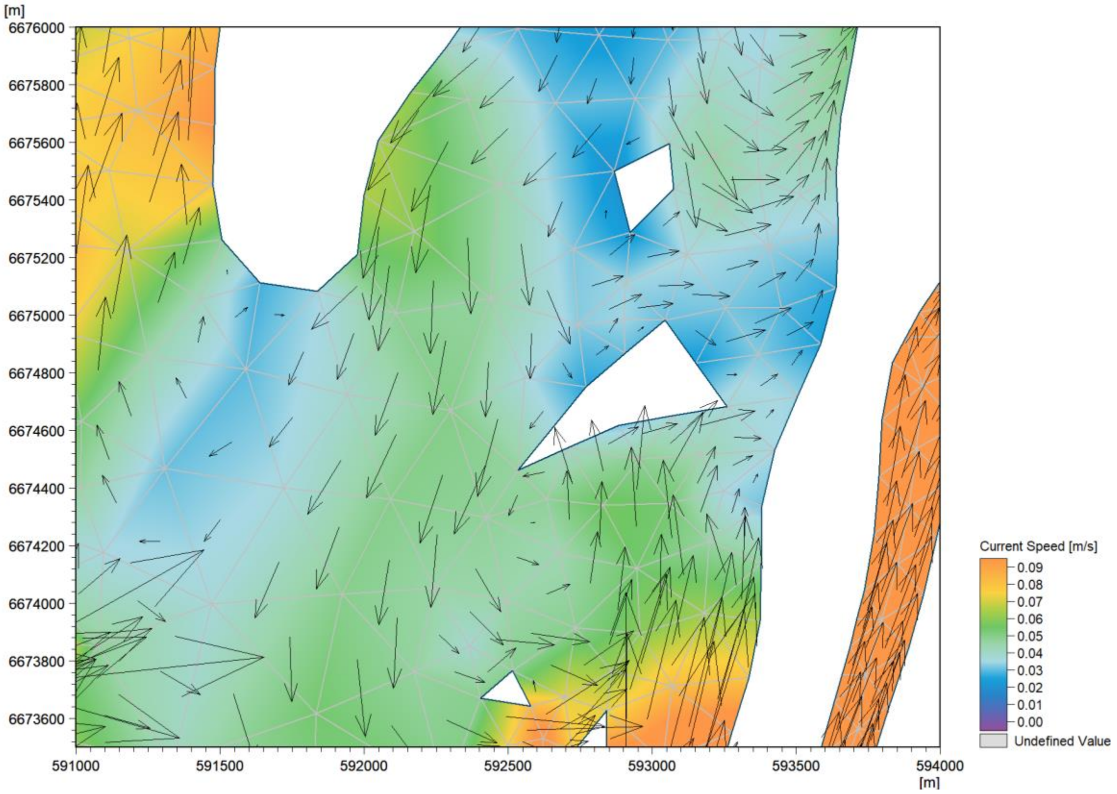


Figure 5.16 Contour plots showing the $HD_{Shetland,Clima}$ annual average surface current speed with net surface current directional vectors (arrows at cell centres) at the entrance of Weisdale Voe

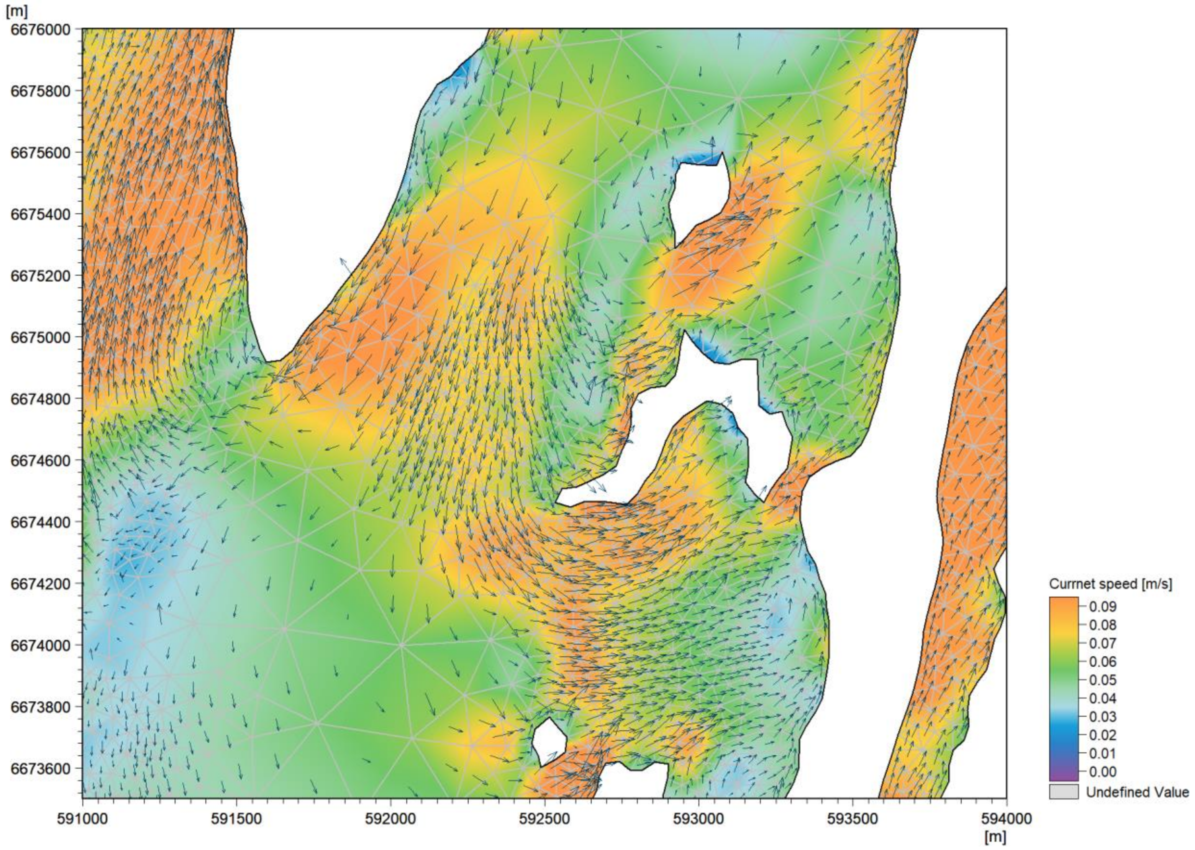


Figure 5.17 Contour plots showing the $HD_{Scalloway,Clima}$ annual average surface current speed with net surface current directional vectors (arrows at cell centres) at the entrance of Weisdale Voe

6 Summary

A 3-dimensional hydrodynamic climatology model database for Shetland has been developed to support fin fish aquaculture projects in Shetland, Scotland. The model database has been established using DHI's MIKE 3 modelling hydrodynamic model, based on upon the existing Scottish Shelf Model climatology developed for Marine Scotland Science.

This Shetland database includes a regional hydrodynamic climatology with a resolution of approximately 250m at the coastline. A separate high-resolution local model of the area around Scalloway (south-west Shetland) has also been developed, with resolution of down to 50m around existing marine pen fish farms.

The hydrodynamic climatology model database provides a basis for future modelling to support regulatory applications such as: assessing connectivity between fish farms sites around Shetland; site selection and site screening; dispersion modelling of waste solids and bath treatment medicines; and to provide boundary conditions for local-scale hydrodynamic climatology models.

7 References

[1] R. J. Shucksmith, “Shetland Islands Marine Region State of the Environment Assessment,” NAFC Marine Centre UHI. Report for the Shetland Islands Marine Planning Partnership. pp 172, 2017.

[2] S. Governmant, “Scotland's Marine Atlas: Information for The National Marine Plan,” 16 03 2011. [Online]. Available: https://www.gov.scot/publications/scotlands-marine-atlas-information-national-marine-plan/pages/. [Accessed 19 02 2021].

[3] M. Office, “Nortern Scotland: climate,” 10 10 2016. [Online]. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/northern-scotland_-climate---met-office.pdf. [Accessed 01 03 2021].

[4] S. P. Neill, A. Vögler, A. Goward-Brown, S. Baston, M. J. Lewis, P. A. Gillibrand, S. Waldman and D. K. Woolf, “The wave and tidal resource of Scotland,” *Vögler,* vol. 114, no. Part A, pp. 3-17, 2017.

[5] R. Halliday, “Shetland Islands Wave and Tidal Resource,” Natural Power for Shetland Island Council (805-NPC-SIC-004), 2001.

[6] Marine Scotland Science, “Scottish Fish Farm Production Survey 2019,” The Scottish Government, October 2020.

[7] M. Scotland, “The Scottish Shelf Model,” [Online]. Available: http://marine.gov.scot/themes/scottish-shelf-model. [Accessed 01 03 2021].

[8] D. Price, C. Stuiver, H. Johnson, A. Galledo and R. O'Hara Murray, “The Scottish Shelf Model. Part 3: St Magnus Bay Sub-Domain,” *Scottish Marine and Freshwater Science,* vol. 7, no. 5, 2016.

[9] J. Wolf, N. Yates, A. Bereton, H. Buckland, M. De Dominicis, A. Gallego and R. O'Hara Murray, “The Scottish Shelf Model. Part 1: Shelf-Wide Domain,” *Scottish Marine and Freshwater Science,* vol. 7, no. 3, 2016.

[10] M. De Dominicis, J. Wolf and R. O'Hara Murry, “Comparative Effects of Climate Change and Tidal Stream Energy Extraction in a Shelf Sea,” *JGR Oceans,* vol. 123, no. 7, pp. 5041-5067, 2018.

[11] C. Chen, H. Liu and R. C. Beardsley, “An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries,” *Journal of Atmospheric and Oceanic Technology,* vol. 20, no. 1, pp. 159-186, 2003.

[12] K. P. Edwards, R. Barciels and M. Butenschön, “Validation of the NEMO-ERSEM operational ecosystem model for the North West European Continental Shelf,” *Ocean Science,* vol. 8, no. 6, pp. 983-1000, 2012.

[13] E. J. O'Dea, A. K. Arnold, K. P. Edwards, R. Furner, P. Hyder and M. J. Martin, “An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf,” *Journal of Operational Oceanography,* vol. 5, no. 1, 2012.

[14] D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli and S. Kobayashi, “The ERA-Interim reanalysis: configuration and performance of the data assimilation system,” *Quarterly Journal of the Royal Meteorological Society,* vol. 137, no. 656, pp. 553-597, 2011.

[15] V. A. Bell, A. L. Kay, R. G. Jones and R. J. Moore , “Development of a high resolution grid-based river flow model for use with regional climate model output,” *Hydrology and Earth System Sciences,* vol. 11, no. 1, pp. 532-549, 2007.

[16] S. J. Cole and R. J. Moore, “Distributed hydrological modelling using weather radar in gauged and ungauged basins,” *Advances in Water Resources,* vol. 32, no. 7, pp. 1107-1120, 2009.

[17] SEPA, “Regulatory Modelling Guidance for the Aquaculture Sector, Version 1.1,” Scottish Environment Protection Agency, July 2019.

[18] DHI, “MIKE 21 & MIKE 3 Flow Model FM, Hydrodynamic and Transport Module, Scientific Documentation,” 2020. [Online]. Available: https://manuals.mikepoweredbydhi.help//2021/Coast_and_Sea/MIKE3HD_Scientific_Doc.pdf. [Accessed February 2021].

[19] R. A. Flather, “A tidal model of the northwest European continental shelf,” *Memories de la Societe Royale des Sciences de Liege,* vol. 6, no. 10, pp. 141-164, 1976.

[20] DHI, “MIKE 3 Flow Model FM, Hydrodynamic and Transport Module, Scientific Documentation,” 2021. [Online]. Available: https://manuals.mikepoweredbydhi.help//2021/Coast_and_Sea/MIKE_3_Flow_FM_Scientific_Doc.pdf. [Accessed 03 2021].

[21] D. L. Codiga, “Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01,” Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp, 2011.

[22] R. Pawlowicz, B. Beardsley and S. Lentz, “Classical tidal harmonic analysis including error estimates in MATLAB using T-TIDE,” *Computers & Geosciences 28,* pp. 929-937, 2002.

[23] M. G. G. Foreman, J. Y. Cherniawsky and V. A. Ballantyne, “Versatile Harmonic Tidal Analysis: Improvements and Applications.,” *J. Atmos. Oceanic Tech. 26,* pp. 806-817. DOI: 810.1175/2008JTECHO1615.1171, 2009.

[24] K. E. Leffler and D. A. Jay, “Enhancing tidal harmonic analysis: Robust (hybrid L-1/L-2) solutions,” *Cont. Shelf Res. 29,* pp. 78-88. DOI: 10.1016/j.csr.2008.1004.1011, 2009.

APPENDICES

APPENDIX A

Hydrodynamic Climatology Model Files

A Hydrodynamic climatology model files

The hydrodynamic climatology models are supplied on a portable hard drive alongside this report. This includes the mesh files, offshore boundary conditions, meteorological conditions, model setup files, and the model results files. The data are provided in DHI MIKE format, and can be used to generate boundary conditions for local climatology modelling or as input for scenario modelling.

Table A.1 summarises the model files provided for the $HD_{Shetland,Clima}$ model.

Table A.2 summarises the model files provided for the $HD_{Scalloway,Clima}$ model.

Table A.1 Hydrodynamic climatology files ($HD_{Shetland,Clima}$)

Folder	File name	File type	File size	Description
0_mesh	Shetland_regional_HD_MSL_EPSG32630_rev05_interptiff_sitebathy_smoothed.mesh	Mesh file (.mesh)	3.51 MB	Numerical model mesh for the Shetland Regional model
1_MetForcing	Climatology_swona_metforcing_TAU_M21_v2.dfsu	MIKE Zero Data Manager (.dfsu)	1.56 GB	SSM climatologically averaged meterological forcing (6-hourly resolution) • U_{10} (wind u-velocity [m/s]) • V_{10} (wind v-velocity [m/s]) • Air pressure [hPa] • Air temperature [°C] • Evaporation [m/s] • Downwards longwave radiation [W/m^2] • Precipitation [m/s] • Relative humidity [%] • Downwards shortwave radiation [W/m^2]

Table A.1 Hydrodynamic climatology files ($HD_{Shetland,Clima}$)

Folder	File name	File type	File size	Description
2_BCs	BC2_concat_clima_wl_01-01to12-31.dfs1	MIKE Zero Profile Series (.dfs1)	762 KB	Open boundary conditions for water level (extracted from Scottish Shelf Model)
	BC3_concat_clima_wl_01-01to12-31.dfs1		762 KB	
	BC4_concat_clima_wl_01-01to12-31.dfs1		762 KB	
	BC5_concat_clima_wl_01-01to12-31.dfs1		762 KB	
	BC6_concat_clima_wl_01-01to12-31.dfs1		762 KB	
	BC2_concat_climatology_0001to0366.dfs2	MIKE Zero Data Manager (.dfs2)	134 MB	2D boundary conditions from Scottish Shelf model: • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • water temperature [°C] • salinity [PSU]
	BC3_concat_climatology_0001to0366.dfs2		268 MB	
	BC4_concat_climatology_0001to0366.dfs2		134 MB	
	BC5_concat_climatology_0001to0366.dfs2		268 MB	
	BC6_concat_climatology_0001to0366.dfs2		134 MB	
	Climatology_swona_3D_IC.dfsu	MIKE Zero Data Manager (.dfsu)	360 MB	3D initial conditions from the Scottish Shelf Model • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • water temperature [°C] • salinity [PSU]
	SSM_2D_uv_surface_-3.500-0.000_59.250-61.200N_01-01_IC.dfsu	MIKE Zero Data Manager (.dfsu)	6.78 MB	2D initial conditions from the Scottish Shelf Model • Surface elevation [mMSL] • u-velocity at surface [m/s] – not used • V-velocity at surface [m/s] – not used
3_setup	HD_Shetland_regional_SSMclimatology_rev04_prod_period_run02f_meteo_DA_TSnudging_p01.m3fm	MIKE Zero Flow Model FM (.m3fm)	153 kB	MIKE3 setup file

Table A.1 Hydrodynamic climatology files ($HD_{Shetland,Clima}$)

Folder	File name	File type	File size	Description
4_Results	HD_Shetland_Clima_2D.dfsu	MIKE Zero Data Manager (.dfsu)	13.6 GB	2-Dimensional model outputs from 1-year model run (1-hour temporal resolution) • Surface elevation [mMSL] • Total water depth [m] • Depth-averaged u-velocity [m/s] • Depth-averaged v-velocity [m/s] • P (power) flux [$m^3s^{-1}m^{-1}$] • Q (volume) flux [$m^3s^{-1}m^{-1}$] • Convective heat flux [Wm^{-2}] • Latent heat flux [Wm^{-2}] • Solar radiation net heat flux [Wm^{-2}] • Long wave radiation heat flux [Wm^{-2}] • Total heat flux [Wm^{-2}]
	HD_Shetland_Clima_3D.dfsu	MIKE Zero Data Manager (.dfsu)	82.6 GB	3-Dimensional model outputs from 1-year model run (1-hour temporal resolution, 10 layers) • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • Density [kgm^{-3}] • Water temperature [°C] • Salinity [PSU]

Table A.2 Hydrodynamic climatology files ($HD_{Scalloway,Clima}$)

Folder	File name	File type	File size	Description
0_mesh	Scalloway_local_HD_MSL_EPSG32630_rev04_mres_interptiff_final_smoothed.mesh	Mesh file (.mesh)	1.87 MB	Numerical model mesh for the Shetland Regional model
1_MetForcing	Climatology_swona_metforcing_TAU_M21_v2.dfsu	MIKE Zero Data Manager (.dfsu)	1.56 GB	SSM climatologically averaged meterological forcing (6-hourly resolution) • U_{10} (wind u-velocity [m/s]) • V_{10} (wind v-velocity [m/s]) • Air pressure [hPa] • Air temperature [°C] • Evaporation [m/s] • Downwards longwave radiation [W/m^2] • Precipitation [m/s] • Relative humidity [%] • Downwards shortwave radiation [W/m^2]

Table A.2 Hydrodynamic climatology files ($HD_{Scalloway,Clima}$)

Folder	File name	File type	File size	Description
2_BCs	BC11_concat_SSM_Scalloway_wl_01-01to12-31.dfs1	MIKE Zero Profile Series (.dfs1)	2.16 MB	Open boundary conditions for water level (extracted from Scottish Shelf Model)
	BC22_concat_SSM_Scalloway_wl_01-01to12-31.dfs1		2.16 MB	
	BC11_concat_SSM_Scalloway_0001to0366.dfs2	MIKE Zero Data Manager (.dfs2)	134 MB	2D boundary conditions from Scottish Shelf model: • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • water temperature [°C] • salinity [PSU]
	BC22_concat_SSM_Scalloway_0001to0366.dfs2		268 MB	
	Scalloway_3D_regional_production_01011993_IC.dfsu	MIKE Zero Data Manager (.dfsu)	360 MB	3D initial conditions from the Scottish Shelf Model • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • water temperature [°C] • salinity [PSU]
	Scalloway_2D_uv_surface_regional_production_01011993_IC.dfsu	MIKE Zero Data Manager (.dfsu)	6.78 MB	2D initial conditions from the Scottish Shelf Model (used for water levels only) • Surface elevation [mMSL] • u-velocity at surface [m/s] – not used • V-velocity at surface [m/s] – not used
3_setup	HD_Shetland_Scalloway_SSMclimatology_rev04_prod_period_DA_TSnudging.m3fm	MIKE Zero Flow Model FM (.m3fm)	116 KB	MIKE3 setup file

Table A.2 Hydrodynamic climatology files ($HD_{Scalloway,Clima}$)

Folder	File name	File type	File size	Description
4_Results	HD_Scalloway_Clima_2D.dfsu	MIKE Zero Data Manager (.dfsu)	11.6 GB	2-Dimensional model outputs from 1-year model run (1-hour temporal resolution) • Surface elevation [mMSL] • Total water depth [m] • Depth-averaged u-velocity [m/s] • Depth-averaged v-velocity [m/s] • P (power) flux [$m^3s^{-1}m^{-1}$] • Q (volume) flux [$m^3s^{-1}m^{-1}$] • Convective heat flux [Wm^{-2}] • Latent heat flux [Wm^{-2}] • Solar radiation net heat flux [Wm^{-2}] • Long wave radiation heat flux [Wm^{-2}] • Total heat flux [Wm^{-2}]
	HD_Scalloway_Clima_3D.dfsu	MIKE Zero Data Manager (.dfsu)	83.9 GB	3-Dimensional model outputs from 1-year model run (1-hour temporal resolution, 10 vertical layers) • u-velocity [m/s] • v-velocity [m/s] • w-velocity [m/s] • Density [kgm^{-3}] • Water temperature [°C] • Salinity [PSU]

APPENDIX B

Definition of model quality indices

B Definition of model quality indices

To obtain an objective and quantitative measure of how well the model data compared to the observed data, a number of statistical parameters so-called quality indices (QI's) are calculated.

Prior to the comparisons, the model data are synchronised to the time stamps of the observations so that both time series had equal length and overlapping time stamps. For each valid observation, measured at time t, the corresponding model value is found using linear interpolation between the model time steps before and after t. Only observed values that had model values within ± the representative sampling or averaging period of the observations are included (e.g. for 10-min observed wind speeds measured every 10 min compared to modelled values every hour, only the observed value every hour is included in the comparison).

The comparisons of the synchronised observed and modelled data are illustrated in (some of) the following figures:

- Time series plot including general statistics
- Scatter plot including quantiles, QQ-fit and QI's (dots coloured according to the density)
- Histogram of occurrence vs. magnitude or direction
- Histogram of bias vs. magnitude
- Histogram of bias vs. direction
- Dual rose plot (overlapping roses)
- Peak event plot including joint (coinciding) individual peaks

The quality indices are described below, and their definitions are listed in Table B.1. Most of the quality indices are based on the entire dataset, and hence the quality indices should be considered averaged measures and may not be representative of the accuracy during rare conditions.

The MEAN represents the mean of modelled data, while the BIAS is the mean difference between the modelled and observed data. AME is the mean of the absolute difference, and RMSE is the root mean square of the difference. The MEAN, BIAS, AME and RMSE are given as absolute values and relative to the average of the observed data in percent in the scatter plot.

The scatter index (SI) is a non-dimensional measure of the difference calculated as the unbiased root-mean-square difference relative to the mean absolute value of the observations. In open water, an SI below 0.2 is usually considered a small difference (excellent agreement) for significant wave heights. In confined areas or during calm conditions, where mean significant wave heights are generally lower, a slightly higher SI may be acceptable (the definition of SI implies that it is negatively biased (lower) for time series with high mean values compared to time series with lower mean values (and same scatter/spreading), although it is normalised).

EV is the explained variation and measures the proportion [0 - 1] to which the model accounts for the variation (dispersion) of the observations.

The correlation coefficient (CC) is a non-dimensional measure reflecting the degree to which the variation of the first variable is reflected linearly in the variation of the second variable. A value close to 0 indicates very limited or no (linear) correlation between the two datasets, while a value close to 1 indicates a very high or perfect correlation. Typically, a CC above 0.9 is considered a high correlation (good agreement) for wave heights. It is noted that CC is 1 (or -1) for any two fully linearly correlated variables, even if they are not 1:1. However, the slope and intercept of the linear relation may be different from 1 and 0, respectively, despite CC of 1 (or -1).

The Q-Q line slope and intercept are found from a linear fit to the data quantiles in a least-square sense. The lower and uppermost quantiles are not included on the fit. A regression line slope different from 1 may indicate a trend in the difference.

The peak ratio (PR) is the average of the N_{peak} highest model values divided by the average of the N_{peak} highest observations. The peaks are found individually for each dataset through the Peak-Over-Threshold (POT) method applying an average annual number of exceedance of 4 and an inter-event time of 36 hours. A general underestimation of the modelled peak events results in PR below 1, while an overestimation results in a PR above 1.

An example of a peak plot is shown in Figure B.1. 'X' represents the observed peaks (x-axis), while 'Y' represents the modelled peaks (y-axis), based on the POT methodology, both represented by circles ('o') in the plot. The joint (coinciding) peaks, defined as any X and Y peaks within ±36 hours[5] of each other (i.e. less than or equal to the number of individual peaks), are represented by crosses ('x'). Hence, the joint peaks ('x') overlap with the individual peaks ('o') only if they occur at the same time exactly. Otherwise, the joint peaks ('x') represent an additional point in the plot, which may be associated with the observed and modelled individual peaks ('o') by searching in the respective X and Y-axis directions, see example with red lines in Figure B.1. It is seen that the 'X' peaks are often underneath the 1:1 line, while the 'Y' peaks are often above the 1:1 line.

[5] 36 hours is chosen arbitrarily as representative of an average storm duration. Often the observed and modelled storm peaks are within 1-2 hours of each other.

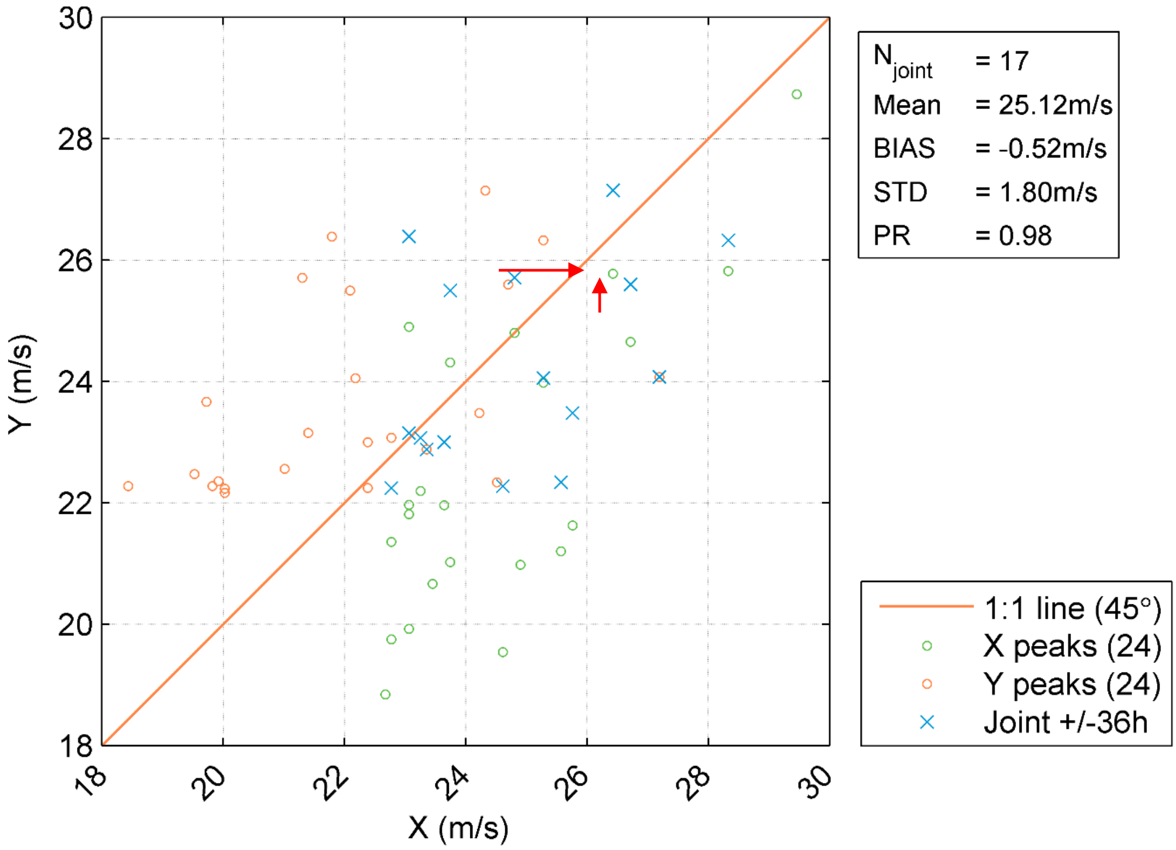


Figure B.1 Example of peak event plot (wind speed).

Table B.1 Definition of model quality indices (X = Observation, Y = Model).

Abbreviation	**Description**	**Definition**
N	Number of data (synchronised)	–
MEAN	Mean of Y data, Mean of X data	$\frac{1}{N}\sum_{i=1}^{N} Y_i \equiv \overline{Y}\ , \frac{1}{N}\sum_{i=1}^{N} X_i \equiv \overline{X}$
STD	Standard deviation of Y data Standard deviation of X data	$\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Y-\overline{Y})^2}\ , \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X-\overline{X})^2}$
BIAS	Mean difference	$\frac{1}{N}\sum_{i=1}^{N}(Y-X)_i = \overline{Y}-\overline{X}$
AME	Absolute mean error	$\frac{1}{N}\sum_{i=1}^{N}(\lvert Y-X\rvert)_i$
RMSE	Root mean square error	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X)_i^{\,2}}$
SI	Scatter index (unbiased)	$\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X-BIAS)_i^{\,2}}}{\frac{1}{N}\sum_{i=1}^{N}\lvert X_i\rvert}$
EV	Explained variance	$\frac{\sum_{i=1}^{N}(X_i-\overline{X})^2-\sum_{i=1}^{N}[(X_i-\overline{X})-(Y_i-\overline{Y})]^2}{\sum_{i=1}^{N}(X_i-\overline{X})^2}$
CC	Correlation coefficient	$\frac{\sum_{i=1}^{N}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{N}(X_i-\overline{X})^2\sum_{i=1}^{N}(Y_i-\overline{Y})^2}}$
QQ	Quantile-Quantile (line slope and intercept)	Linear least square fit to quantiles
PR	Peak ratio (of N_{peak} highest events)	$PR = i = 1NpeakY_i \sum_{i=1}^{N_{peak}} X_i$

APPENDIX C

Regional hydrodynamic climatology verification plots

C Regional hydrodynamic climatology verification plots

The verification plots of the regional hydrodynamic climatology model against the SSM wider domain model are provided as digital files (.jpg) accompanying this report. The data are provided as zip file:

- *26801650_1_Shetland_Climatology_Model_Setup_Report_AppC.zip*