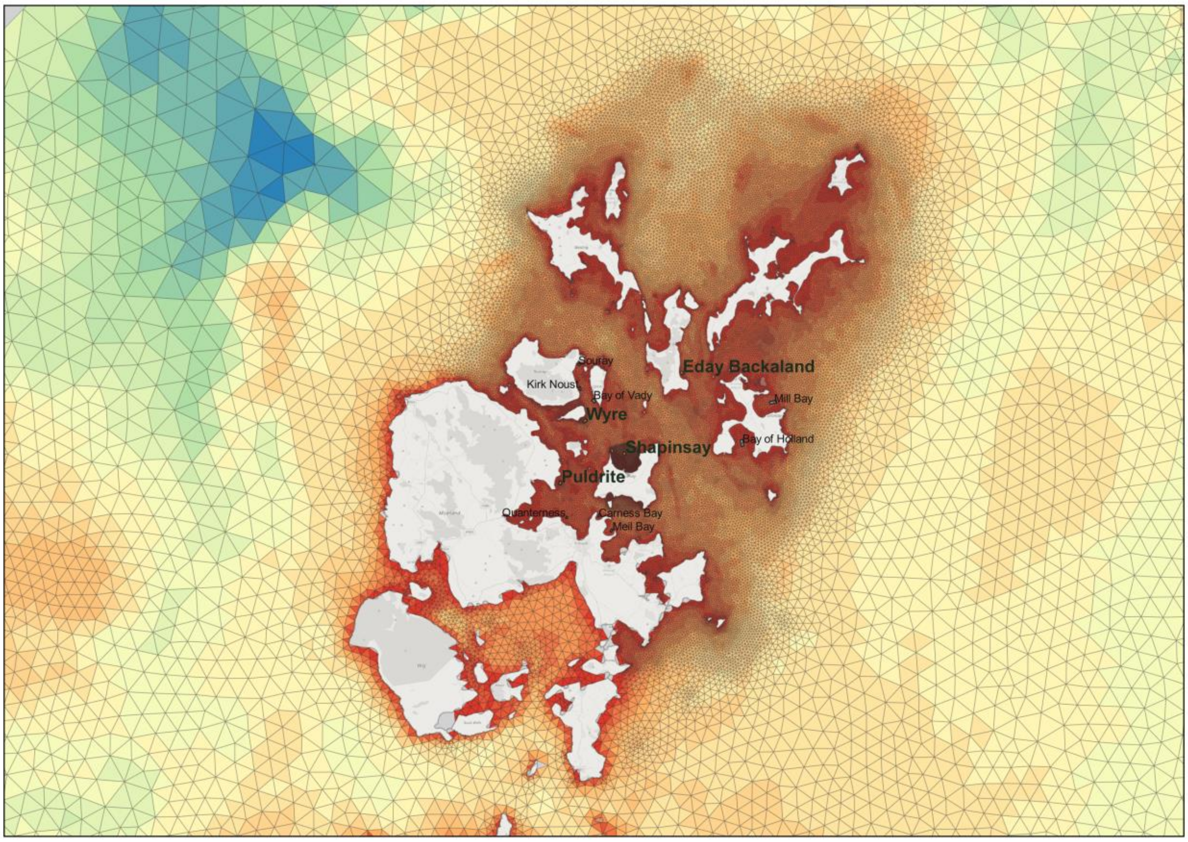
North Orkney Aquaculture Modelling

Hydrodynamic Climatology and Hindcast Models

Model Setup Report



Scottish Sea Farms

Report

Aug 2022

This report has been prepared under the DHI Business Management System certified by Bureau Veritas to comply with ISO 9001 (Quality Management)

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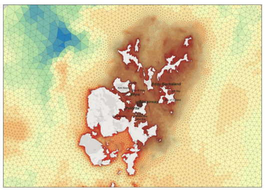

Area of interest and computational mesh of North Orkney hydrodynamic model

Prepared for Scottish Sea Farms Ltd.
Represented by [redacted] (Scottish Sea Farms Ltd.)

[redacted]

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CONTENTS

FIGURES

TABLES

APPENDICES

NOMENCLATURE

Abbreviations	
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
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

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 (EPSG code: 32630)
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 Climatology Model and respective meteorological forcing.

Executive Summary

Scottish Sea Farms (SSF) is a leading producer of farmed Atlantic salmon throughout the Scottish Mainland, Orkney and Shetland. To support ongoing operations, site developments, and regulatory applications, SSF requires a detailed numerical hydrodynamic database covering the North Orkney islands complex. A particular focus is on the area around Shapinsay (North Orkney) which contains an aquaculture site of immediate interest.

This report describes the development of a 2-dimensional (2D) hydrodynamic climatology model database for the North Orkney. Climatology models offer a simple technique for predicting the mean status of the atmospheric and oceanographic conditions over an annual period. The North Orkney model aims to effectively downscale the climatology Scottish Shelf Model (SSM) (developed for and maintained by Marine Scotland Science). The SSM provides a climatological perspective of the circulation of the Scottish continental shelf waters in terms of 'average' conditions.

The hydrodynamic model has been established using the MIKE 21 FM modelling suite (ver.2021) developed by DHI. This numerical engine simulates the water level variations and flows in response to a variety of forcing conditions. The regional model of North Orkney and Shetland is based on a variable resolution unstructured horizontal mesh with a resolution of <200m along the coastline of North Orkney islands complex and identified areas of interest. The model is forced by offshore boundaries and climatologically averaged meteorological conditions from the SSM hydrodynamic database and is verified against the SSM at offshore locations. There is significant refinement of mesh discretisation as we proceed inshore to North Orkney islands complex with spatial resolution of around 40m in the area around existing marine pen fish farms.

A climatology is constructed as a representation of the 'mean' status of hydrodynamics over a period of years. Therefore, it is by definition hard to justify the validation of a climatology forced model against an observational measurement campaign to determine model skill based on commonly used metrics. A hindcast version $HD_{NO\_hindcast}$ was thus constructed to inform on parameterisation of model settings and verification of model solution against the available observational record.

The hydrodynamic climatology model database and also the hindcast version are provided alongside this report.

1 Introduction

This report has been prepared for **Scottish Sea Farms Ltd.** (SSF) by DHI in relation to hydrodynamic modelling services for aquaculture sites in the North Orkney islands complex. The project will establish a dedicated two-dimensional hydrodynamic numerical model inclusive of the waters around North Orkney:

- A one-year hydrodynamic climatology model
- A one-year hydrodynamic hindcast model (summer-to-summer)

This document and its accompanying appendices constitute the **hydrodynamic database (climatology/hindcast) model** report.

1.1 Background to the study

The Orkney Islands are an archipelago of around 70 islands located approximately 10km 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 coastline is characterised by numerous inlets and bays.

Aquaculture produces Scotland's most valuable food export, and the Northern Isles are 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 is one of the main producers of farmed salmon in the North Orkney. The company currently operates 4 active fish farms sites, situated throughout the islands. SSF are seeking to understand the risk associated with existing and prospect operations related to aquaculture fish farming, with a focus on assessing prospects for development of a new site and its interaction with existing operational sites. The area around Shapinsay island located in Veantrow Bay at the north (primarily) is of immediate interest for SSF.

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 in 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 2-dimensional hydrodynamic database to inform a risk-based approach to management and development of aquaculture sites in the waters within the North Orkney archipelago.

To achieve this aim, the objectives of this hydrodynamic modelling report are to develop a 2-dimensional hydrodynamic climatology model database that sufficiently represents the hydrodynamics as expressed by marine currents and water exchange around the Northern Isles with a specific focus on the North Orkney archipelago.

The model will provide a database for future modelling to support regulatory applications such as: assessing connectivity between fish farms sites around North Orkney islands; site selection and site screening; dispersion modelling of waste solids and bath treatment medicines.

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 episodic weather events as for example winter storms which occur at relatively high frequency at these latitudes.

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 the North Orkney islands.
- 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 2D hydrodynamic model of North Orkney. 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 validation of the hindcast version and verification of the hydrodynamic climatology.
- Section 6 provides a summary of the hydrodynamic model climatology.

2 Geographic and environmental setting

2.1 Geographic setting

Orkney is an archipelago in the North Sea consisting of approximately 70 islands, of which approximately 20 are inhabited. The islands are located approximately 10km from north coast of mainland Scotland (Figure 2.1) covering an area of approximately 974 km^2.

The coastline of North Orkney archipelago (~1,246 km) is characterised by a rugged outer rocky shore. The inner part of the coastline comprised of many long open sea lochs, former river and glacial valleys that are now flooded by the sea.

Orkney is separated from the mainland of Scotland by the Pentland Firth, a ten-kilometre-wide seaway between the island of South Ronaldsay and mainland of Scotland. It is separated from the Shetland Islands by the Fair Isle Channel body of water. The archipelago measures 85 kilometres from northeast to southwest and 37 kilometres from east to west.

The islands are mainly low-lying except for some sharply rising sandstone hills on Mainland, Rousay and Hoy and rugged cliffs on some western coasts. Nearly all of the islands have lochs, but the watercourses are merely streams draining the high land.

The tidal currents off many of the isles are swift, with frequent whirlpools. The islands are notable for the absence of trees, which is partly accounted for by the strong winds.

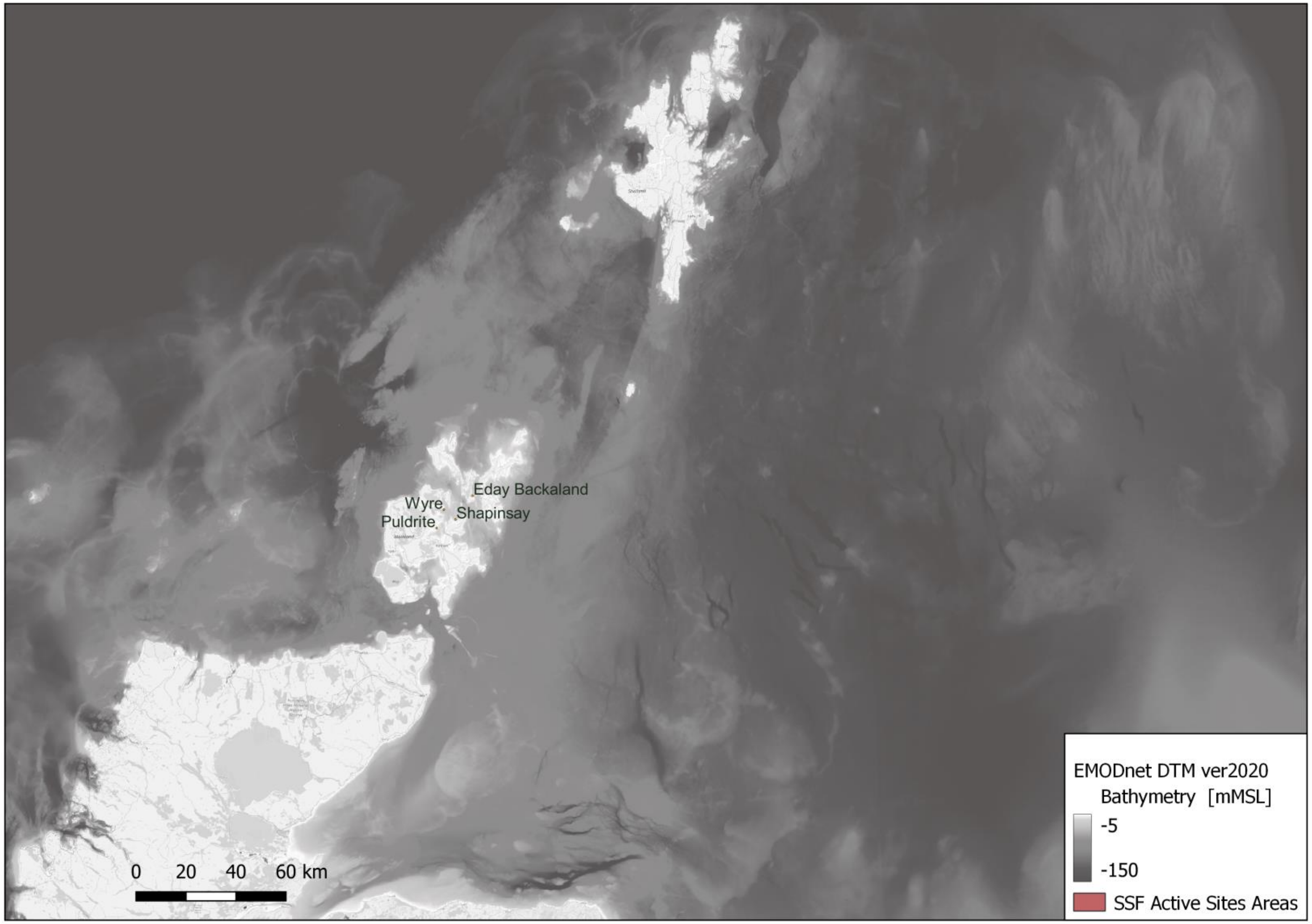

Figure 2.1 Map showing the geographic position of Northern Isles in relation to the UK mainland (left bottom corner) and North Orkney area of interest with chosen aquaculture farms site names displayed.

2.2 Climatic and oceanographic conditions

Currents

Considering its position at around 59°N of the equator, the climate of the Northern Isles 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) [1]. 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 relatively stable sea temperatures typically ranging from approximately 8°C in March to a peak of 13°C in August [2]. 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 [1].

Winds

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 the Orkneys 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.

Tides

The Orkney islands lie near the boundary between the North Atlantic and North Sea tidal systems creating a natural blockage and thus asynchrony in timing of high and low-water between the incoming North Atlantic tide [4], advancing by several hours the North Sea tide. The resulting net flow of water from west to east during flood tide creates energetic and strong tidal streams characterising the archipelago as a high-capacity marine renewable energy production area. The presence of the islands themselves, reefs and local bathymetric features further modulate tidal flow in complex and highly variable local expressions. The tides all around Scotland are semi-diurnal and characterised by a high and low water every ~12.5 hours. However, in the enclosed and deep water inlets, tidal currents are generally weak and the circulation is strongly influenced by wind and to some extent density-driven current conditions.

Strong tidal streams occur where water is forced through constrained channels and around headlands, as between Pentland Firth and some of the channels between the Orkney Islands, the north of Papa Westray and North Ronaldsay. The strongest flows in the Orkney island complex have been identified in the following areas [5]:

-North of Papa Westray
-North and northeast of North Ronaldsay
-North Ronaldsay Firth between North Ronaldsay and Sanday
-Lashy Sound (northern part of Eday Sound between Eday and Sanday)
-Calf Sound between Eday and Calf of Eday
-Westray Firth between Westray and Rousay
-Stronsay Firth between Shapinsay and Stronsay
-Eynhallow Sound between Mainland and Rousay
-The String and Shapinsay Sound between Mainland and Shapinsay
-Channels leading to Scapa Flow (Hoy Sound, Burra Sound and Sound of Hoxa)

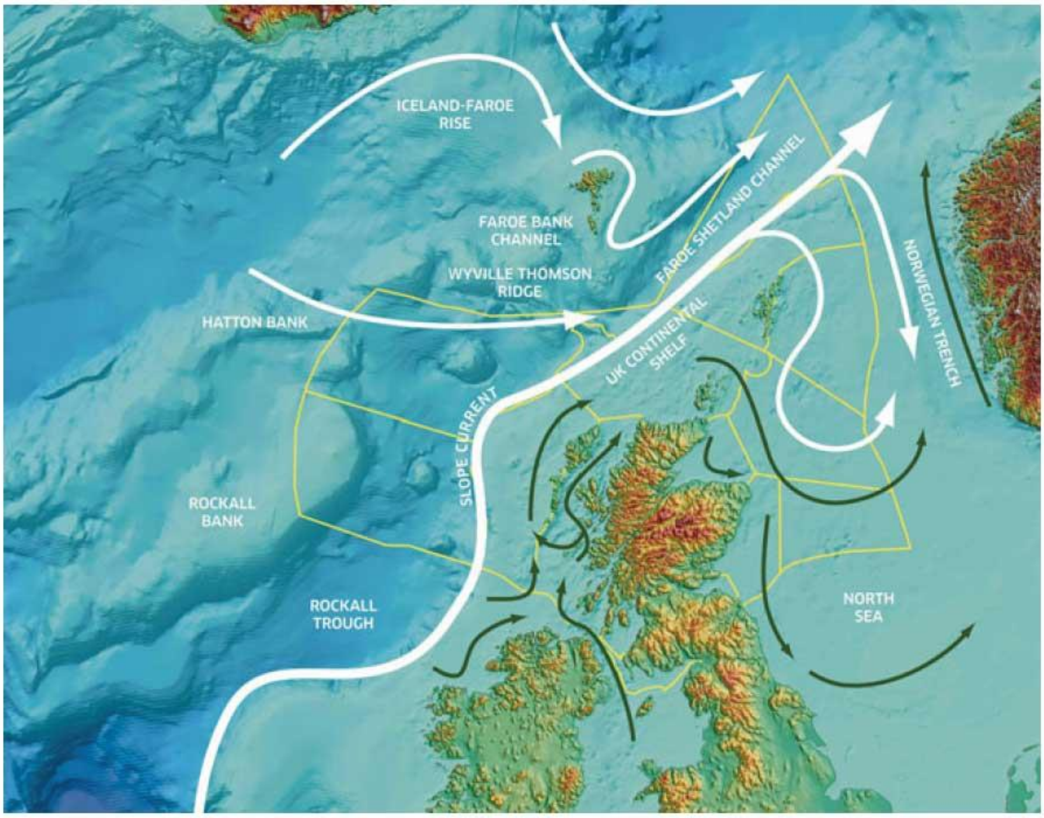

Figure 2.2 Map of the general circulation pattern within the North Atlantic and North Sea around Scotland (reproduced from [1]). The white arrows show the circulation of Atlantic water, while green arrows represent costal circulation.

2.3 Aquaculture in North Orkney

Around 21,000 tonnes of farmed salmon were produced in the Orkneys in 2020 with a gradual increase on an annual basis since 2011 [6]. With a total number of fin fish farms at 21, Orkney's economy has a measurable dependence on the aquaculture industry [2]. Production takes place within the inlets and sounds around the coastline, with the highest concentration of sites within the archipelago (Figure 2.3).

Fin fish production is dominated by Atlantic salmon (*Salmo salar*). In the decade 2011-2020, the annual Salmon production in the waters around Orkney averaged around 15,000 Tonnes, representing a value of over £30 million. The sector directly employs over 120 full time staff [7], plus supports the wider economy of the islands via fish processing, marine engineering, and transportation [2].

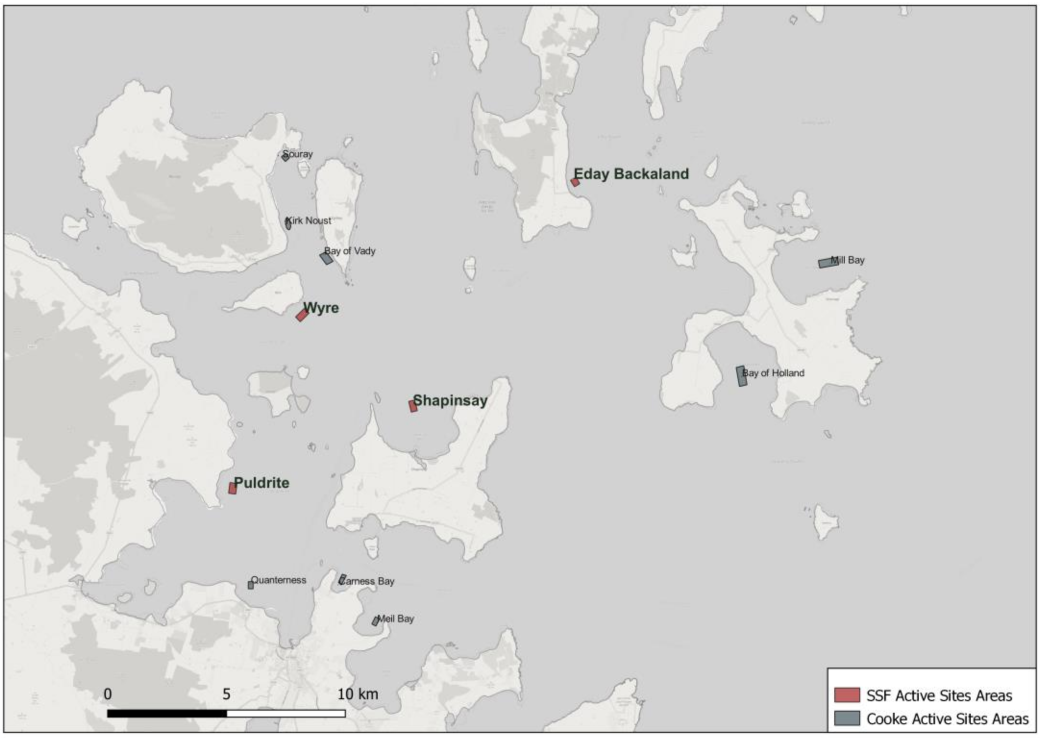

Figure 2.3 Map of showing the locations of SSF's active sites within the North Orkney archipelago (also shown are Cooke Aquaculture active sites within the same area).

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 for the hindcast and climatology versions (Section 4.3.4), and the meteorological forcing (Section 4.3.5).

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

The 2D North Orkney hydrodynamic model bathymetry was informed by a composite bathymetric database from open-source datasets[3] and proprietary surveys provided by SSF. These are summarised in Table 3.1 and briefly described below. The vertical reference datum of the baseline bathymetric dataset (EMODnet DTM) was Lowest Astronomical Tide[4] (LAT). All data were converted to a common reference vertical datum of mean-sea-level (MSL), see also section 4.2.

UKHO Admiralty Data

High-resolution bathymetry data for the waters in the North Orkney archipelago around Orkneys were obtained from the United Kingdom Hydrographic Office (UKHO) Marine Data Portal[5]. 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 3.2 shows the high-resolution datasets in and around North Orkney.

Local site bathymetry data

A multibeam survey[6] (Veantrow Bay) and bathymetry soundings in and around marine pen fish farms (MPFF's) were provided by SSF (Figure 3.1). The multibeam derived dataset was a primary source in the composite bathymetric database used to inform the model bathymetry. The soundings derived bathymetric 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

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[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] While high-resolution bathymetry comprises a high percentage coverage of the North Orkney archipelago there still exist areas, especially straights and shallows that could have a distinct impact of modelled hydrodynamics, currently informed by the GEBCO 2020 DTM. The GEBCO global model is less accurate and detailed in coastal areas and should be used with caution when alternative datasets are not available.

[4] EMODnet uses a global tide surge model (GTSM, Deltares) for LAT to MSL vertical datum references, https://portal.emodnet-bathymetry.eu/

[5] Admiralty Marine Data Solution, Marine Data Portal (UKHO) accessed Jan 2022

[6] The professional multibeam survey was commissioned from Triscrom Marine in 2018 (pers.comm. SSF).

surface and the predicted local tidal height. These spot depths were mainly used to cross-validate model bathymetry and inform of appropriateness of respective available sources.

EMODnet Digital Terrain Model (DTM)

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 EMODnet Bathymetry portal (version 2020). This portal was initiated by the European Commission as part of developing the European Marine Observation and Data Network (EMODnet). The EMODnet digital terrain model 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 57m, zonal x 115m, meridional). Vertical datum is referenced to LAT derived from the Global Tide and Surge Model (GTSM) developed by Deltares[7].

Table 3.1 Summary of bathymetric databases used to inform HD_{NO} model bathymetry in order of highest to lowest priority

Source	Resolution	Vertical Reference	Date
Triscrom Marine multibeam survey (Veantrow Bay)	10m	Chart Datum [mCD]	2018
UKHO Admiralty Data	2m to 8m	Chart Datum [mCD]	Various
EMODnet DTM	57m x 115m grid resolution	Lowest Astronomical Tide [mLAT]	2020 version
C-MAP	Isobaths/spot depths	Lowest Astronomical Tide [mLAT]	Variable
Local soundings at fish farm sites	Spot depth soundings	Chart Datum [mCD]	2000 – 2020

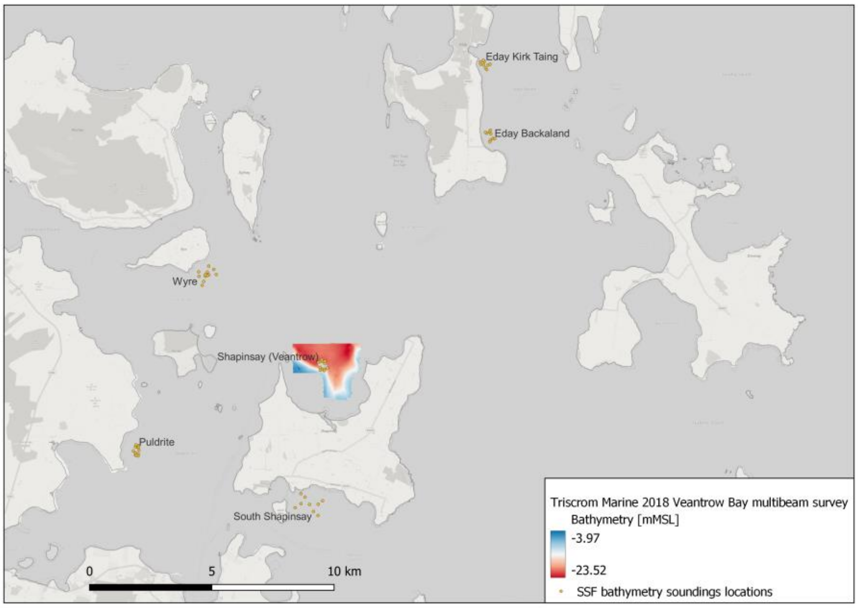

Figure 3.1 Map showing locations of bathymetry soundings (orange markers) at MPFF sites and multibeam survey at Veantrow Bay provided by SSF.

[7] Which information layers? - Data products - EMODnet Bathymetry (emodnet-bathymetry.eu)

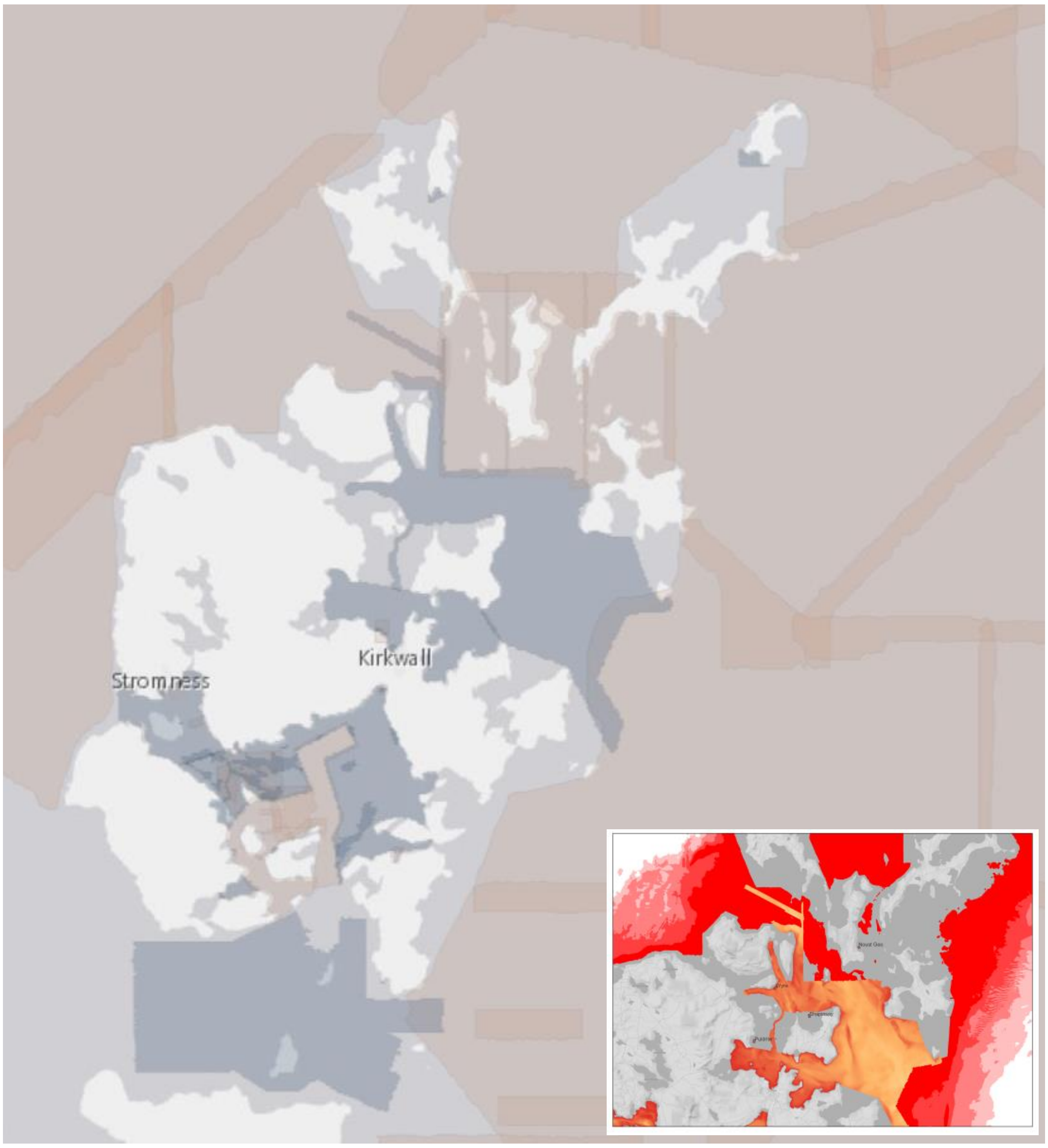

Figure 3.2 Map showing areas of high resolution multibeam gridded bathymetry (grey patched areas) and lower resolution (as xyz triplets) bathymetric datasets (orange patched areas) around North Orkney used to inform model bathymetry herein (source UKHO Marine Data Portal). Note that the baseline EMODnet 2020 bathymetric database incorporates already most of the available datasets from UKHO (even though the multibeam datasets are upscaled significantly at a final grid resolution of 60x117m^2 from 4-8m^2. Gaps (light purple areas), due to lack of available higher resolution bathymetric surveys, in the EMODnet composite product are filled in with the GEBCO 2021 global bathymetric model.

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 inlets where high-resolution bathymetric data or local soundings are not available. Due to the scarcity of available data points in the area of interest within the coastal areas of North Orkney, C-MAP data were only used to cross-validate the bathymetry at the respective point locations.

3.2 Measurements

3.2.1 ADCP campaigns

Information on current speeds/directions, water levels and sea water temperature were provided by SSF during a series of Acoustic Doppler Current Profiler (ADCP) campaigns between 2007 and 2020, see also Table 3.2. Survey periods for each observational deployment provided by SSF are shown in Figure 3.3 and their respective geographic location in Figure 3.4.

The ADCP instruments were frame mounted on the seabed and use acoustic signals to record the current velocity vectors at various depths (bins) through the water column. The derived timeseries were examined to ensure that any anomalous or erroneous data were removed. This included data from the water surface, which are often contaminated by reflections from the surface (so-called side-lobe interference). Observed current speed and direction was depth averaged (current velocity vectors averaging) through the water column in order to be comparable to the depth averaging modelled currents.

The observational records included a total water depth record derived via a pressure sensor. Surface elevation for each site was determined by adding the frame height of the ADCP (sensor distance to seabed – included in the information shared by SSF) to the sensor depth record and then subtracting the MSL value for the ADCP deployment location from the data record.

The surface elevation and velocity vectors timeseries were further processed under the unified tidal analysis and prediction framework U-tide [8] in order to derive the tidal and residual components for records with sufficient duration (>30 days), see also Figure 3.5.

A temperature sensor affixed to the ADCP was also provided for certain deployments.

From the available datasets, two periods, Period 1 and 2, were identified for the hindcast model calibration and validation respectively, see also Figure 3.3:

- Period 1 (light green) covering all records in year 2018
- Period 2 (light blue) covering all records in year 2019

Period 1 was chosen as deployments in this era provide an overall good spatial coverage of the central model domain, see also Figure 3.4. Period 2 was chosen as deployments in this period are closely related to the ongoing and prospect aquaculture activities within the Veantrow Bay in the North Orkney archipelago.

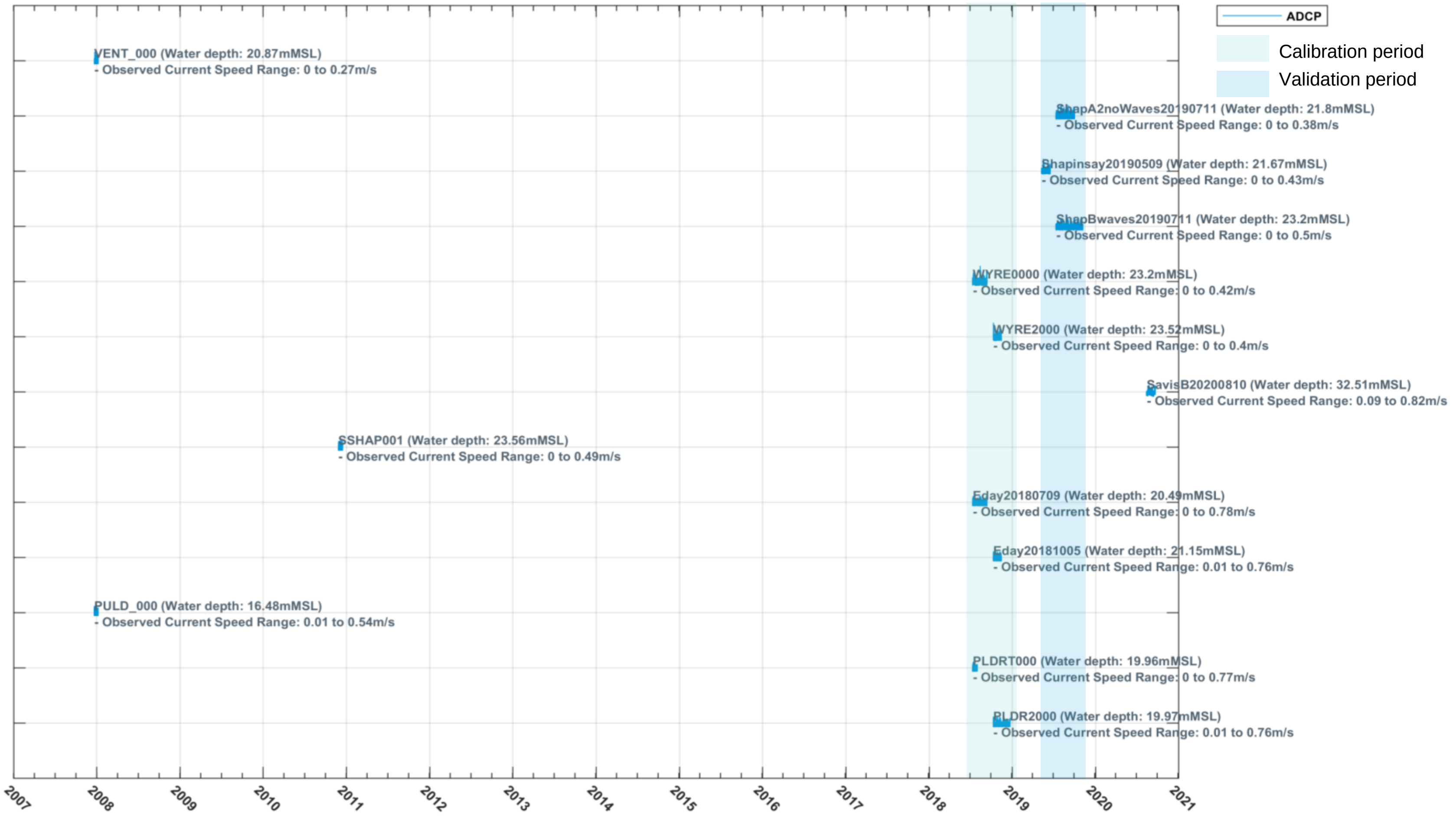

Figure 3.3 Survey periods of ADCP deployments by SSF at North Orkney sites of interest for the period 2007-2020 that were considered during the hindcast model calibration and validation development stages (current speed ranges for each respective site also documented)

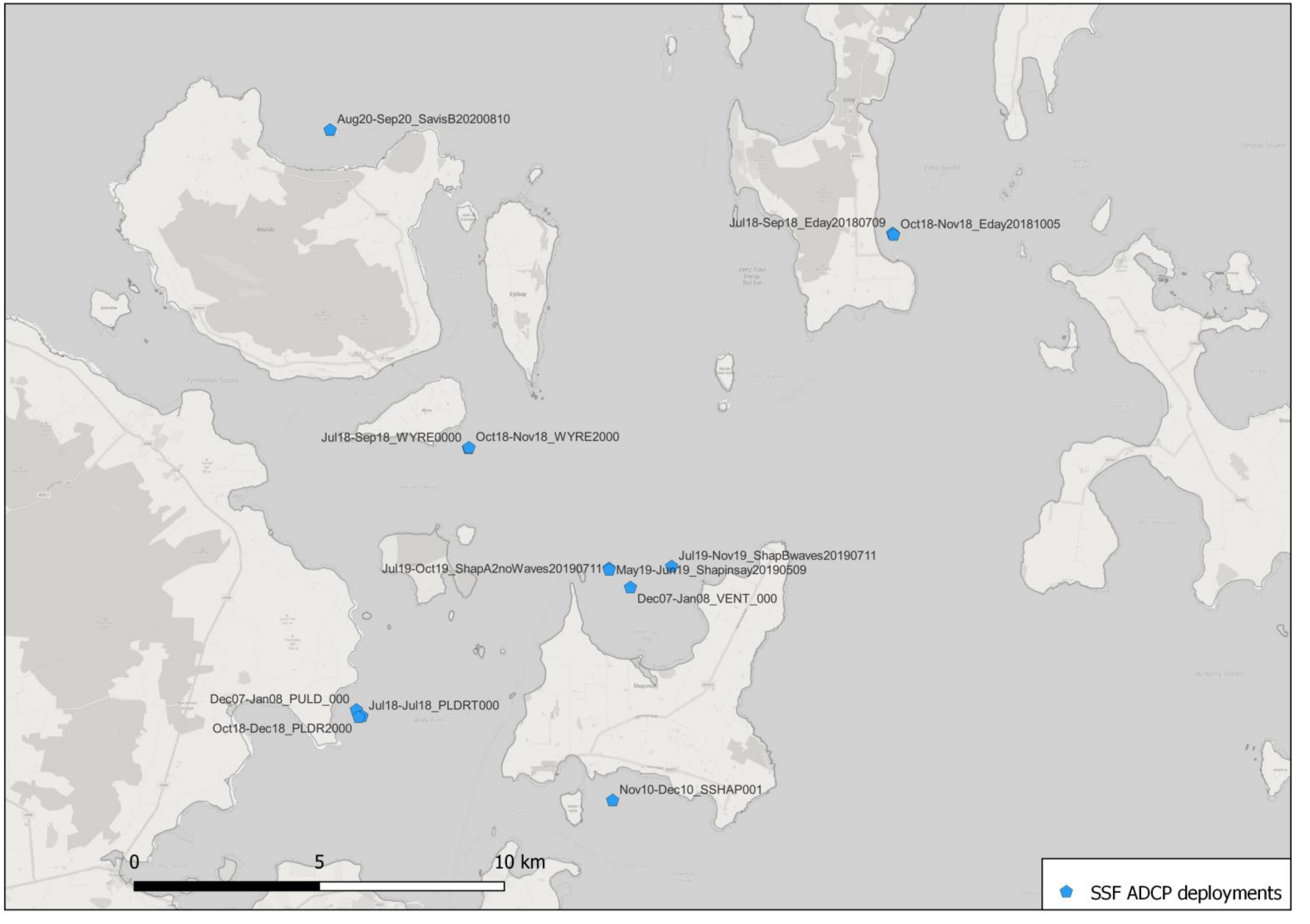

Figure 3.4 Geographic locations of ADCP deployments by SSF at North Orkney sites of interest for the period 2007-2020 that were considered during the calibration and validation stages of the hindcast model development (not some locations due to spatial overlapping are not displayed).

Table 3.2 Observational records database provided by SSF[8] in order to inform on hydrodynamic conditions in the area of interest and calibration stage of the HD model development

Site	ID	Instrument	SurveyStart GMT	SurveyEnd GMT	Duration (days)	Lat	Long	MeanRecDepth + frame	Declination (degrees)	Recording Interval [mins]	Bin size [m]
Eday Backaland	Eday20180709	Sentinel v50	10/07/2018 11:00:00	12/09/2018 10:20:00	63.97	59.161933	-2.749917	20.49	-2.346	20	1
Eday Backaland	Eday20181005	Sentinel v50	09/10/2018 10:20:00	14/11/2018 15:40:00	36.22	59.161583	-2.749400	21.15	-2.296	20	1
Puldrite	PULD_000	TRDI Workhorse	20/12/2007 15:28:21	07/01/2008 12:28:21	17.88	59.046630	-3.003264	16.48	-4.954	20	0.5
Puldrite	PLDRT000	TRDI Workhorse	10/07/2018 07:53:00	31/07/2018 22:33:00	21.61	59.045133	-3.000650	19.96	-2.453	20	1
Puldrite	PLDR2000	TRDI Workhorse	09/10/2018 12:41:54	22/12/2018 09:41:54	73.88	59.044900	-3.002133	19.97	-2.378	20	1
Shapinsay (Veantrow)	VENT_000	TRDI Workhorse	21/12/2007 10:58:00	07/01/2008 13:18:46	17.10	59.076267	-2.874083	20.87	-4.900	20	0.5
Shapinsay A	ShapA2noWaves 20190711	Sentinel v50	11/07/2019 14:30:00	01/10/2019 12:10:00	81.90	59.080883	-2.884183	21.8	-2.150	20	1
Shapinsay A	Shapinsay20190509	Sentinel v50	09/05/2019 10:26:12	16/06/2019 22:26:12	38.50	59.080567	-2.884100	21.67	-2.205	20	1.2
Shapinsay B	ShapBwaves20190711	Sentinel v50	11/07/2019 10:10:00	06/11/2019 17:30:00	118.31	59.081333	-2.854667	23.2	-2.125	20	1.2
Wyre	WYRE0000	TRDI Workhorse	10/07/2018 08:23:02	12/09/2018 14:03:02	64.24	59.110100	-2.950383	23.2	-2.427	20	1
Wyre	WYRE2000	TRDI Workhorse	09/10/2018 11:58:38	14/11/2018 13:38:38	36.07	59.110200	-2.950167	23.52	-2.377	20	1
Saviskaill Bay	SavisB20200810	Sentinel v50	11/08/2020 13:40:00	19/09/2020 15:00:00	39.06	59.187250	-3.015683	32.51	-1.982	20	1.2
South Shapinsay	SSHAP001	NDP[9]	26/11/2010 10:45:00	15/12/2010 11:45:00	19.04	59.024648	-2.88265	23.56	-4.201	20	1

[8] Following DHI's quality assessment and SSF's commentary on sensor errors and/or instrument drift during survey campaigns

[9] Nortek Doppler Profiler 500 kHz

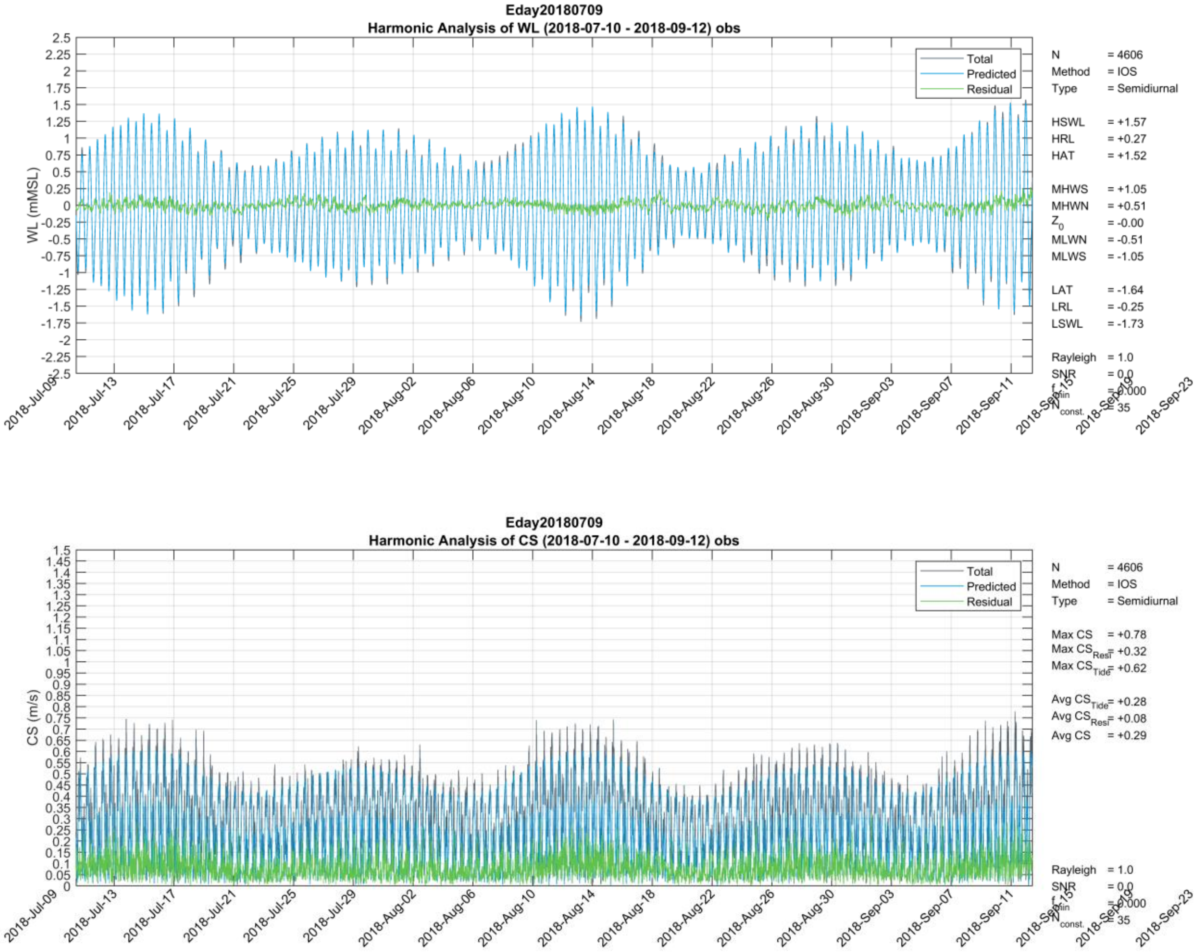

Figure 3.5 Harmonic analysis for surface elevation (top panel) and current speeds (bottom panel) for observational station Eday Backaland during deployment 10.07.2018-12.09.2018

4 Model Development

This section describes the development of the 2-dimensional North Orkney hydrodynamic models (hindcast and climatology) within the scope of the project.

4.1 Model selection

4.1.1 Two-dimensional model

A two-dimensional (2D) solution was chosen as a valid approach to simulate the hydrodynamics in the North Orkney archipelago, with due consideration of the scope of this project being to inform dispersion-based risk-assessment studies. On the basis of a tidally dominated environment, as shown from the observational records (see for example Figure 3.5), with a well-mixed water column and due to a relatively shallow basin, a 2D solution was considered most suitable. This was to balance the most computationally logistical option considering the spatial resolution requirements and a suitably accurate representation of the depth averaged hydrodynamics.

4.1.2 MIKE 21 FM hydrodynamic model

The North Orkney hydrodynamic modelling has been performed using the MIKE 21 FM modelling package developed by DHI (version 2022) [9]. MIKE 21 FM includes the simulation tools to model 2D free surface flows and associated sediment or water quality processes.

The Hydrodynamic Module is the basic computational component of the entire MIKE 21 FM, and has been developed for applications within oceanographic, coastal, and estuarine environments [10]. The hydrodynamic module provides the basis for the other modules such as sand transport, mud transport, particle tracking, and ECO Lab. 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 2D 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 modelling system is based on the numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds averaged Navier-Stokes equations. Thus, the model consists of continuity, momentum, (temperature, salinity and density equations – for baroclinic flows). In the horizontal domain both Cartesian and spherical coordinates can be used.

The spatial discretization of the primitive equations is performed using a cell-centred finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping element/cells. In the horizontal plane an unstructured grid is used comprising of triangles or quadrilateral element. An approximate Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions. The unstructured grid gives maximum degree of flexibility when handling problems in complex domains (such as in the inlets and narrow straits at North Orkney). For the time integration an explicit scheme is used.

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). Conversion from LAT to MSL is performed using EMODnet LAT to MSL gridded product[10].

4.3 North Orkney hydrodynamic hindcast and climatology models

The regional 2D hydrodynamic model of North Orkney was established both as a hindcast and climatology version. The HD_{NO_clima} model is a dynamically downscaled version of the SSM (see Section 4.3.1). Thus, HD_{NO_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 the North Orkney archipelago.

A climatology is constructed as a representation of the ‘mean’ status of hydrodynamics over a period of years. On that basis, it is by definition difficult to justify a calibration/validation of a climatology forced model with an observational record as a measure of model skill. Therefore, a hindcast version $HD_{NO\_hindcast}$ was constructed which was calibrated and then validated against the available observational records through the measurement campaigns provided by SSF, see also section 3.2, to justify parameterisations and calibration settings considered applicable then for the climatology version of the model.

The following sections describe the establishment of the $HD_{NO\_hindcast}$ and subsequently HD_{NO_clima} model, including the model mesh and bathymetry, the specification, and model outputs.

4.3.1 The Scottish Shelf Climatology 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 [11]. 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 4.1). The horizontal resolution varies from approximately 10km in the outer domain to around 1km around the Scottish Coast (Figure 4.2). 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, St Magnus Bay and the east Coast of Lewis and Harris (see [11]). In this report we shall only be using the wider domain Scottish Shelf Model (version 2.01) as this provides the most suitable climatology based boundary forcing for the North Orkney and shall henceforth use the abbreviation SSM when referring to this model.

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[10] EMODnet uses a global tide surge model (GTSM, Deltares) for LAT to MSL vertical datum references, https://portal.emodnet-bathymetry.eu/

Full details of the SSM climatology are provided in [12, 13], 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) [14]. 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) [15, 16]
- Climatology atmospheric forcing is also included based on monthly 1990–2014 data set derived from ERA-Interim data [17] (further discussed in Section 4.3.1.1)
- Freshwater inputs from river runoff volume flux climatology were obtained from the Centre for Ecology and Hydrology (CEH) Grid-to-Grid (G2G) model [18, 19], 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.

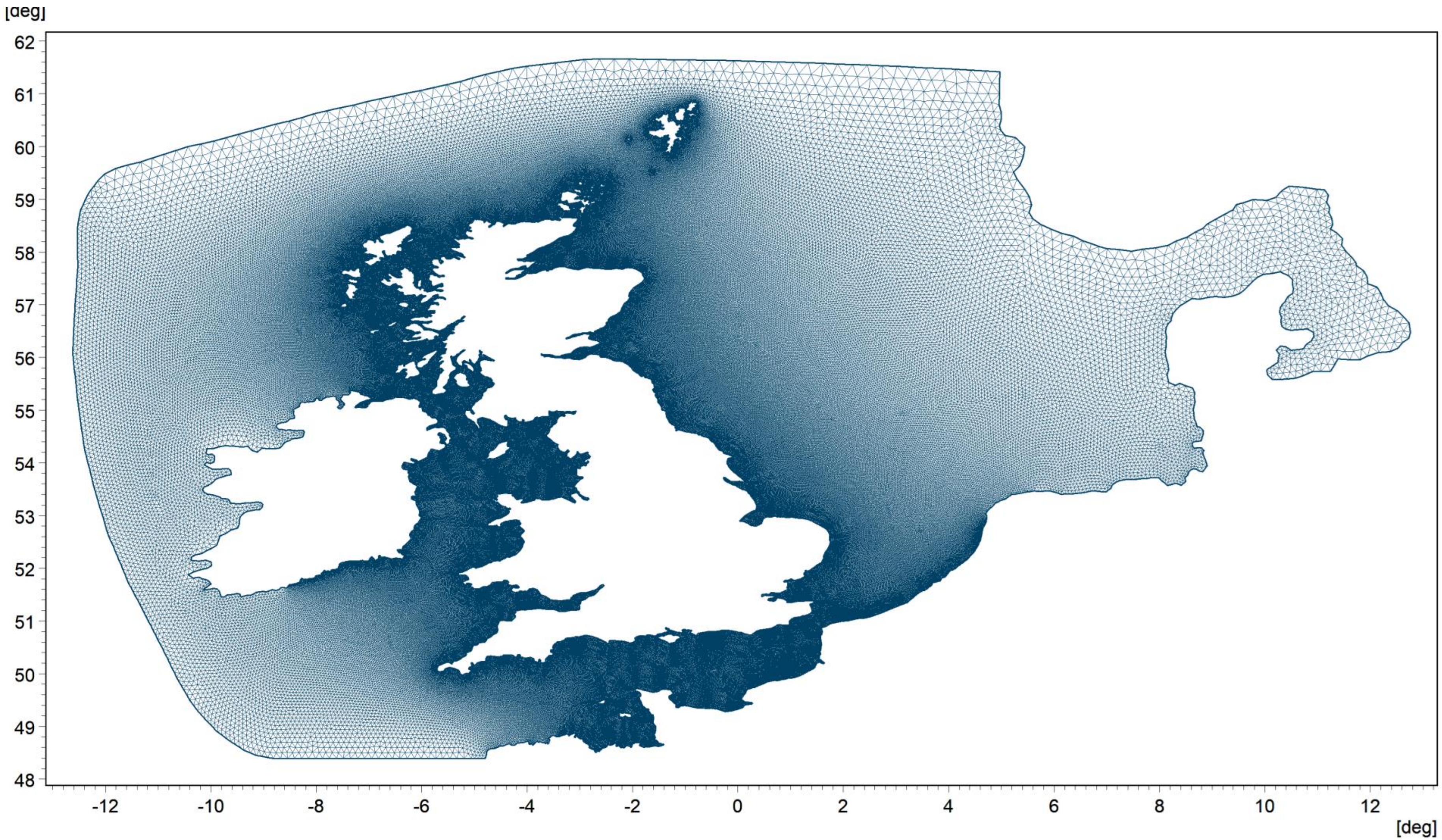


Figure 4.1 Scottish Shelf Model (SSM) numerical mesh showing the entire model domain

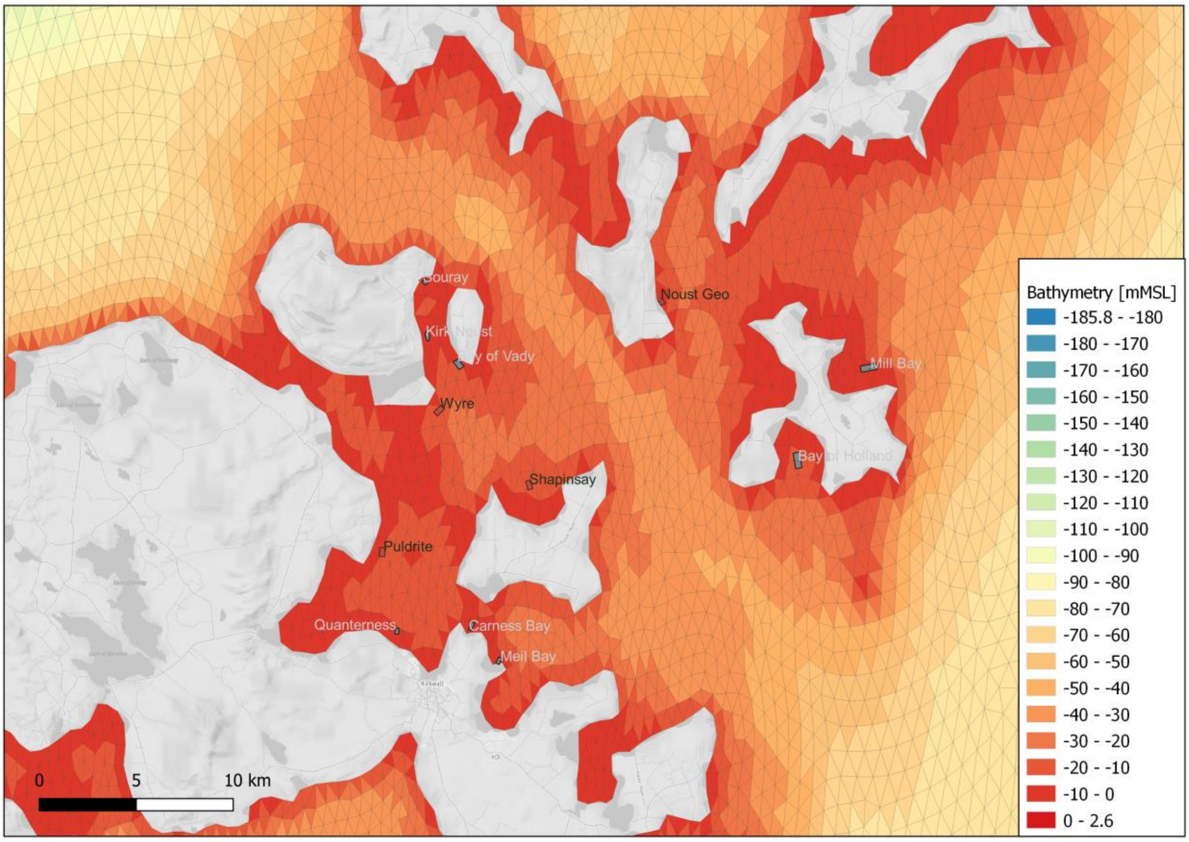


Figure 4.2 Scottish Shelf Model (SSM) computational mesh showing the area within the North Orkney archipelago. See also Figure 4.5 (right panel) for a comparison in spatial discretisation improvement for the area of interest.

4.3.1.1 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) [17]. A monthly mean wind climatology was derived from these data. 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 [12]).

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 [13]. 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 4.3 shows a time-series plot of the climatologically averaged meteorology for selected parameters for a location at the centre of the $HD_{NO\_hindcast/clima}$ computation domain (offshore of north-east North Orkney). 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 wind 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 4.3) shows only very slight variation throughout the year. This can also be observed in Figure 4.4, which shows a rose plot of the distribution of wind speed and wind direction (coming from) extracted the climatologically averaged meteorology for the same offshore location. 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 the Northern Isles. However, this does not reflect the full range of wind directions that may occur on these latitudes during the passage of low-pressure systems (as mentioned in Section 2.2), which are averaged out in the model climatology.

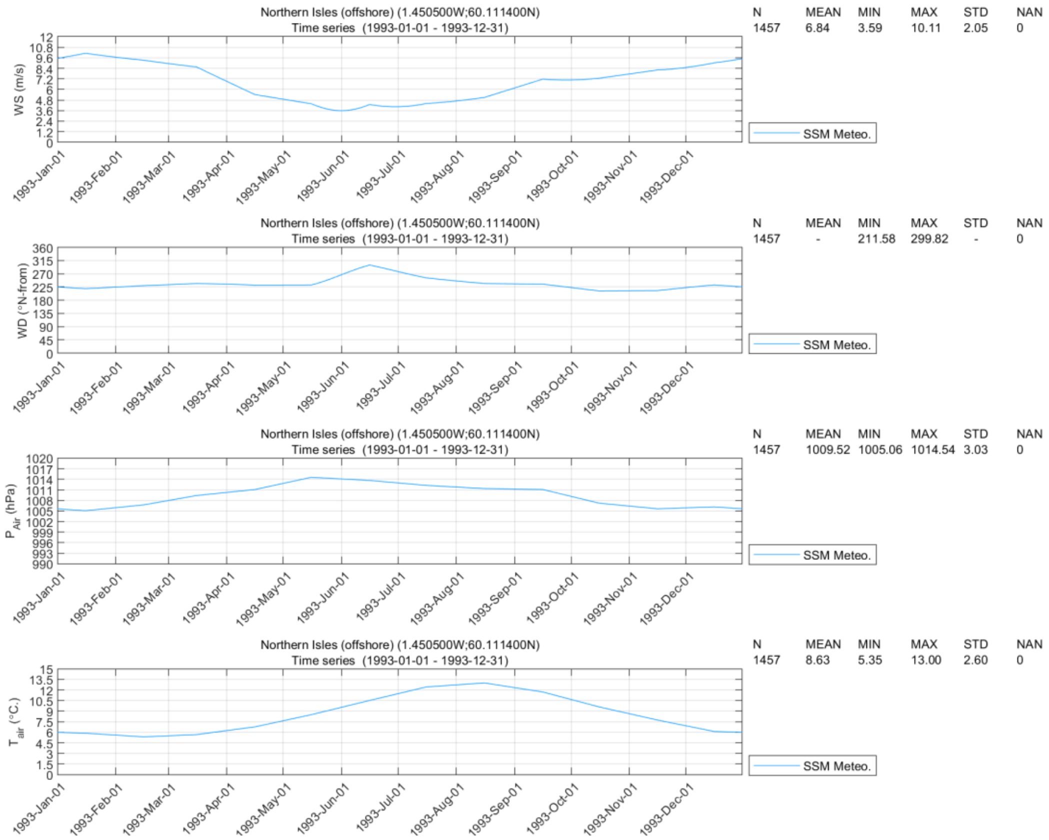


Figure 4.3 Time-series and annual statistics of climatologically averaged meteorological conditions for a location at the centre of the $HD_{NO\_hindcast/clima}$ computational domain. From top to bottom: wind speed, wind direction, atmospheric pressure, and air temperature.

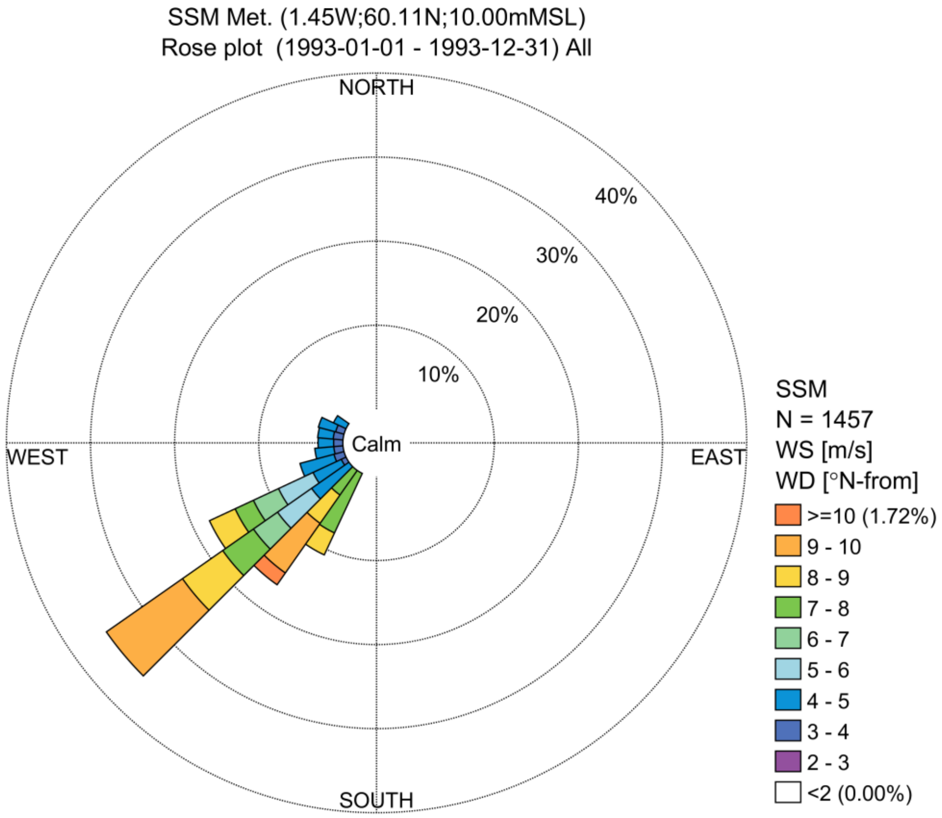


Figure 4.4 Annual wind rose for a location at the centre of the $HD_{NO\_hindcast/clima}$ computational domain, offshore of the north-east boundaries of North Orkney archipelago, from the climatology atmospheric forcing used as input to the SSM

4.3.2 Model domain

The computational domain of the regional model encompasses the entire area of the Northern Isles including both the North Orkney (area of interest) and Shetlands archipelagos, see Figure 4.5. The model has six 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 66,300 km^2.

4.3.3 Mesh and bathymetry

The computational mesh is based on a variable resolution unstructured grid in the horizontal direction. The mesh resolution was chosen to capture the important hydrodynamic processes within the scope of this hydrodynamic database construction, while maintaining 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 following discussions with SSF on model scoping .

The computational mesh of the hydrodynamic model is shown in Figure 4.5. 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 400m and 150m in the coastal areas within the North Orkney archipelago (right panel, Figure 4.5). The highest resolution is specified in Veantrow Bay (element side length ~40m) and subsequently near the shoreline, designated PMF areas, narrow straits between islands and within inlets. In these areas, the mesh element length is <150m. In total the horizontal mesh consists of 52,282 nodes defining 99,656 mesh elements.

Thus, the down-scaled regional climatology model HD_{NO_Clima} offers significant improvement in the resolution around the coastline and includes details of features (e.g., smaller islands and inlets) that are absent in the shelf-sea scale SSM model, see also Figure 4.5 - right panel.

The bathymetry datasets described in Section 3.1.2 were interpolated to the computational mesh as shown in Figure 4.5. Careful attention was given to smoothing of bathymetry to alleviate large bathymetric gradients between adjacent computational cells.

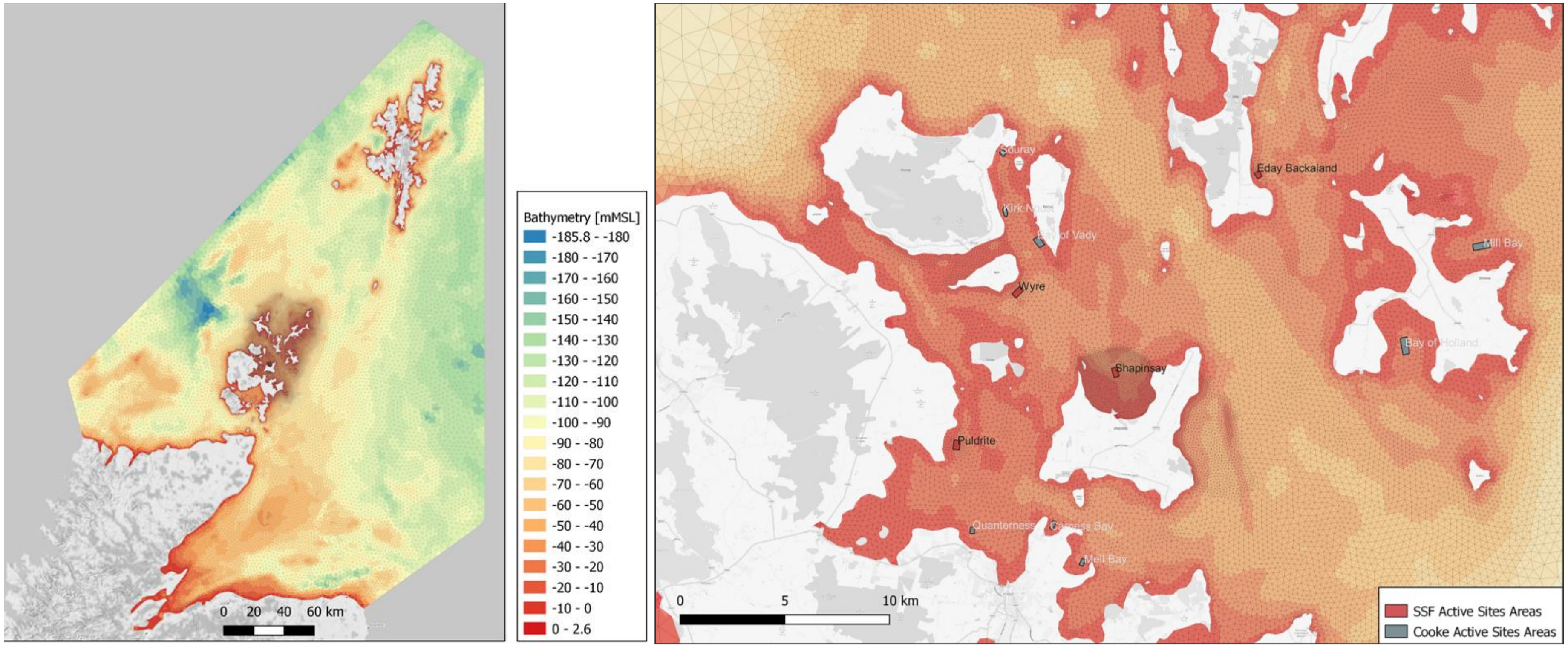


Figure 4.5 Computational domain of the regional North Orkney hydrodynamic model (left) and zoomed in perspective of the main area of interest in North Orkney archipelago (right). Mesh resolution is significantly improved in the area of interest versus SSM, as seen with Figure 4.2, allowing for a better representation of coastal and bathymetric features within the North Orkney archipelago.

4.3.4 Initial and boundary conditions

4.3.4.1 Hindcast - DTU10 – Global tidal solution

The barotropic component comes from a global tidal model produced by *Denmark's Technical University* at DTU Space in 2010 (DTU10)[11] using a response method of residual analysis of multi mission altimeter data. The model has a resolution of 0.125 x 0.125 degrees and includes the 12 major tidal constituents. The model is an empirical ocean tide model which means that it does not include tidal currents. As such, only sea surface height was used for boundary forcing [20].

4.3.4.2 Climatology

Initial and boundary conditions were derived from the SSM one-year climatology (see Section 4.3.1). This included temporally and spatially varying water surface elevation (1D, horizontal), and current velocities (2D, horizontal).

Hydrodynamic boundaries (water levels and current velocities) were specified as Flather boundary conditions [21]. This is an efficient open boundary condition method for downscaling coarse model simulations to local areas. When also imposing stratified density at water level boundaries (not herein) can generally help to avoid model instabilities .

Initial conditions were set for the spatially varying distribution of water levels (2D) throughout the computational domain at the beginning of the simulation. These were derived from the SSM starting conditions (interpolated onto the HD_{NO_clima} computational mesh).

4.3.5 Atmospheric forcing

4.3.5.1 Hindcast

ERA5 (ECMWF meteorological reanalysis 5)

The ERA5 dataset is a reanalysis of hourly meteorological conditions from 1979 to present, established by the European Centre for Medium Range Weather Forecasting (ECMWF) and provided by Copernicus, the European Union's Earth Observation Programme. The dataset was extracted from the meteorological ERA5 database and combines a meteorological model with observational data from satellites and ground sensors to build a consistent long-term record of the climate [22].

ERA5 offers a resolution of ~30 km in space and assimilates more observational datasets than previous ECMWF's re-analyses. It contains estimates of atmospheric variables such as air temperature, pressure and wind at different altitudes, as well as surface variables such as rainfall, soil moisture content and ocean wave height.

The ERA5 parameters applied in this study are summarised in Table 4.1. Based on experience, DHI approximate the temporal scale of the ERA5 wind datasets to be equivalent of a 2-hour averaging period.

[11] https://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Ocean_Tide_Model.aspx

Table 4.1 Specification of ERA5 atmospheric model.

Abbreviation	Unit	Description
U_{10}	m/s	Wind speed at 10m above MSL
D_{10}	˚N (coming from)	Wind direction at 10m above MSL

4.3.5.2 Climatology

Atmospheric forcing applied in HD_{NO_Clima} model include the wind speed and wind direction at 10mMSL and atmospheric pressure at mean-sea-level. This forcing was adopted climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis product (see Section 4.3.1.1). This is the same meteorological forcing as used in the wider domain SSM model; hence, achieving consistency with the model boundary forcing.

4.3.6 Model configuration

The configuration of the $HD_{NO\_hindcast/clima}$ 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 [9, 23].

Table 4.2 Summary of $HD_{NO,hindcast/clima}$ model settings.

Setting	Description/Value
Basic equations	Shallow water equations
Numerical scheme	Higher order scheme (time integration and space discretisation)
Horizontal mesh	Variable resolution unstructured grid (see Section 4.3.3)
Simulation period	Hindcast: A one-year hindcast run representing actual conditions in the period June 2017- June 2018 Climatology: A one-year climatological run, which represents average conditions for the period 1990-2014 with a 1993 tidal component.
Model time step (adaptive)	0.01 to 30 seconds
Flooding and drying	Drying depth 0.005m, wetting depth 0.1m
Density	Barotropic
Horizontal Eddy viscosity	Smagorinsky formulation with constant = 0.28
Vertical Eddy viscosity	K-epsilon formulation with eddy viscosity values min:1.8e-06/max:0.4 [m^2/s]
Bed resistance	Manning's M number constant over domain 32 [$m^{1/3}/s$]
Coriolis Forcing	Varying in domain
Wind forcing	Hindcast: Varying in time and domain specified from ERA5 reanalysis Climatology: Varying in time and domains climatologically averaged meteorological conditions derived from the ERA-40 and ERA-Interim re-analysis products
Wind friction	Varying with wind speed (Linear variation Speed): • 7 [m/s] Friction: 0.001255 • 25 [m/s], Friction: 0.002425
Tidal potential	Not included
Precipitation/Evaporation	Not included
Initial conditions	Hindcast: Spatially varying surface elevation derived from DTU10 global tide model (interpolated to the $HD_{NO\_hindcast}$ mesh) Climatology: Spatially varying surface elevation derived from SSM (interpolated to the HD_{NO_clima} mesh)
Boundary conditions	Flather boundary conditions, temporally and spatially varying water levels and 2D current velocities from the DTU10 and SSM for the hindcast and climatology versions respectively (see section 4.3.4)

4.4 Model outputs

The 2-dimensional outputs from the hydrodynamic hindcast and climatology models are summarised in Table 4.3 and Table 4.4. All parameters were saved in all model mesh elements (grid cells) at 0.5-hourly time intervals.

Table 4.3 2D model outputs from HD_{NO_clima}.

Parameter	Unit	Description
Surface elevation	m	Still water level relative to MSL
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
Eddy viscosity	m^2s^{-1}	Eddy viscosity
Bed shear-stress	Nm^{-2}	Bed shear-stress magnitude and directional components

Table 4.4 2D model outputs from $HD_{NO\_hindcast}$.

Parameter	Unit	Description
Surface elevation	m	Still water level relative to MSL
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
Wind U velocity	ms^{-1}	Wind velocity in the west-to-east direction at 10m above MSL
Wind V velocity	ms^{-1}	Wind velocity in the south-to-north direction at 10m above MSL
Air pressure	Pa	Air pressure at 10m above MSL
Eddy viscosity	m^2s^{-1}	Eddy viscosity
Bed shear-stress	Nm^{-2}	Bed shear-stress magnitude and directional components

Also provided are the decoupled files comprising of setup files, area output (Total water depth, U, V - velocity components) and fluxes which can be utilised to run both future AD simulations and particle tracking results. Still water depth and element size of the computational mesh (common for both model realisations) are provided as a separate time-invariant output.

4.5 Model files

The hydrodynamic climatology and hindcast models are supplied to SSF as part of the project deliverables. The data are provided in DHI MIKE format and can be used to generate boundary conditions for local climatology/hindcast modelling or as input for scenario modelling.

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

5 Hydrodynamic hindcast model calibration and validation

In this section, the calibration and validation of the 2D hydrodynamic hindcast models are presented.

5.1 Model Calibration

The North Orkney hydrodynamic hindcast model was calibrated against observed hydrographic data (water levels and currents) provided by SSF as part of their measurement campaigns in respective sites of interest within the North Orkney archipelago, see also section 3.2.

The model calibration/validation periods were selected based on the temporal and spatial coverage of the available data as described in section 3.2. These are detailed in Table 5.1 and shown in Figure 5.1.

Table 5.1 North Orkney hydrodynamic hindcast model calibration/validation deployment campaigns.

Site	ID	Survey Start	Survey End	Duration (days)	Lat	Long
Calibration period						
Eday Backaland	Eday20180709	10/07/2018	12/09/2018	63.97	59.161933	-2.749917
Eday Backaland	Eday20181005	09/10/2018	14/11/2018	36.22	59.161583	-2.749400
Puldrite	PLDRT000	10/07/2018	31/07/2018	21.61	59.045133	-3.000650
Puldrite	PLDR2000	09/10/2018	22/12/2018	73.88	59.044900	-3.002133
Wyre	WYRE0000	10/07/2018	12/09/2018	64.24	59.110100	-2.950383
Wyre	WYRE2000	09/10/2018	14/11/2018	36.07	59.110200	-2.950167
Validation period						
Shapinsay A	Shapinsay20190509	09/05/2019	16/06/2019	38.50	59.080567	-2.884100
Shapinsay A	ShapA2noWaves20190711	11/07/2019	01/10/2019	81.90	59.08088	-2.88418
Shapinsay B	ShapBwaves20190711	11/07/2019	06/11/2019	118.31	59.081333	-2.854667

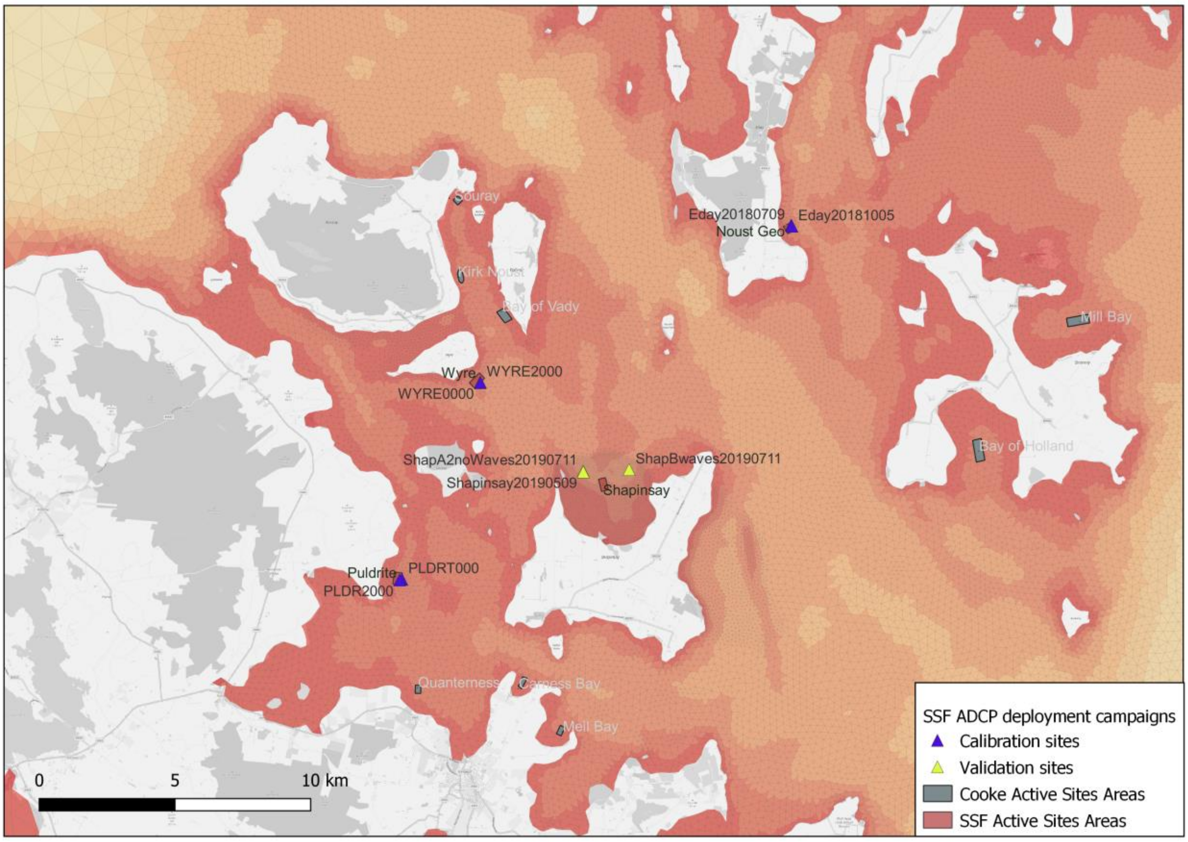


Figure 5.1 North Orkney hydrodynamic hindcast model calibration and validation sites' locations

Section 5.3 details the results from these calibration periods and sites. A brief mention at each calibration site is detailed below. The full set of calibration plots for water level, current speed and direction for the SSF sites are detailed in Appendix C.

A number of iterations in the context of sensitivity runs, involving parameter adjustments (for example spatial varying bed friction and bathymetric adjustments), were initially assessed to define calibration limits. Choice of final setup was on the basis of achieving good model skill (in terms of performance metrics against the observational record) collectively in the whole North Orkney archipelago and optimal performance measured against the Shapinsay measurement campaigns with focus to the north-east area of Veantrow Bay.

In general, the model exhibits a very good representation of the tidal component in areas informed by a detailed bathymetric dataset as also in places where the model bathymetry is based on the baseline EMODnet DTM (e.g. Puldrite). Timeseries and frequency plots for all calibration sites are provided in Appendix C.

5.1.1 Water levels

Surface elevation (water level), both total and tidal components, was well represented at the majority of the calibration sites as seen in Figure 5.2. Thus, tidal signals are correctly propagated through the computational domain. Below an account on model performance at the respective calibration sites is provided.

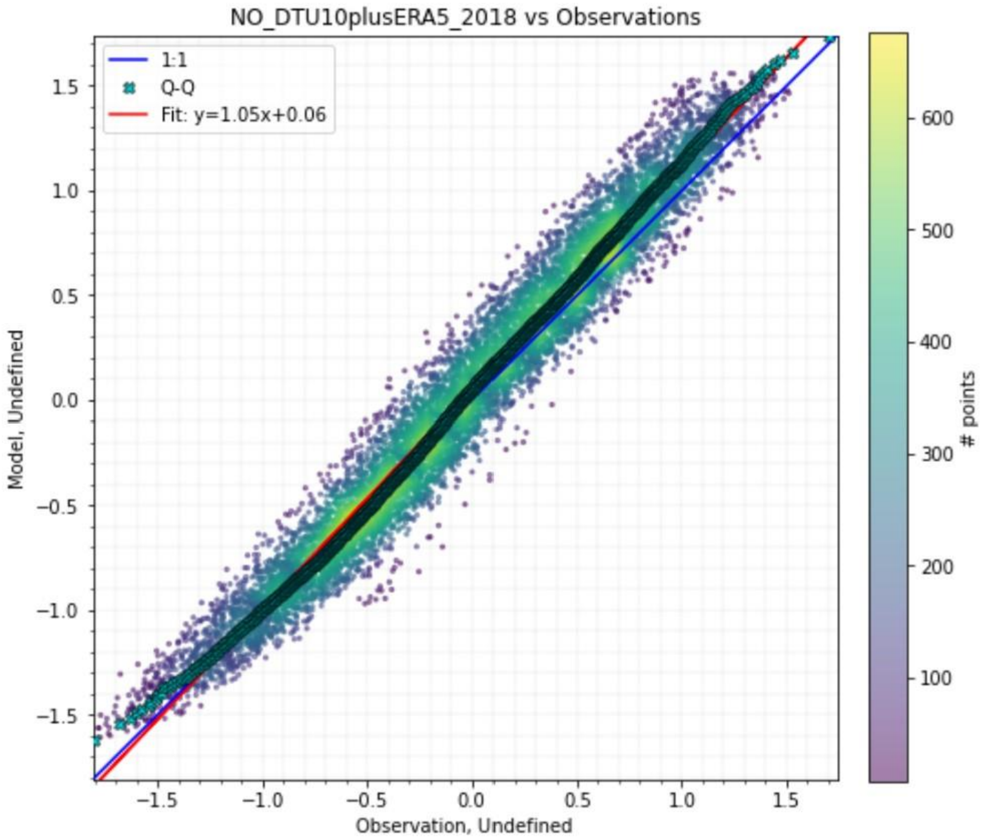


Figure 5.2 Scatter plot of modelled vs observed total water level at all calibration sites.

Scatterplots comparisons of observed versus modelled water levels for all calibration sites are presented in Figure 5.3. Inspection of the calibration plots show that for total (and tidal water level – not shown herein) there is a good overall fit between the observations and the model output especially with respect to the timing of high and low water. Not all stations within the same observation location (e.g. PLDR2000 and PLDRT00) are verified equally well. Discrepancies can be attributed to the observational record itself and/or misrepresentation of local bathymetric features rather than episodic events not within the variability resolution capacity of the modelled hydrodynamics.

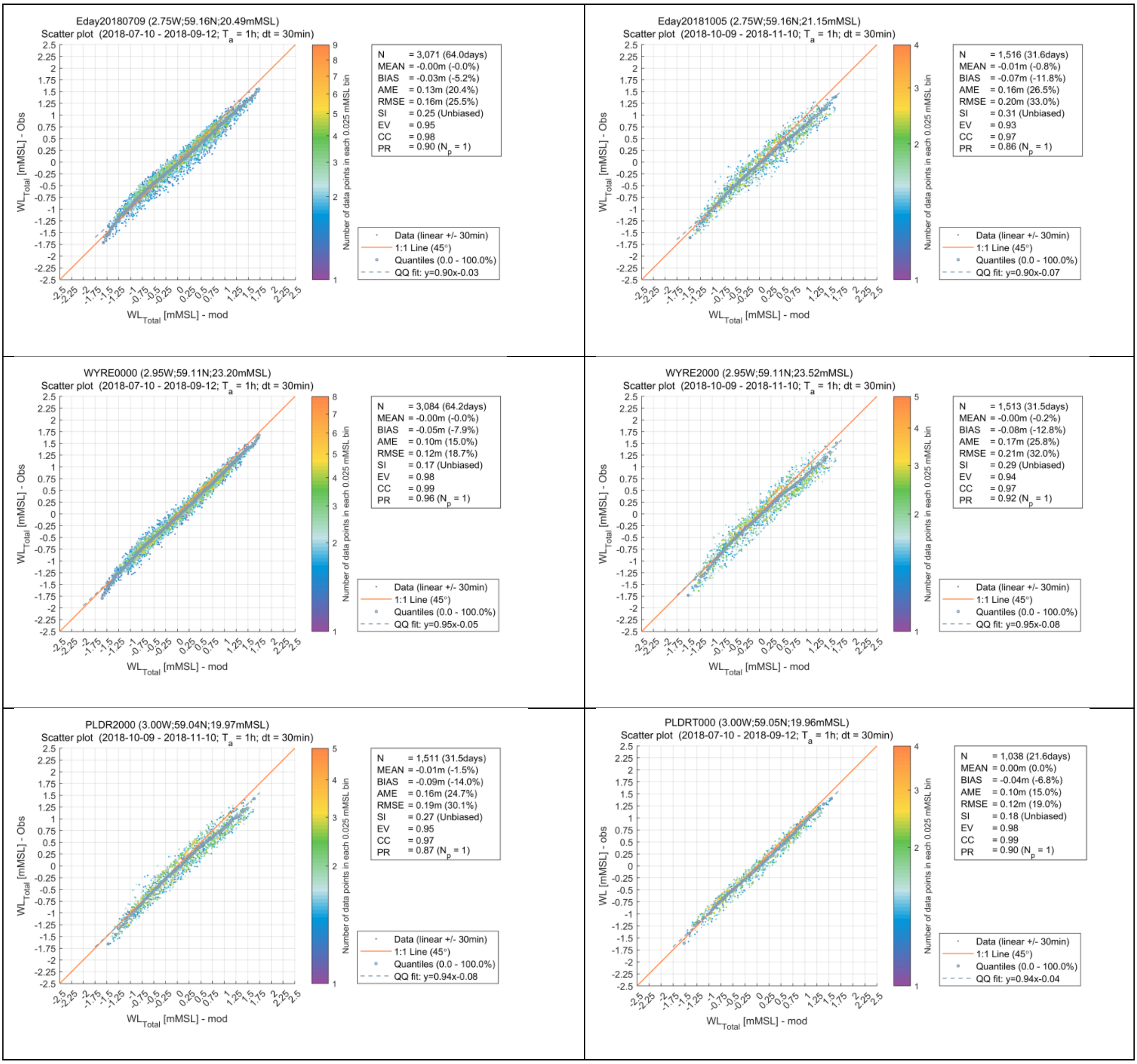


Figure 5.3 Scatterplot comparisons of observed versus modelled water levels at all calibration sites as in Table 5.1. (Eday Backaland, Wyre and Puldrite – top to bottom) ADCP deployments.

5.1.2 Currents

The model skill on current speed and directions representation throughout the computational domain within the North Orkney archipelago is considered good, see Figure 5.4. Wyre site was the exception to this, with current direction not well matched between model and observation at the exact ADCP location.

Specifically, Eday Backaland has a nice representation of both dominant current directions and magnitude while Puldrite is missing the southward current direction attributed to misrepresentation of bathymetry in the computational mesh at the respective location in lack of accurate bathymetric information. The Wyre location exhibited a very good current magnitude comparison, but the directional distribution of current speeds was not depicted correctly.

Scatterplot comparisons of observed versus modelled currents speeds are shown in the left panels and rose plot comparisons of the distribution of current speed and directions are shown in the right-hand panel of Figure 5.5 respectively.

For the Wyre site and considering the available ADCP locations nearby computational elements were used to examine sensitivity of current speed directional distributions and a potential better match to the observational record. In Figure 5.4, model location WYRE_1, used as the alternative comparison point, exhibits good agreement to both of the observational records, WYRE0000 and WYRE2000 (not shown herein), with a considerable improvement when compared to the prior comparison point (see also Figure 5.6 for scatterplot and rose plot comparisons versus original location in Figure 5.5).

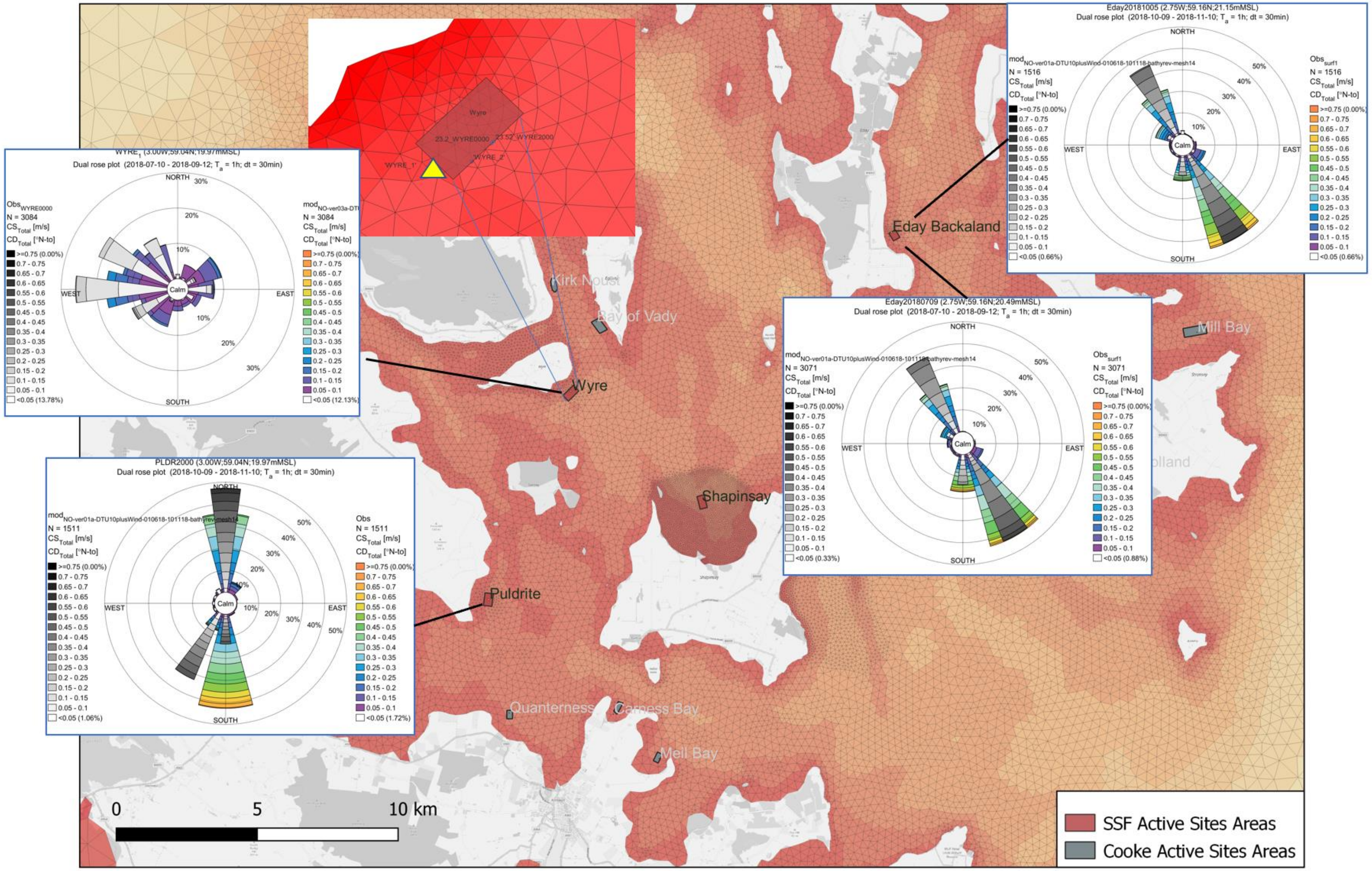
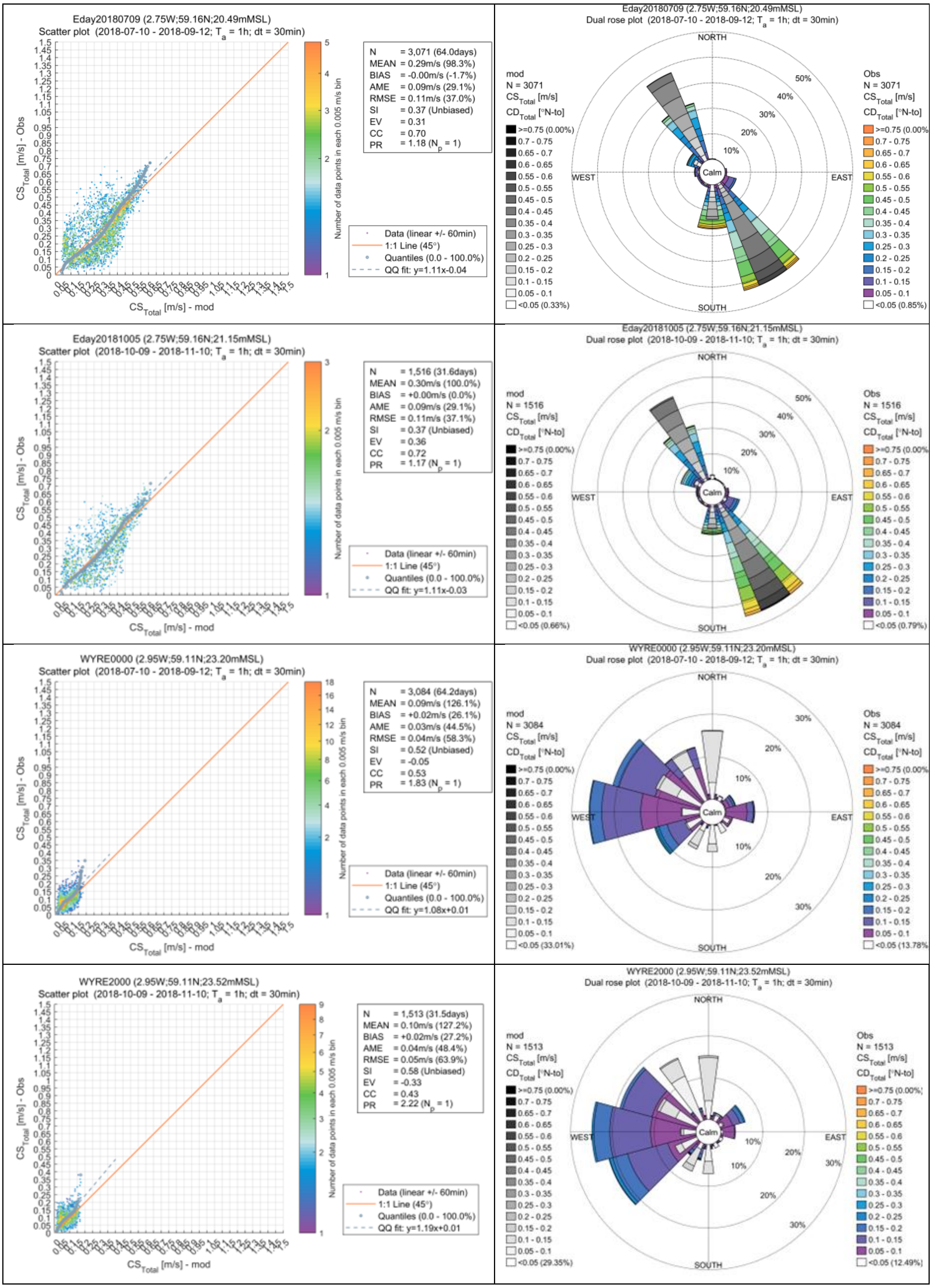


Figure 5.4 Dual rose plots of current speed and directions of observational records vs model output for all calibration sites. Inset image for WYRE site depicts alternative verification location (herein WYRE_1) extracted from the computational domain that compared better to the respective observational records. WYRE site is characterised by a specific bathymetric feature that appends an east-to-west directional character to currents which while present in the model bathymetry (shallow reef – red coloured, south of southwest corner of WYRE site polygon) is not depicted when using the actual observational locations for model extracted timeseries.


Eday20180709 (2.75W;59.16N;20.49mMSL)
Scatter plot (2018-07-10 - 2018-09-12; T_a = 1h; dt = 30min)
N = 3,071 (64.0days)
MEAN = 0.29m/s (98.3%)
BIAS = -0.00m/s (-1.7%)
AME = 0.09m/s (29.1%)
RMSE = 0.11m/s (37.0%)
SI = 0.37 (Unbiased)
EV = 0.31
CC = 0.70
PR = 1.18 (N_p = 1)
Data (linear +/- 60min)
1:1 Line (45°)
Quantiles (0.0 - 100.0%)
QQ fit: y=1.11x-0.04
CS_Total [m/s] - Obs
CS_Total [m/s] - mod
Number of data points in each 0.005 m/s bin
Eday20180709 (2.75W;59.16N;20.49mMSL)
Dual rose plot (2018-07-10 - 2018-09-12; T_a = 1h; dt = 30min)
mod
N = 3071
Obs
N = 3071
NORTH
SOUTH
WEST
EAST
Calm
Eday20181005 (2.75W;59.16N;21.15mMSL)
Scatter plot (2018-10-09 - 2018-11-10; T_a = 1h; dt = 30min)
N = 1,516 (31.6days)
MEAN = 0.30m/s (100.0%)
BIAS = +0.00m/s (0.0%)
AME = 0.09m/s (29.1%)
RMSE = 0.11m/s (37.1%)
SI = 0.37 (Unbiased)
EV = 0.36
CC = 0.72
PR = 1.17 (N_p = 1)
QQ fit: y=1.11x-0.03
Eday20181005 (2.75W;59.16N;21.15mMSL)
Dual rose plot (2018-10-09 - 2018-11-10; T_a = 1h; dt = 30min)
N = 1516
WYRE0000 (2.95W;59.11N;23.20mMSL)
Scatter plot (2018-07-10 - 2018-09-12; T_a = 1h; dt = 30min)
N = 3,084 (64.2days)
MEAN = 0.09m/s (126.1%)
BIAS = +0.02m/s (26.1%)
AME = 0.03m/s (44.5%)
RMSE = 0.04m/s (58.3%)
SI = 0.52 (Unbiased)
EV = -0.05
CC = 0.53
PR = 1.83 (N_p = 1)
QQ fit: y=1.08x+0.01
WYRE0000 (2.95W;59.11N;23.20mMSL)
Dual rose plot (2018-07-10 - 2018-09-12; T_a = 1h; dt = 30min)
N = 3084
WYRE2000 (2.95W;59.11N;23.52mMSL)
Scatter plot (2018-10-09 - 2018-11-10; T_a = 1h; dt = 30min)
N = 1,513 (31.5days)
MEAN = 0.10m/s (127.2%)
BIAS = +0.02m/s (27.2%)
AME = 0.04m/s (48.4%)
RMSE = 0.05m/s (63.9%)
SI = 0.58 (Unbiased)
EV = -0.33
CC = 0.43
PR = 2.22 (N_p = 1)
QQ fit: y=1.19x+0.01
WYRE2000 (2.95W;59.11N;23.52mMSL)
Dual rose plot (2018-10-09 - 2018-11-10; T_a = 1h; dt = 30min)
N = 1513

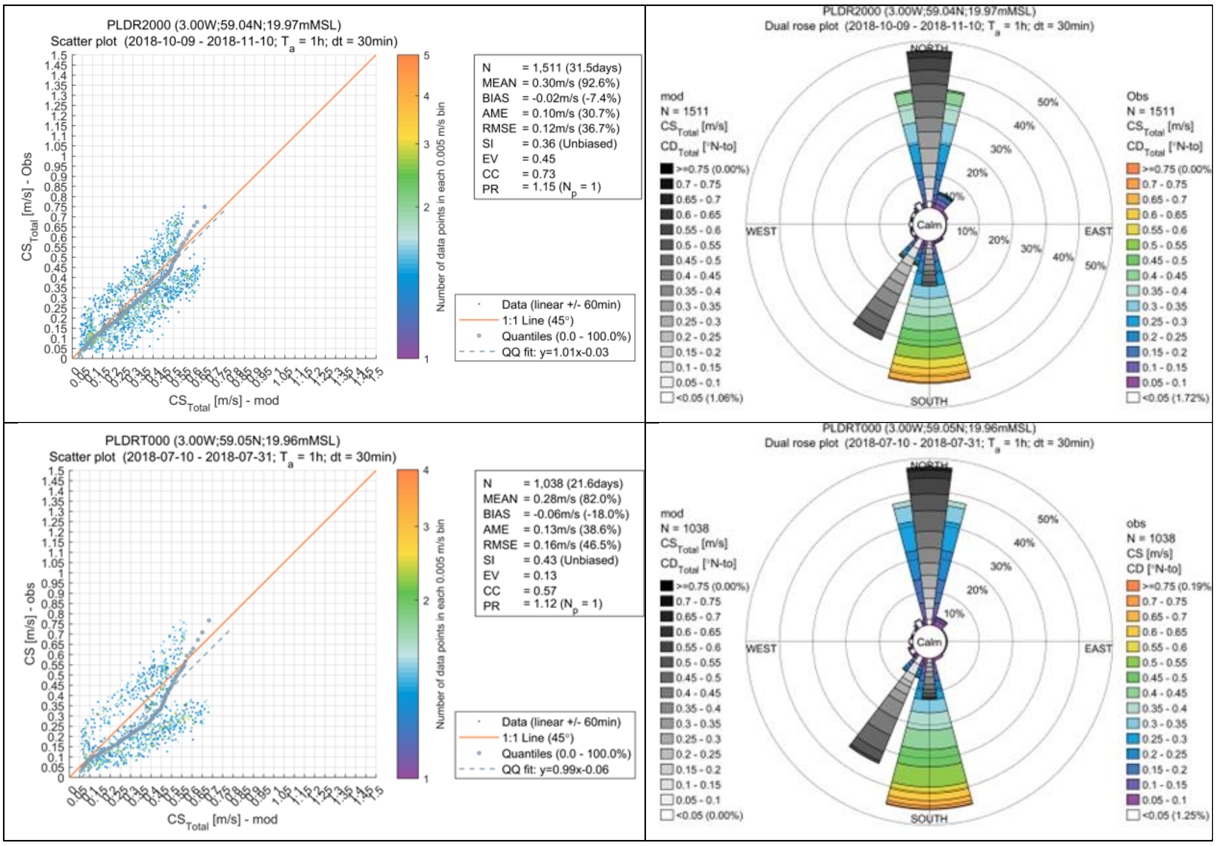


Figure 5.5 Scatterplot (left) and rose plot (right) comparisons of observed versus modelled currents through the water column at all SSF calibration sites.

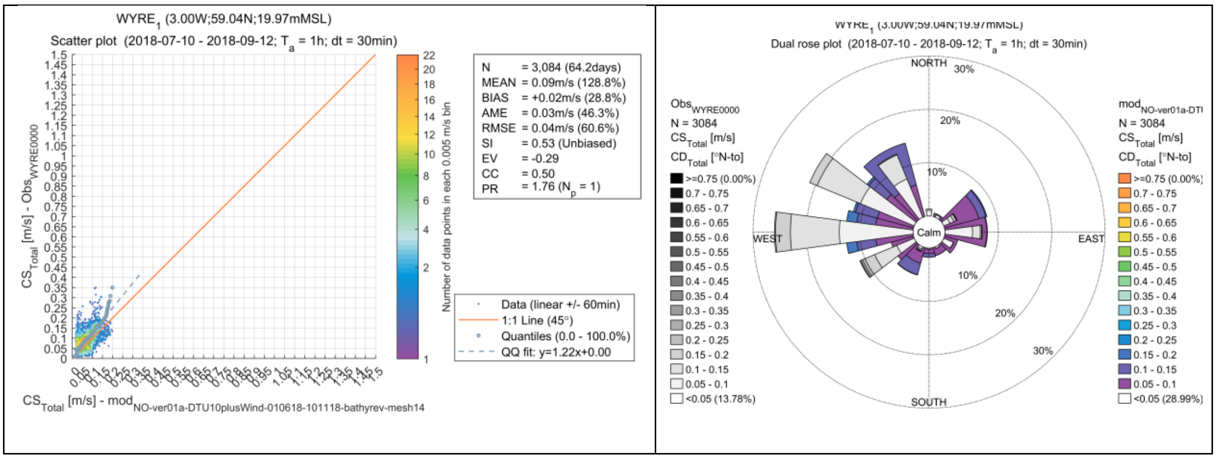


Figure 5.6 Same as in Figure 5.5 but using model location WYRE_1, see also Figure 5.4, against the observational record at WYRE0000 site. There is a distinct improvement in current speed directional distributions as seen from the rose plots with a slight deterioration of current speed verification as seen from the timeseries and scatter plots.

5.2 Model Validation

The North Orkney hydrodynamic hindcast model was validated against observed hydrographic data (water levels and currents) from three (3) measurement campaigns in Shapinsay (Veantrow Bay) in the North Orkney archipelago. SSF has a specific interest in the area of Veantrow Bay where both active sites exist, and prospect developments are scheduled as denoted in the initial scope requirements of the North Orkney hydrodynamic database.

The model validation periods were selected based primarily on the spatial relevance of the available data to the main area of interest. These are detailed in Table 5.1 and Figure 5.1.

Section 5.3 details the results from these sites for the validation period. All validation images are included as a digital appendix to this report (Appendix C). Validation plots for Shapinsay are shown in the following section.

In addition, SEPA's hydrodynamic model criteria as in [24], p.34, Table 3 are presented along with the timeseries and scatterplots.

5.2.1 Water Levels

Surface elevation (water level), both total and tidal components, was well represented at all of the validation sites as seen in Figure 5.7. Below an account on model performance at each of the observational records at the Shapinsay site is provided.

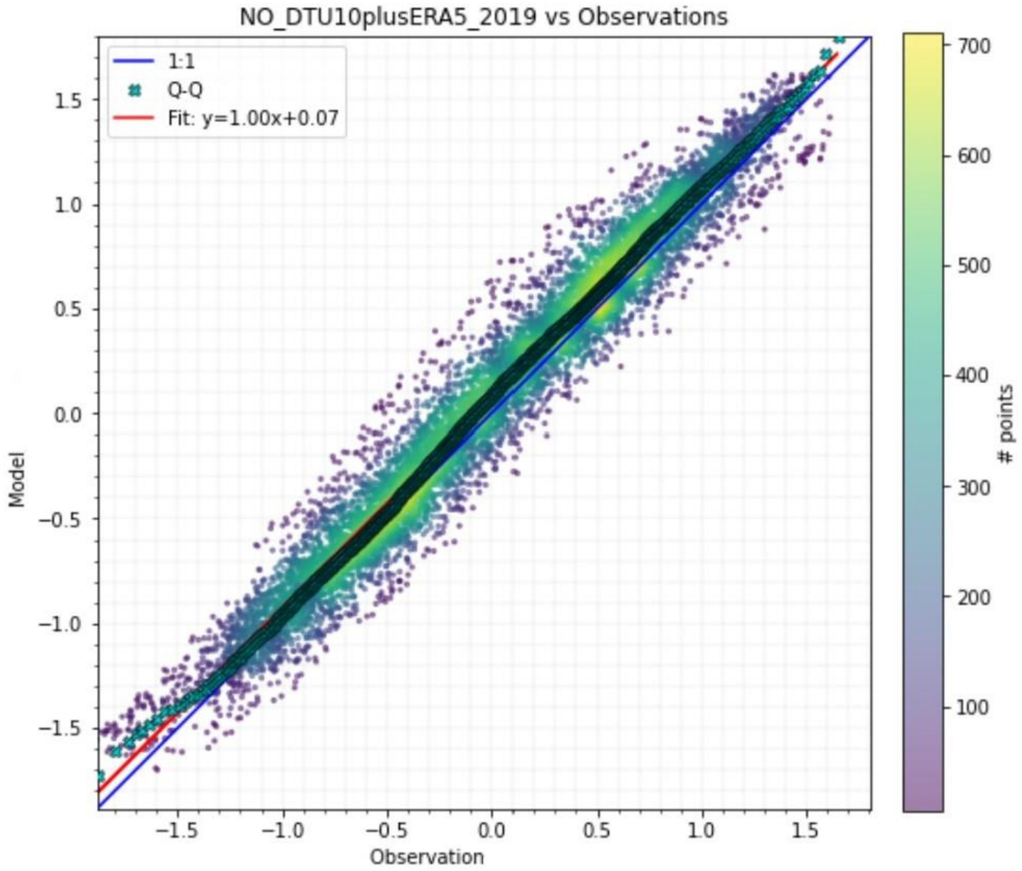


Figure 5.7 Scatter plot of modelled vs observed total water level at all validation sites.

Timeseries and scatterplot comparisons of observed and modelled water levels at ShapinsayB is presented in Figure 5.8. Inspection of the validation plots shows that for total and tidal water level there is good overall fit between the observations and the model output with q-q fit at 1.00. The model has on overall a bias of 0.07m and shows a slight overestimation of high water and similarly occasional underestimation of low water values especially at stations ShapA2noWaves and ShapBwaves. The residual component, de-tided water signal, is less well represented (see Appendix C) and while q-q fit is good it appears to have a high scatter index.

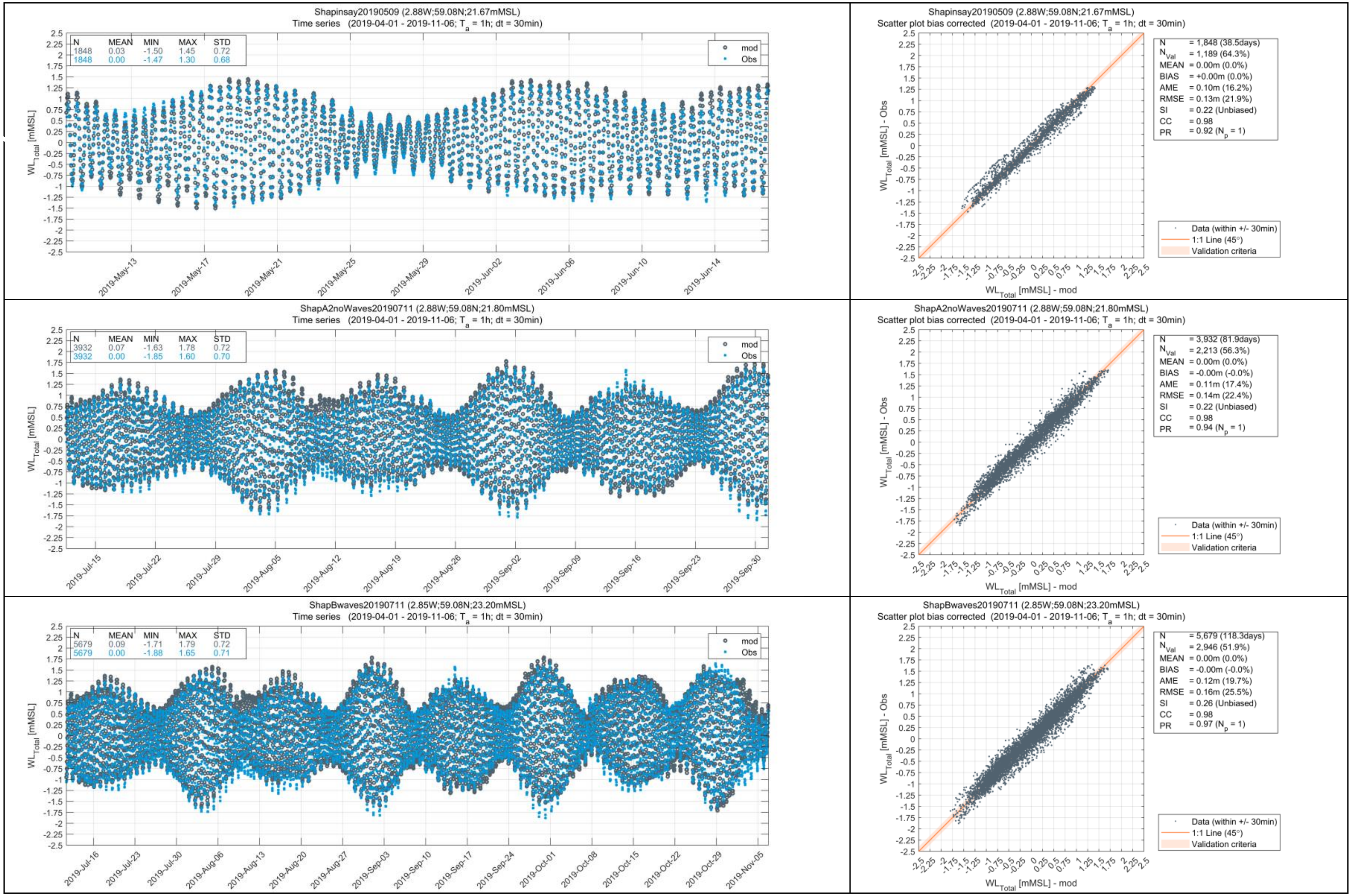


Figure 5.8 Timeseries (left) and scatterplot (right) comparisons of observed and modelled water levels at SSF's Shapinsay ADCP locations, see also Table 5.1.

5.2.2 Currents

Focusing on Veantrow Bay, the main area of interest for this hydrodynamic database, the model is effectively representing circulation in terms of magnitude and direction of currents as seen from the dual rose plots in Figure 5.9. A dominant eastward direction in ShapinsayB and a northwest-southeast direction in ShapinsayA are both well captured with the model slightly overestimating the eastward component in ShapinsayB and the westward sector in ShapinsayA.

Timeseries comparison of observed versus modelled depth-averaged current speeds at the respective sites in Shapinsay are presented in the left-hand panel of Figure 5.10. The model does an overall good job of capturing the variability of current speed both in space and time. Notwithstanding, the model fails to capture in full a number of episodic events during spring tides, which at least for ShapinsayB are still present in the tidal component and thus not necessarily due to discrepancies in the atmospheric forcing[12] used herein. Nonetheless, and given the magnitude of observed currents in Veantrow Bay (max<0.5m/s) RMSE and AME is throughout all observational stations around 0.05m/s which is considered acceptable, and meet the criteria in [24], given uncertainties in forcing and the 2D representation of the flow.

Timeseries and scatterplot comparisons of observed and modelled currents speeds (Figure 5.10 left and middle panels) shows that the model slightly underpredicts current speeds at spring tides, and sightly overpredicts them at the station ShapinsayA2 during spring tides with the exception of episodic events not captured by the model.

Rose plot comparisons of the distribution of current speed and directions are shown in the right-hand panel of Figure 5.10. There is very good agreement overall at all validated observational stations.

[12] It needs to be pointed out that the ERA5 grid resolution is relatively coarse for the spatial scales considered herein

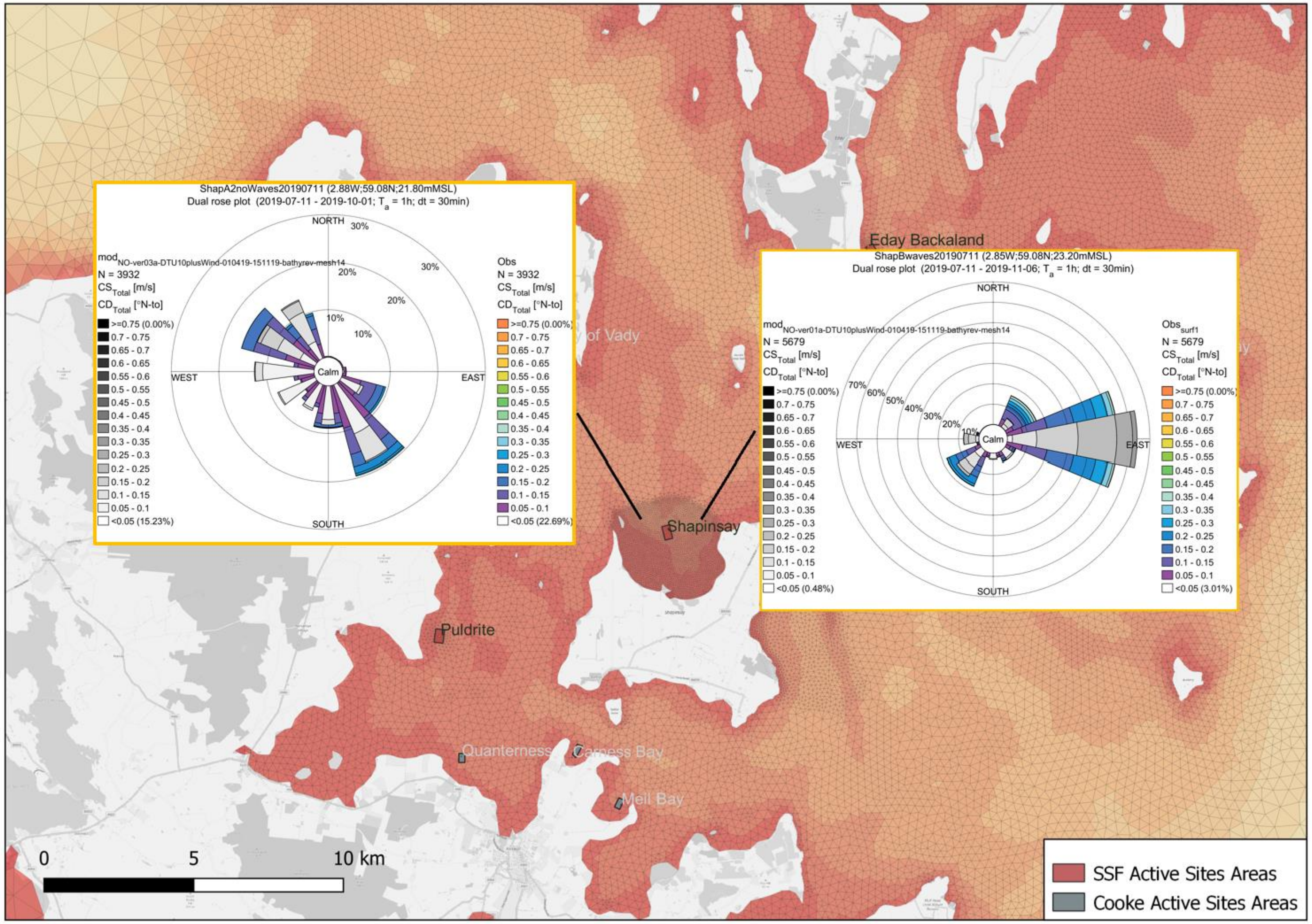


Figure 5.9 Dual rose plots of current speed and directions of observational records vs model output at the Shapinsay validation sites as in Table 5.1.

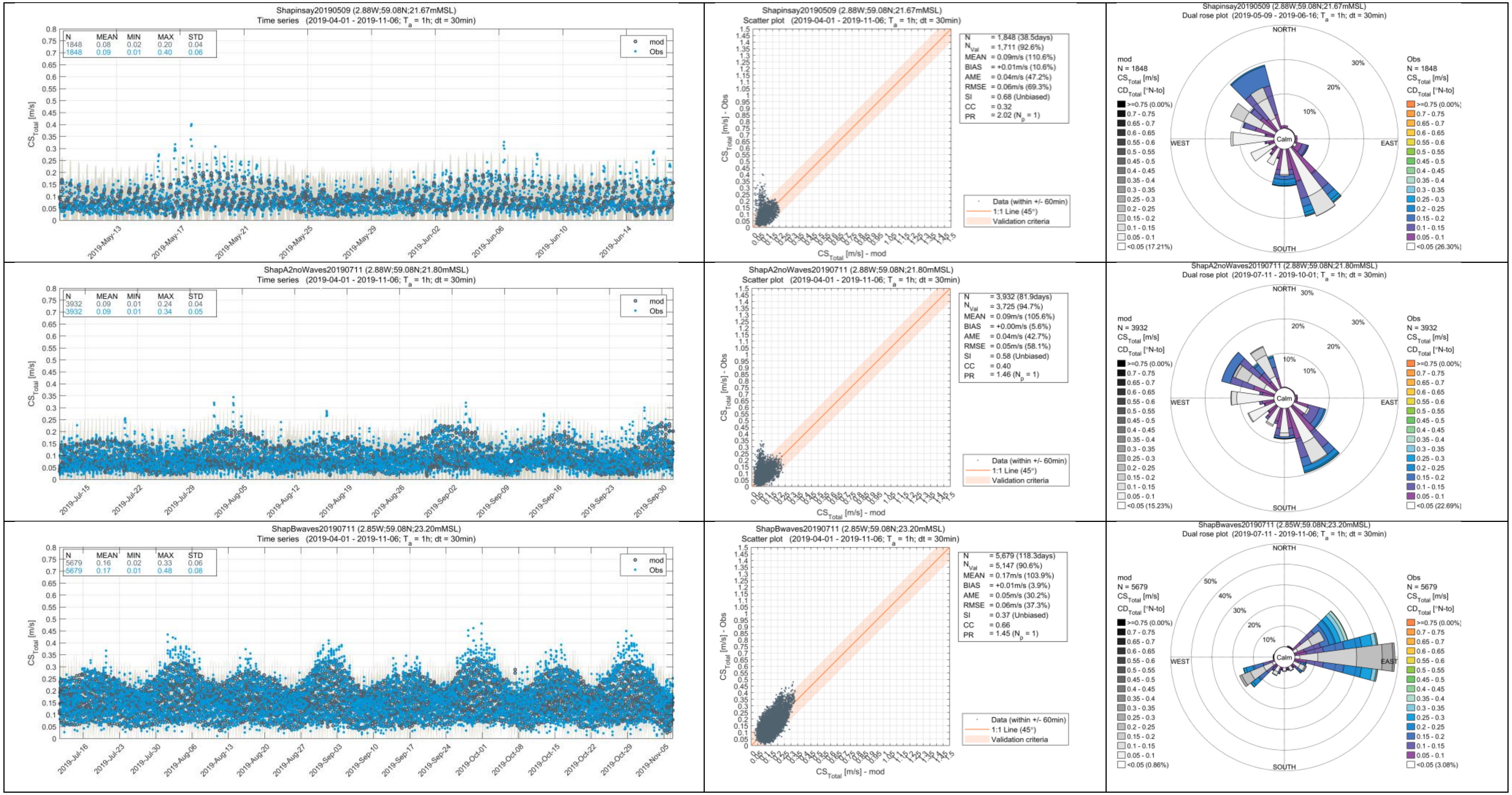


Figure 5.10 Timeseries (left), scatterplot (middle) and rose plot (right) comparisons of observed and modelled depth-averaged currents at SSF's Shapinsay deployments for year 2019. SEPA's regulatory criteria for current speeds shown as shaded area with percentage of conformity as N_{val} (only at scatterplots).

5.3 Summary of model quality indices

Below a summary of quality indices for the calibration and validation periods is presented for water level (WL), current speed (CS) and current directions (CD) for all observational records used during the calibration and validation stages of the hydrodynamic database development.

5.3.1 Water Level (WL)

Table 5.2 Summary of the North Orkney hydrodynamic hindcast model against calibration/validation sites, water level (WL) quality indices with conformity percentage (Nval %) to SEPA's criteria as in [24].

CALIBRATION																										
	WL - Obs					WL - Model					WL															
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %	Mean	Mean %	Bias	Bias %	AME m	AME %	RMSE m	RMSE %	SI	CC	PR	
NO_ver03a_DTU10_ERA5_hindcast_calibration.m3fm - Result Files																										
Eday20180709	3071	0.00	-1.71	1.55	0.65	3071	0.03	-1.58	1.72	0.72	3071	64.00	1463	47.6	0.00	0.0	-0.03	-5.2	0.13	20.4	0.16	25.5	0.25	0.98	0.90	Np = 1
Eday20181005	1516	-0.01	-1.61	1.39	0.66	1516	0.07	-1.47	1.63	0.73	1516	31.60	544	35.9	-0.01	-0.8	-0.07	-11.8	0.16	26.5	0.20	33.0	0.31	0.97	0.86	Np = 1
PLDRT000	1038	0.00	-1.61	1.40	0.69	1038	0.04	-1.52	1.52	0.74	1038	21.60	622	59.9	0.00	0.0	-0.04	-5.8	0.09	13.9	0.11	17.4	0.16	0.99	0.92	Np = 1
PLDR2000	1511	-0.01	-1.66	1.43	0.69	1511	0.08	-1.48	1.64	0.74	1511	31.50	546	36.1	-0.01	-1.5	-0.09	-14.1	0.16	24.7	0.19	30.1	0.27	0.97	0.87	Np = 1
WYRE0000	3084	0.00	-1.79	1.67	0.71	3084	0.05	-1.60	1.73	0.75	3084	64.20	1832.00	59.4	0.00	0.0	-0.05	-7.9	0.10	15.0	0.12	18.7	0.17	0.99	0.96	Np = 1
WYRE2000	1513	0.00	-1.73	1.51	0.71	1513	0.08	-1.51	1.64	0.76	1513	31.50	568	37.5	0.00	-0.2	-0.08	-12.8	0.17	25.8	0.21	32.0	0.29	0.97	0.92	Np = 1
VALIDATION																										
	WL - Obs					WL - Model					WL															
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %	Mean	Mean %	Bias	Bias %	AME m	AME %	RMSE m	RMSE %	SI	CC	PR	
NO_ver03a_DTU10_ERA5_hindcast_validation.m3fm - Result Files																										
Shapinsay20190509	1848	0.00	-1.47	1.30	0.68	1848	0.03	-1.50	1.45	0.72	1848	38.50	1189	64.3	0.00	0.0	-0.00	0.0	0.11	17.4	0.14	22.6	0.22	0.98	0.90	Np = 1
ShapA2noWaves20190711	3932	0.00	-1.85	1.60	0.70	3932	0.07	-1.63	1.78	0.72	3932	81.90	2213	56.3	0.00	0.0	+0.03	-0.1	0.12	19.7	0.16	25.2	0.22	0.98	0.90	Np = 1
ShapBwaves20190911	5679	0.00	-1.88	1.65	0.71	5679	0.09	-1.71	1.79	0.72	5679	118.30	2946	51.9	0.00	0.1	-0.00	-0.1	0.14	22.6	0.18	28.8	0.25	0.98	0.92	Np = 1

5.3.2 Current Speed (CS)

Table 5.3 Summary of the North Orkney hydrodynamic hindcast model against calibration/validation sites, current speed (CS) model quality indices with conformity percentage (Nval %) to SEPA's criteria as in [24].

CALIBRATION																										
	CS - Obs					CS - Model					CS															
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %	Mean m/s	Mean %	Bias m/s	Bias %	AME m/s	AME %	RMSE m/s	RMSE %	SI	CC	PR	
NO_ver03a_DTU10_ERA5_hindcast_calibration.m3fm - Result Files																										
Eday20180709	3071	0.29	0.02	0.72	0.15	3071	0.29	0.04	0.61	0.13	3071	64	1978	64.4	0.29	103.1	0.01	3.1	0.08	28.2	0.1	35.7	0.36	0.74	1.24	Np = 1
Eday20181005	1516	0.3	0.02	0.72	0.15	1516	0.3	0.04	0.61	0.14	1516	31.6	987	65.1	0.3	100	0.00	0	0.09	29.1	0.11	37.1	0.37	0.72	1.17	Np = 1
PLDRT000	1038	0.28	0.03	0.77	0.16	1038	0.35	0.06	0.68	0.16	1038	21.6	441	42.5	0.28	82	-0.06	-18	0.13	38.6	0.16	46.5	0.43	0.57	1.12	Np = 1
PLDR2000	1511	0.30	0.02	0.75	0.16	1511	0.32	0.04	0.65	0.16	1511	31.5	818	54.1	0.3	92.6	-0.02	-7.4	0.1	30.7	0.12	36.7	0.36	0.73	1.15	Np = 1
WYRE0000	3084	0.09	0.01	0.35	0.04	3084	0.07	0.01	0.20	0.03	3084	64.2	2972	96.4	0.09	128.8	0.05	28.8	0.03	46.3	0.04	60.6	0.53	0.50	1.76	Np = 1
WYRE2000	1513	0.10	0.01	0.38	0.05	1513	0.08	0.01	0.22	0.04	1513	31.5	1429	94.4	0.1	130	0.02	30	0.04	50.2	0.05	65.6	0.58	0.41	1.73	Np = 1
VALIDATION																										
	CS - Obs					CS - Model					CS															
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %	Mean m/s	Mean %	Bias m/s	Bias %	AME m/s	AME %	RMSE m/s	RMSE %	SI	CC	PR	
NO_ver03a_DTU10_ERA5_hindcast_validation.m3fm - Result Files																										
Shapinsay20190509	1848	0.09	0.01	0.4	0.06	1848	0.08	0.02	0.2	0.04	1848	38.5	1711	92.6	0.09	110.6	0.01	10.6	0.04	47.2	0.06	69.3	0.68	0.32	2.02	Np = 1
ShapA2noWaves20190711	3932	0.09	0.01	0.34	0.05	3932	0.09	0.01	0.24	0.04	3932	81.9	3725	94.7	0.09	105.6	0.00	0	0.04	42.7	0.05	58.1	0.58	0.40	1.46	Np = 1
ShapBwaves20190911	5679	0.17	0.01	0.48	0.08	5679	0.16	0.02	0.33	0.06	5679	118.3	5147	90.6	0.17	103.9	3.90	3.9	0.05	30.2	0.06	37.3	0.37	0.66	1.45	Np = 1

5.3.3 Current Direction (CD)

Table 5.4 Summary of the North Orkney hydrodynamic hindcast model against calibration/validation sites, current direction (CD) model quality indices with conformity percentage (Nval %) to SEPA's criteria as in [24].

CALIBRATION														
	CD - Obs					CD - Model					CD			
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %
NO_ver03a_DTU10_ERA5_hindcast_calibration.m3fm - Result Files														
Eday20180709	3071	209.1	2.37	359.25	78.23	3071	231.36	3.42	352.40	80.33	3071	64.0	2351	76.6
Eday20181005	1516	207.04	5.27	358.49	80.23	1516	227.55	0.07	356.31	82.95	1516	31.6	1179	77.8
PLDRT000	1038	151.61	0.06	360.00	110.65	1038	131.21	0.06	359.92	114.66	1038	21.6	765	73.7
PLDR2000	1511	143.26	0.01	360.00	108.52	1511	137.14	0.02	359.99	117.78	1511	31.5	1153	76.4
WYRE0000	3084	246.62	1.73	358.97	83.07	3084	242.34	0	359.99	106.74	3084	64.2	1037	34.6
WYRE2000	1513	232.03	0.05	356.87	82	1513	244.37	0.04	359.69	106.71	1513	31.5	393	26
VALIDATION														
	CD - Obs					CD - Model					CD			
	N	Mean	Min	Max	STD	N	Mean	Min	Max	STD	N	Ndays	Nval	Nval %
NO_ver03a_DTU10_ERA5_hindcast_validation.m3fm - Result Files														
Shapinsay20190509	1848	220.12	1.72	356.73	79.3	1848	230.25	1.48	357.27	69.66	1848	38.5	1139	61.6
ShapA2noWaves20190711	3932	213.21	0.87	359.11	76.59	3932	227.41	2.56	359.68	72.04	3932	81.9	2409	61.3
ShapBwaves20190911	5679	115.72	2.66	354.07	65	5679	126.46	26.05	347.88	64.96	5679	118.3	4355	76.7

6 Model Results

In this section, the results of the 2D hydrodynamic models are presented. This includes a qualitative verification of the climatological model against the hindcast version, and a brief description of modelled hydrodynamics over the area of interest.

6.1 Model outputs

The residual circulation and statistical maximum depth-averaged current speed of HD_{NO_Clima} and $HD_{NO\_hindcast}$ are shown in Figure 6.2 (Veantrow Bay close up - Figure 6.1), Figure 6.3 and Figure 6.4 and Figure 6.5 and respectively. Strong currents are found where the flow is constrained around the headlands and in narrow channels driven in principle by the tidal dynamics that dominate the Northern Isles, lying as they are between the North Atlantic and North Sea. This tidal dominance is verified by the consistency between the climatological realisation and the hindcast yearly run, see Figure 6.4 and Figure 6.5.

At all of SSF's MPFF active sites the hydrodynamic field can be considered to be 'weak' (white to light blue areas Figure 6.2 -Figure 6.5) which would suggest also a reduced dispersion capacity with the exception of Puldrite and Eday Backaland and the outer area of Veantrow Bay, see Figure 6.1. Specifically for Veantrow Bay Figure 6.1 showcases a rather weak residual circulation which is almost 'isolated' by a prominent almost cyclonic circulation pattern immediately to the north east 'boundary' of the bay.

Maximal currents are in excess of 3m/s in the main channels within the North Orkney archipelago justifying the characterisation as one of the most energetic tidal current sites worldwide. The consistency in statistics of current speed and direction between the climatology and hindcast version supports the dominant tidal character of the area, see also Section 4.3.1, and demonstrates that the atmospheric forcing is of secondary importance in longer timescale extremities herein. This of course does not negate both the significance of variability and seasonal signals in meteorological conditions in the area and how they affect and/or drive episodic events, potentially also affecting dispersion, at shorter timescales similar to usual storm durations at these latitudes for example.

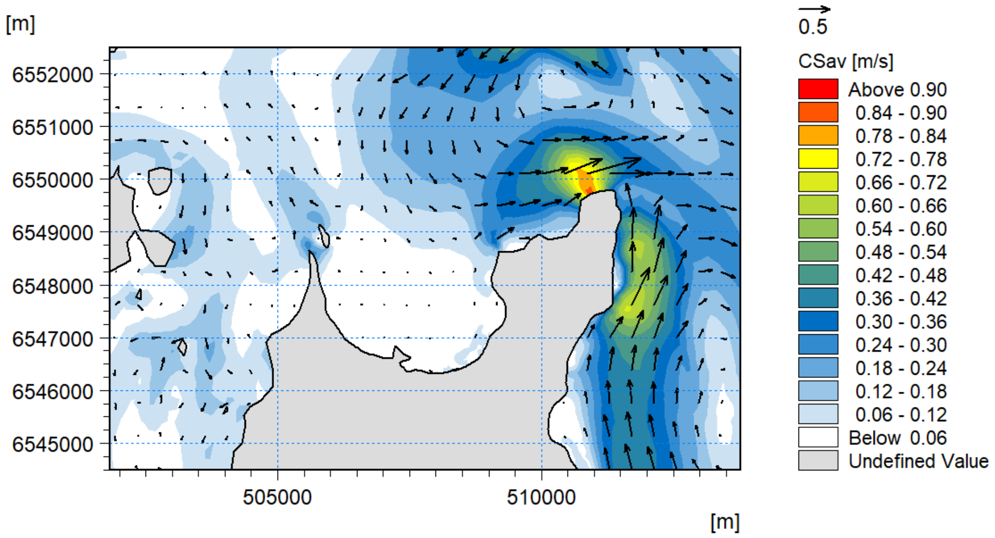


Figure 6.1 Residual circulation around Veantrow Bay at North Orkney based on the hydrodynamic climatology model (HD_{NO_Clima}).

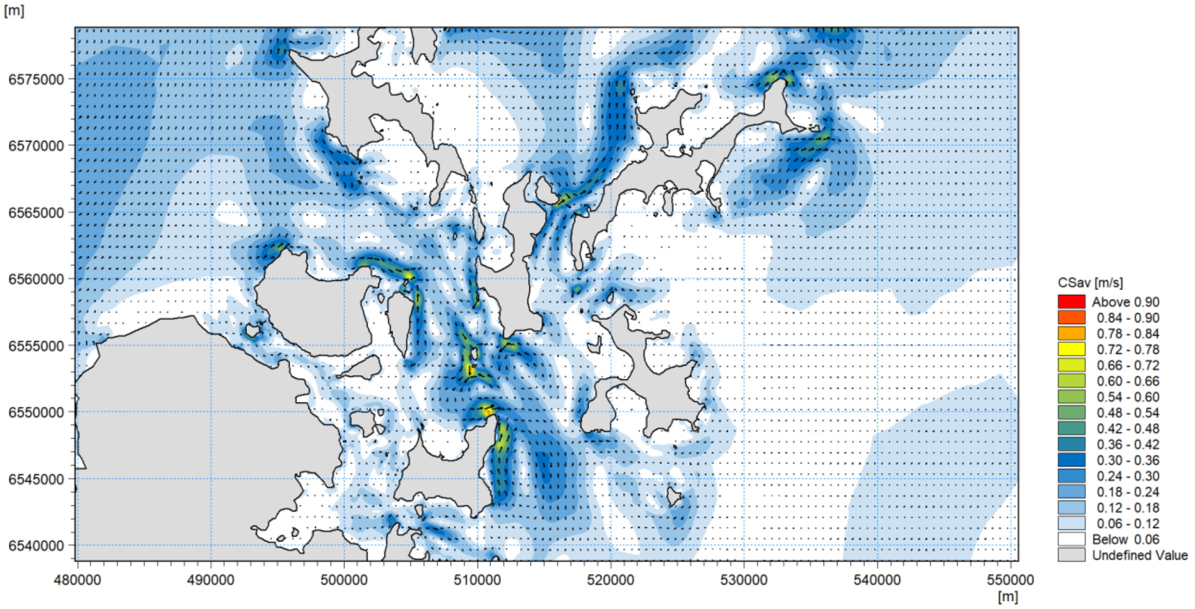


Figure 6.2 Residual circulation around North Orkney based on the hydrodynamic climatology model (HD_{NO_Clima}).

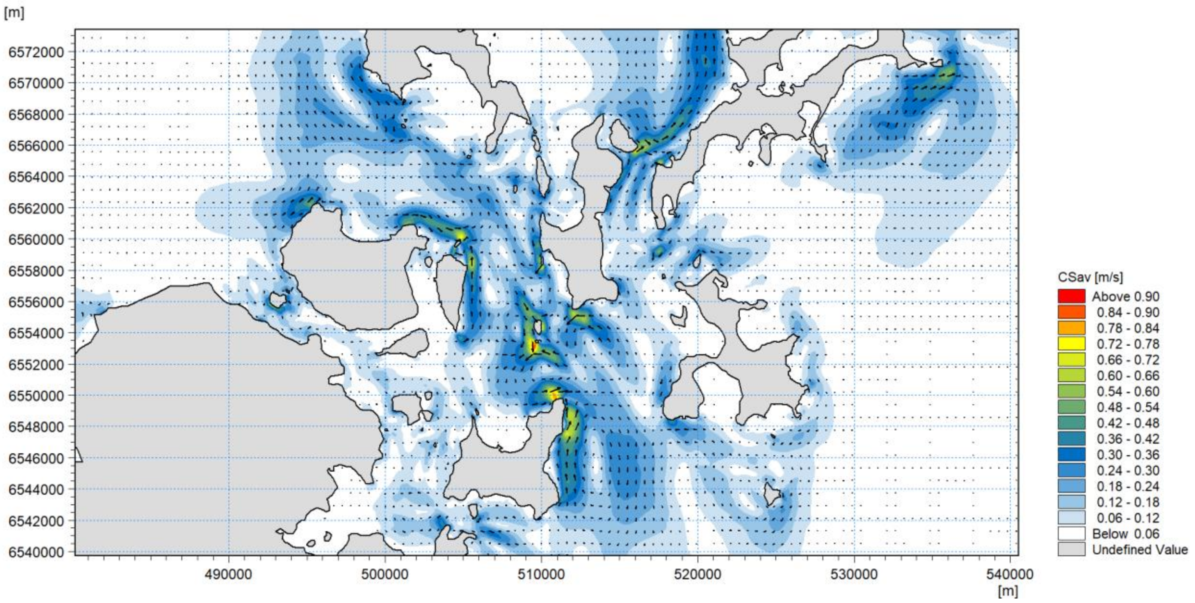


Figure 6.3 Residual circulation around North Orkney based on the hydrodynamic hindcast model ($HD_{NO\_hindcast}$).

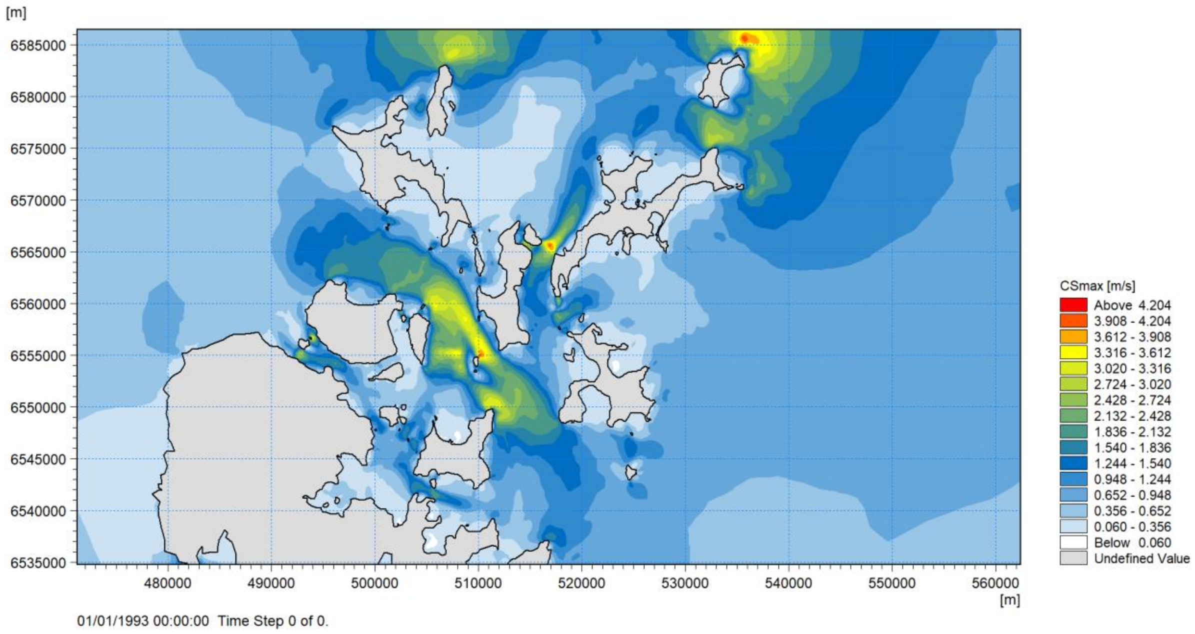


Figure 6.4 Statistical maximum surface current speed around North Orkney based on the hydrodynamic climatology model (HD_{NO_Clima}).

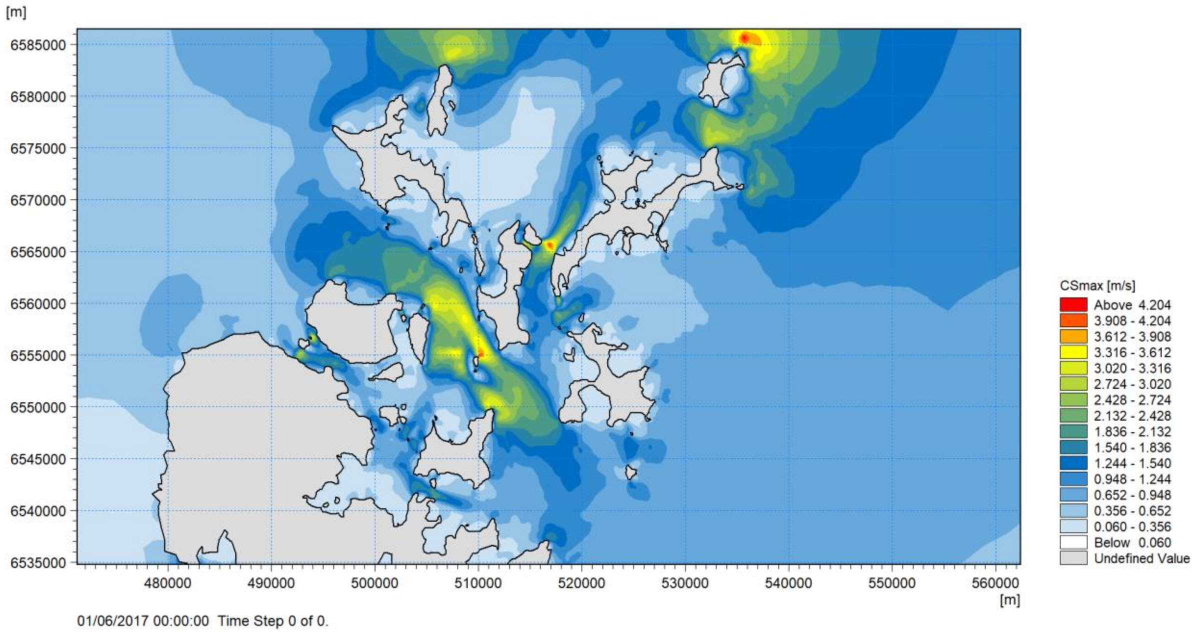


Figure 6.5 Statical maximum surface current speed in area around North Orkney based on the hydrodynamic hindcast model ($HD_{NO\_hindcast}$).

7 Summary

A 2-dimensional hydrodynamic hindcast and climatology model database for the North Orkney archipelago has been developed to support marine pen fin fish aquaculture projects in North Orkney, Scotland. The model database has been established using DHI's MIKE 21 FM numerical engine. The climatology version was based on upon the existing Scottish Shelf Model climatology developed for Marine Scotland Science.

The hydrodynamic database includes a regional hydrodynamic climatology, and a hindcast version, with a resolution of approximately <150m at the coastline and ~40m at Veantrow Bay (main area of interest). The model has refined resolution of down to 150m around existing marine sensitive areas (PMFs).

The hydrodynamic hindcast and climatology model databases provide a basis for future modelling to support regulatory applications such as: assessing connectivity between fish farms sites around North Orkney archipelago; site selection and site screening; dispersion modelling of waste solids and bath treatment medicines.

8 References

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APPENDICES

APPENDIX A

Hydrodynamic Model Database Files

A Hydrodynamic model database 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_{NO_clima} model.

Table A.2 summarises the model files provided for the $HD_{NO\_hindcast}$ model.

Table A.1 Hydrodynamic climatology files ($HD_{NO,Clima}$)

Folder	File name	File type	File size	Description
0_MetForcing	Climatology_swona_metforcing_TAU_M21_v2.dfsu	MIKE Zero Data Manager (.dfsu)	1.56 GB	SSM climatologically averaged meteorological 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 ($HD_{NO,Clima}$)

Folder	File name	File type	File size	Description
NO_ver03a_SSM_climatology_production.m21fm - Result Files	area.dfsu	MIKE Zero Data Manager (.dfsu)	61.3 GB	2-Dimensional model outputs from 1-year model run (0.5-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 [$m^3s^{-1}m^{-1}$] • Eddy viscosity [m^2s^{-1}] • Bed shear stresses (and x,y-components) [Nm^{-2}]
climatology_production_decoupled	NO_ver03a_SSM_climatology_production_Decoupled.m21fm	Setup (.m21fm)	141 KB	
	NO_ver03a_SSM_climatology_production_DecouplingArea.dfsu	MIKE Zero Data Manager (.dfsu)	20.4 GB	• Total water depth [m] • Depth-averaged u-velocity [m/s] • Depth-averaged v-velocity [m/s]
	NO_ver03a_SSM_climatology_production_DecouplingFlux.dfsu		10.4 GB	• Flux [undefined]

Table A.2 Hydrodynamic hindcast files ($HD_{NO\_hindcast}$)

Folder	File name	File type	File size	Description
NO_ver03a_DTU10_ERA5_hindcast_production.m21fm - Result Files	Elmnt_area.dfsu	MIKE Zero Data Manager (.dfsu)	4.55 MB	• Still water depth [mMSL] • Element area [m^2]
	area.dfsu	MIKE Zero Data Manager (.dfsu)	88.6 GB	2-Dimensional model outputs from 1-year model run (0.5-hour temporal resolution) • Surface elevation [mMSL] • Depth-averaged u-velocity [m/s] • Depth-averaged v-velocity [m/s] • P (power) flux [$m^3s^{-1}m^{-1}$] • Q (volume) flux [$m^3s^{-1}m^{-1}$] • Wind U-velocity [m/s] • Wind V-velocity [m/s] • Air pressure [Pa] • Eddy viscosity [m^2s^{-1}] • Bed shear stresses (and x,y-components) [Nm^{-2}]
hindcast_production_decoupled	NO_ver03a_DTU10_ERA5_hindcast_production_Decoupled.m21fm	Setup (.m21fm)		
	NO_ver03a_DTU10_ERA5_hindcast_production_DecouplingArea.dfsu	MIKE Zero Data Manager (.dfsu)	23 GB	• Total water depth [m] • Depth-averaged u-velocity [m/s] • Depth-averaged v-velocity [m/s]
	NO_ver03a_DTU10_ERA5_hindcast_production_DecouplingFlux.dfsu		11.8 GB	• Flux [undefined]

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[13] 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.

[13] 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.

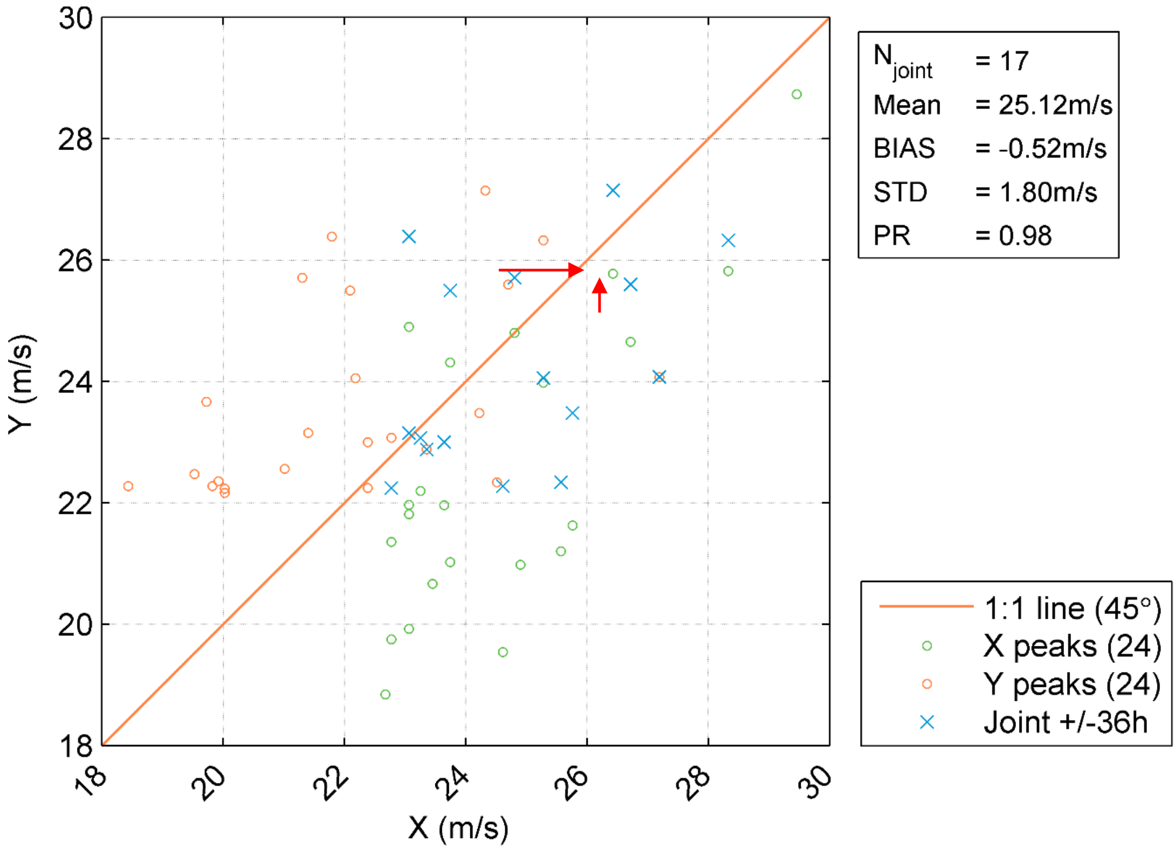

Figure B.1 Example of peak event plot (wind speed).

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)	$\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X-\mathrm{BIAS})_i^{\,2}}}{\frac{1}{N}\sum_{i=1}^{N}\lvert X_i\rvert}$
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)	$\mathrm{PR} = \mathrm{i} = 1\mathrm{Npeak}\mathrm{Y_i}\sum_{i=1}^{N_{peak}} X_i$

APPENDIX C

Digital container of calibration/validation plots

C Digital container of calibration/validation plots