Scottish Shelf Model : Development of Clyde Sub-Model

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Scottish Shelf Model : Development of Clyde Sub-Model

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Executive Summary

A new high-resolution hydrodynamic model has been developed covering the Clyde Sea. This report describes the model setup in detail. Initial validation of the model is mixed, suggesting that it correctly predicts the broad patterns of water structure and behaviour in the region but cannot currently be fully relied upon for precise time-specific predictions. Further development and validation is recommended.

Introduction

The Scottish Shelf Model (SSM) is a suite of regional-scale hydrodynamic models commissioned, developed and/or maintained by Marine Scotland Science. It consists of a shelf-wide domain (Wolf et al., 2016), which covers all Scottish shelf waters and beyond at a relatively coarse resolution (approximately 1 km in the most detailed areas), and a number of higher-resolution sub-models covering specific shelf and inshore areas of particular interest. These sub-models are intended to be forced by the shelf-wide model (sometimes described as "one-way nesting"), but can also be run independently as standalone models. All models within the SSM framework are implemented using the Finite Volume Community Ocean Model (FVCOM).

This report describes the development and use of a new sub-model covering the Clyde Sea area. Initial FVCOM modelling of this area was conducted by PhD student Alessandro Sabatino, who constructed a model that is described in his thesis (Sabatino, 2016) and in Sabatino et al. (2016). Unfortunately, due to licensing restrictions on the bathymetry used, and the need to use spherical (lat/lon) coordinates for consistency with other SSM components, it was not possible to adapt this model directly for use

within the SSM framework. Instead, it was used as a prototype, and a totally new model was developed with approximately the same open boundaries.

This report will describe the setup of the new model, including the data sources used and the processing applied to those sources, and the calibration and validation that has been performed. Appendix A provides instructions on setting up the model to run for different dates as a stand-alone model or nested within the SSM as a climatology. Specific instructions for time-specific nested model runs are not presented in this report.

Model Setup

In common the other SSM components, the Clyde model is implemented using the Finite Volume Community Ocean Model (FVCOM) code (Chen et al., 2003), in this case version 4.01. FVCOM uses a staggered finite volume approach to solve the Reynolds-averaged Navier-Stokes equations, in their shallow water form, under assumptions of incompressibility and optionally, as in this case, hydrostatic pressure. Horizontal spatial discretization is on an unstructured triangular mesh, while vertical discretization uses sigma layers.

Domain

The Clyde model covers a relatively wide domain, with the open boundaries in the same locations as Sabatino (2016): one to the north and west just north of the islands of Coll and Tiree, and one to the south and east south of the Isle of Man (

). The nodes at these open boundaries coincide with nodes in the shelf-wide SSM, in order to facilitate a wider variety of future nesting approaches.
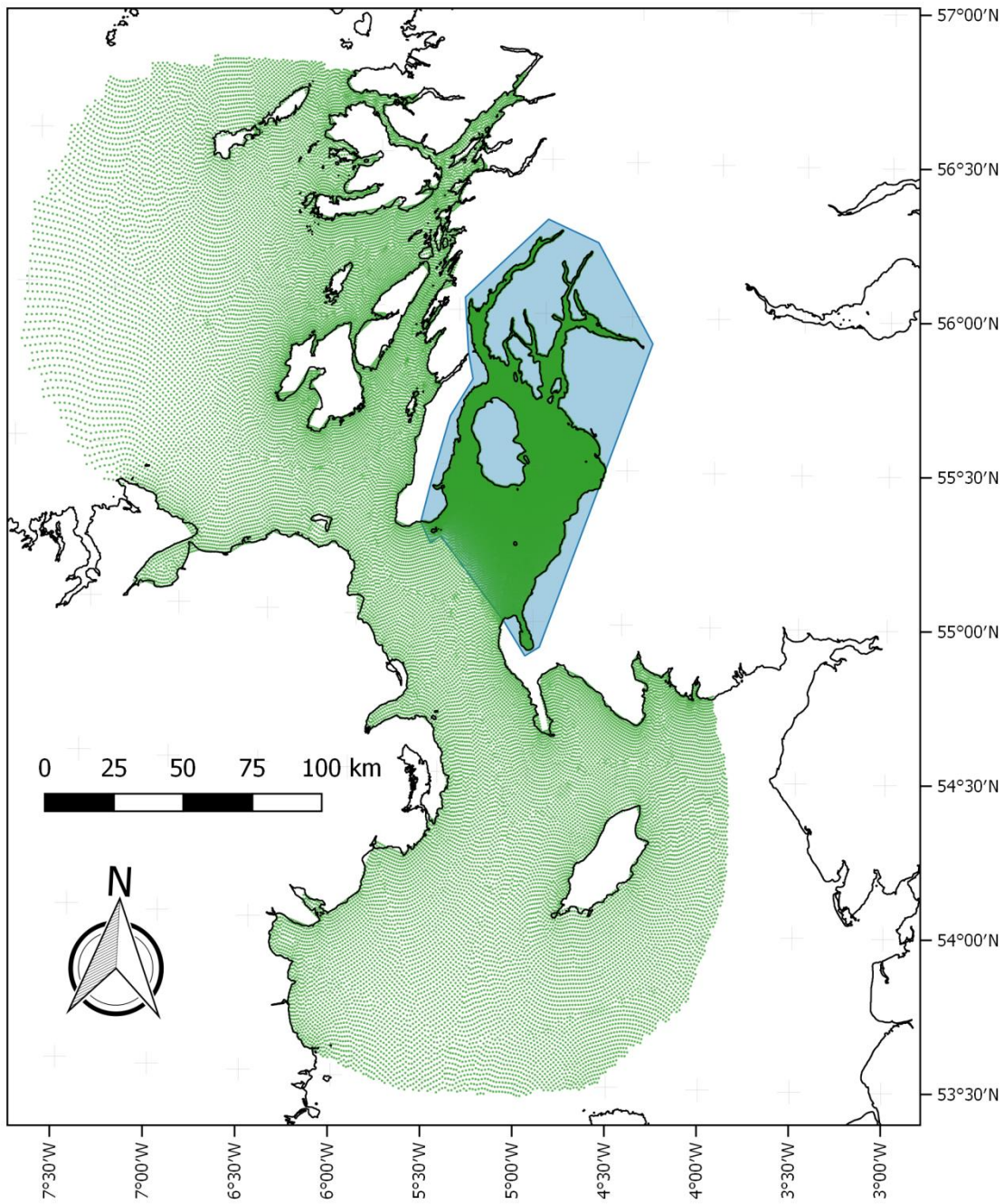
Figure 1: Map showing the full domain of the Clyde model (green dots represent mesh nodes) and the "inner Clyde Sea area" (blue shading).

The mesh is specified in spherical coordinates using the WGS84 geodetic coordinate system (EPSG ref 4326).

Coastlines

For the Scottish coast, a coastline supplied by colleagues from the Scottish Association for Marine Science (SAMS) was used. This coastline dataset is a good match to WGS84 and Google Earth (Google LLC) coastlines. The coast of the island of Ireland was taken from the global GSHHS dataset (Wessel and Smith, 1996). Note that outside the "inner Clyde Sea area" (see Figure 1) the choice of coastline in the present model is of little importance, as no new significant mesh development has been carried out there (see below).

Mesh

The mesh can be divided into two zones: an "inner Clyde Sea area" (Figure 1), defined as the area enclosed by the Kintyre and Galloway peninsulas to the north-west and south-east respectively, and an outer zone of the surrounding area. This inner zone (shaded blue in

) is the focus area from which model output.

The mesh for the outer zone is based on that of the wider-domain SSM, with minor alterations for mesh quality and to restore the channel between Islay and Jura (which is closed in the wider-domain SSM). Within the inner Clyde Sea area the mesh diverges from the SSM to offer higher resolution in the area of interest. To simplify integration into SSM outputs, there is a line of nodes across the entrance of the Clyde Sea which coincides exactly with wider-domain SSM nodes. The node numbers for this line are given in Appendix B.

The inner area was meshed using the SMS software[1] and then adjusted by hand to improve mesh quality. Typical triangle face lengths range from approximately 1 km at the interface with the wider-domain SSM mesh to 80-150 m in the inner parts of the estuary and sea lochs.

In the vertical, the model uses ten equally spaced sigma layers, similarly to other fine-resolution sub-models which are part of the SSM framework.

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[1] https://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction
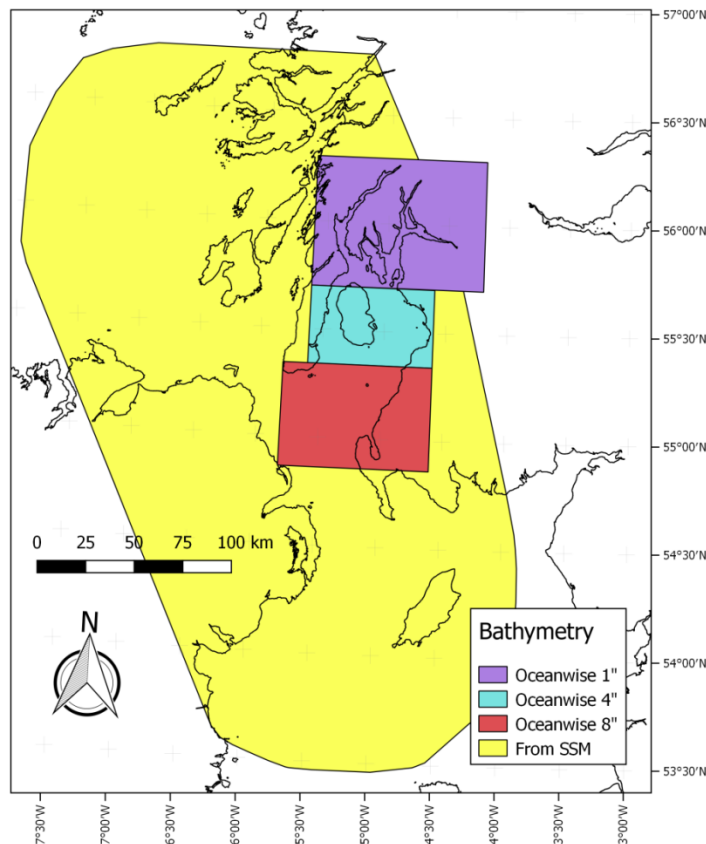
Bathymetry

Figure 2: Map showing the extents of the bathymetry sources used in various parts of the model domain.

Bathymetry for the model was obtained from two sources: In the outer zone it was imported directly from the wider SSM mesh, as this guarantees a good match in bathymetry at the open boundaries when nested within the wider SSM. Inside the Clyde Sea, the Oceanwise 1-arcsecond raster product was used, under the "Scottish Government Framework" license. An exemption from the standard license conditions was obtained to permit distribution of the model with this bathymetry incorporated. The Oceanwise data was datum-shifted from Chart Datum to mean sea level using the UKHO VORF gridded dataset (University College London, 2012). Following a visual inspection, some areas of clearly erroneous data were removed and the gaps interpolated over. The bathymetry was then aggregated to a coarser resolution in some areas to reduce the number of points to be processed. In all areas where a new mesh was used, the resolution of the bathymetry was at least twice that of the mesh. See Figure 2 for the areas in which different sources and resolutions were used.
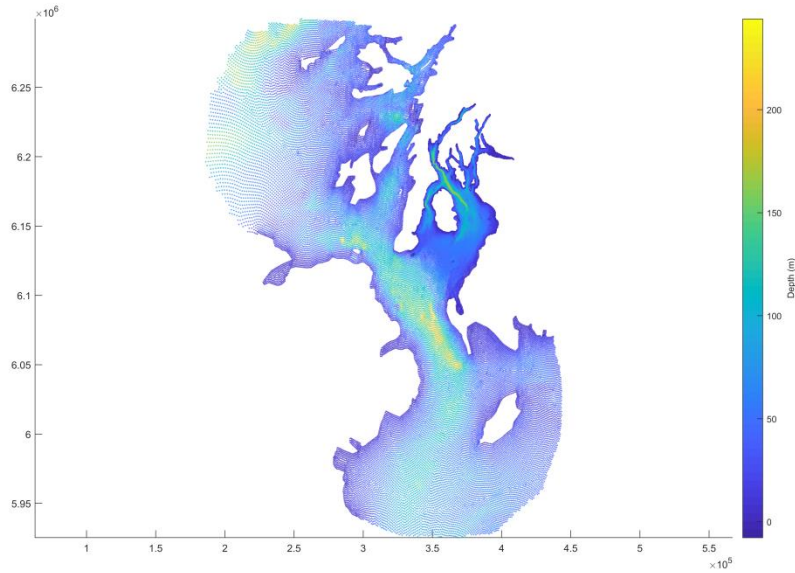
Figure 3: Plot showing model bathymetry on the model mesh. Each point is a mesh node. Spatial coordinates are in metres, using the UTM coordinate system zone 30N.

Bathymetry was interpolated to the model mesh using the Natural Neighbour algorithm (Sibson, 1980) available in the SMS software. **Error! Reference source not found.** shows the bathymetry interpolated onto the mesh.

Model Physics

Turbulence parameterisation uses FVCOM's standard approaches of the Smagorinsky and updated Mellor & Yamada methods for horizontal and vertical eddy viscosity, respectively. Tuning parameters on these turbulence models were kept at their default values. For full details, see the FVCOM documentation.

Seabed drag is implemented in FVCOM by applying quadratic drag to the bottom layer of the model. The value of the drag coefficient C_d is calculated by assuming a logarithmic boundary layer. Hence the bottom roughness is controlled by the user by setting the value of z_0 in the formula,

$$C_d = \frac{K^2}{\ln\left(\frac{z_{ab}}{z_0}\right)^2}$$

where $K = 0.4$ is the von Karman constant and z_{ab} is the distance from the seabed to the centre of the bottom layer of the model (Chen et al., 2013). Additionally, a floor is

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specified for the value of C_d to prevent it from becoming very small, or negative, in very shallow areas.

For this model z_0 was fixed at 0.01 m in outer areas to match the SSM, and smoothly transitioned over a distance of twelve mesh elements to a value of 0.001 m in the Clyde Sea (see Figure 3). The value of 0.001 m was arrived at through a calibration process (see section on calibration, below). The floor for the value of C_d was set to 0.0018.
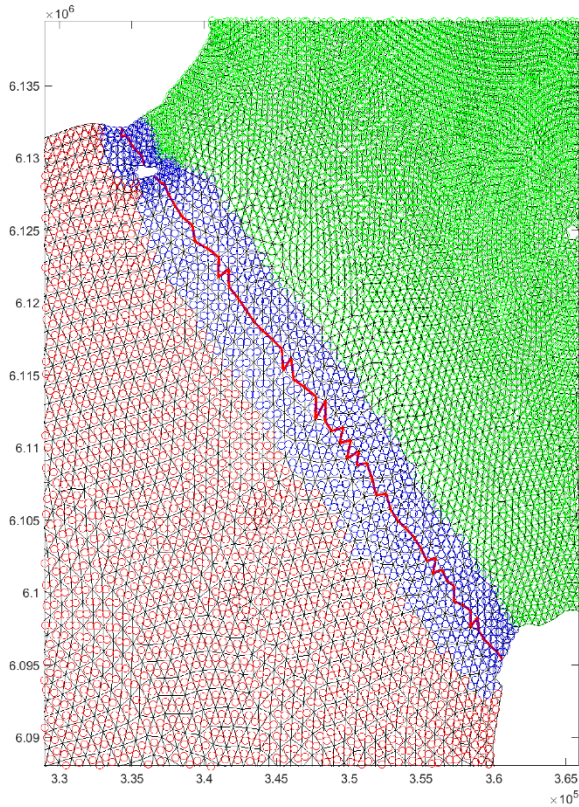

Figure 3: Map showing the zone, across the mouth of the Clyde Sea, used to smooth the transition between zones of different bottom roughness. Elements marked in red use z_0 = 0.01m, those in green use 0.001m, and those in blue are linearly interpolated between the two. Spatial coordinates are in metres using the UTM coordinate system zone 30N.

Open Boundaries

When run as a standalone model, open boundary conditions were sourced from the AMM7 model (Edwards et al., 2012) for sea surface level, currents, temperature and salinity. "Type 3 nested" forcing was used. This creates a transition zone in the outermost elements of the model where both the external forcing and the internal model influence parameter values, with varying weighting according to proximity to the boundary. See the FVCOM documentation (Chen et al., 2013) for more detail.

When run nested in the wider SSM, open boundary conditions were supplied by the SSM. Because nodes at the boundary are coincident with SSM nodes, "Type 1" nesting could be used, in which the values from the SSM are imposed on the open boundary of the Clyde model without interpolation or transition. However, testing with this approach produced poorer results than the Type 3 approach, and so use of Type 3 was continued. No sponge cells were used.

Other forcing

When running as a stand-alone model, meteorological forcing data (wind, precipitation and air pressure) were interpolated onto the model grid from the ECMWF ERA-Interim reanalysis, which has a 0.7° resolution. When running nested in the SSM, these data were interpolated from the SSM forcing files to ensure consistent inputs.

Solar heating is not currently included, but is planned for a future revision of the model. Fresh water inputs from 213 rivers are included based on "Grid-to-Grid" model (Bell et al., 2009) climatological output purchased from the Centre for Ecology & Hydrology, Wallingford. The daily discharge of these rivers is based on daily means from the years 1962-2011, which are predicted by a rainfall-runoff model with a 1 km resolution (Bell et al., 2009). Locations of the river mouths can be seen in Figure 4, and their discharge during the climatological year in Figure 5.

In the present version of the model, all rivers are set to have a fixed temperature of 10°C and salinity of 0 PSU. Both of these are likely to be incorrect most of the time, as temperature will vary through the year and the rivers enter the model well below their tidal limits. It is recommended that in future these fixed values should be replaced with monthly varying temperatures and more realistic salinity values.
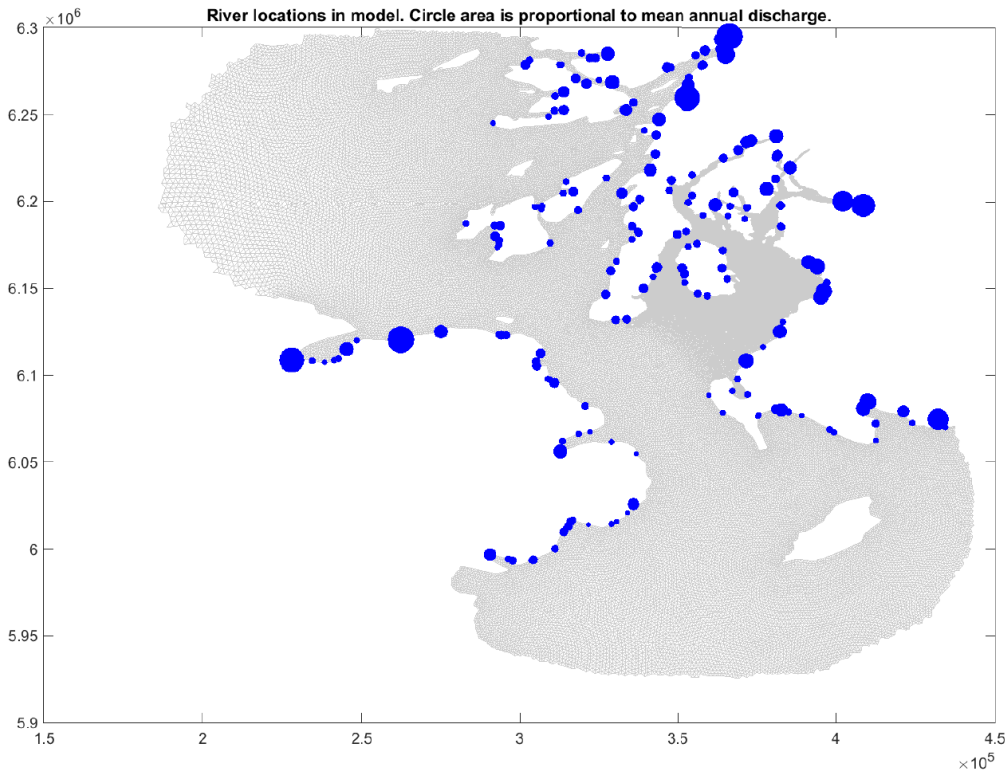
Figure 4: Locations of rivers entering the model. Areas of circles are proportional to mean annual discharge. Spatial coordinates are in metres using the UTM coordinate system, zone 30N.
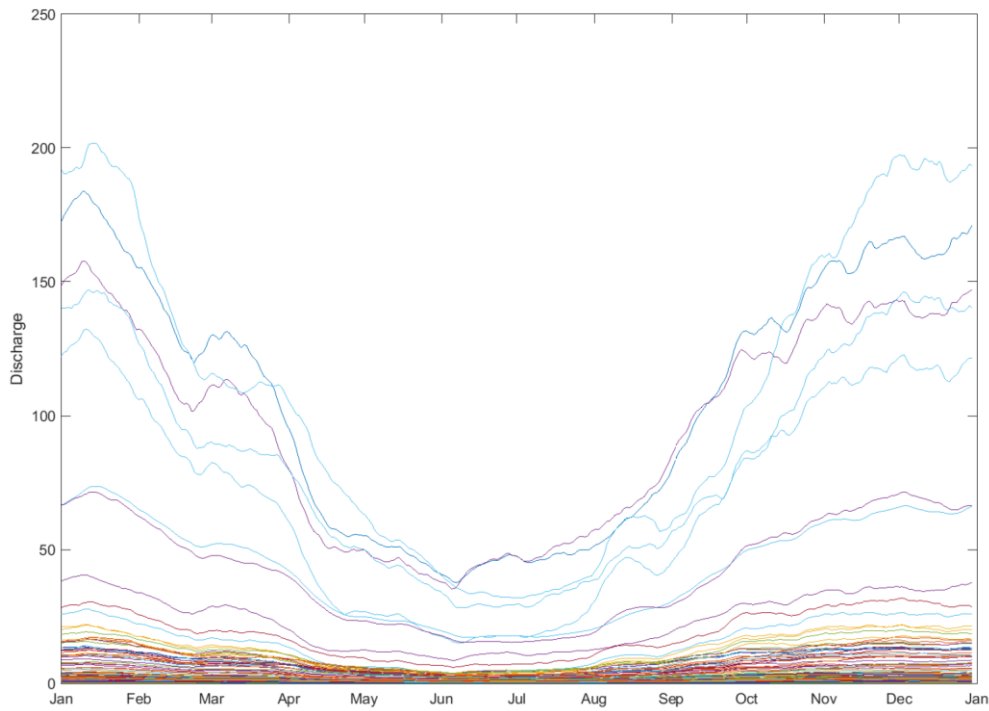

Figure 5: Changes in discharge (in m³/s) of rivers over the climatological year.

Initial Conditions

A "hot start" is used, with initial water level, current, temperature and salinity fields based on the AMM7 or SSM models for standalone or nested operation, respectively.

Numerical Options

To obtain numerical stability it was found necessary to use a relatively short timestep: 0.2 seconds for the external mode, and two seconds for the internal mode. Given additional time to experiment, it is possible that better runtimes might be obtained by increasing the external timestep while retaining the internal one, or by adjusting the mesh and/or bathymetry.

FVCOM's "scalar positivity control" was set to "on".

Calibration and Validation

Calibration was conducted by adjusting the bottom roughness in the Clyde Sea (the roughness in the outer parts of the model remained fixed at $z_0 = 0.01$m, as per the wider domain SSM). A barotropic version of the simulation was used, with only tidal forcing. It was determined by visual inspection that approximately 48 hours of spin-up was required for the model to behave realistically. Consequently, calibration runs were 16 days in duration, and the first two days of output were discarded.

Values of z_0 in the inner zone of 0.001, 0.002, 0.004 and 0.008 m were tested, and M2 phase and amplitude of water levels at Millport were compared with measurements. 0.001 m was selected as the closest match.

For validation, the full baroclinic model was run for two one-month time periods: November 2014 and October 2016. These months were chosen for the availability of both measurement data and AMM7 forcing data. In each case the model was run for two months and the first month's output discarded, to allow for some model spin-up. For locations of all validation data, see Figure 6. This validation should be taken as a preliminary one due to weaknesses that will be discussed below, and as such has only been undertaken on a visual, qualitative, basis.
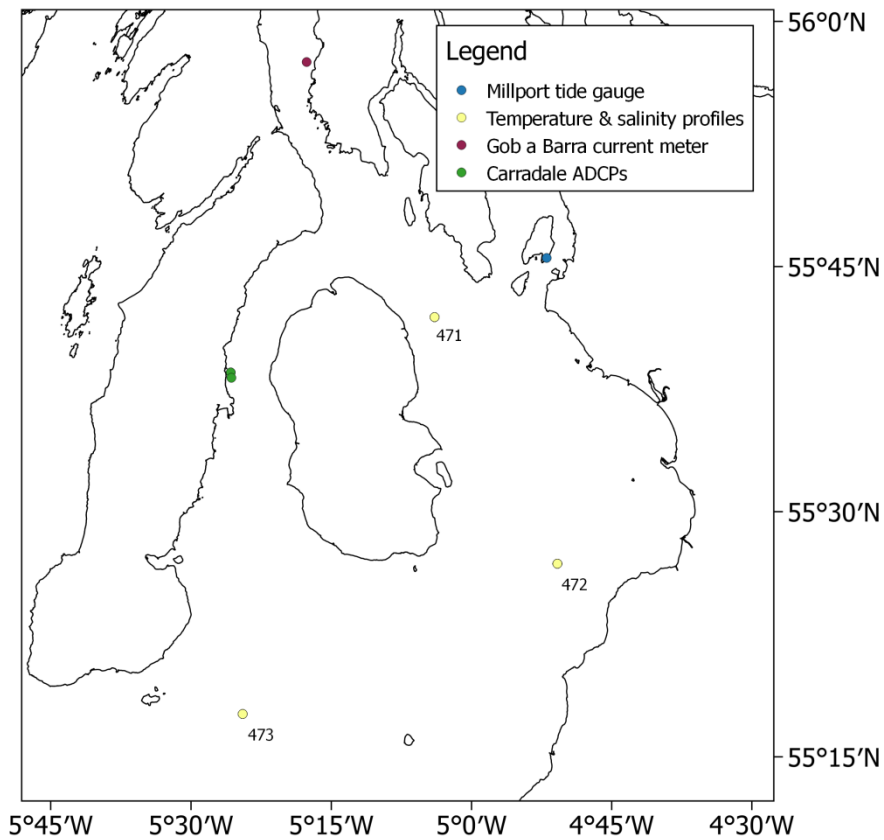
Figure 6: Locations of measurements used for validation.

Figure 7 shows a comparison of predicted and observed sea surface elevation at the Millport tide gauge. The match was judged to be acceptable. The horizontal line of points at the lower left of the plot reflects a difference in depth at this inshore location between the model bathymetry and the actual water depth at the tide gauge location.

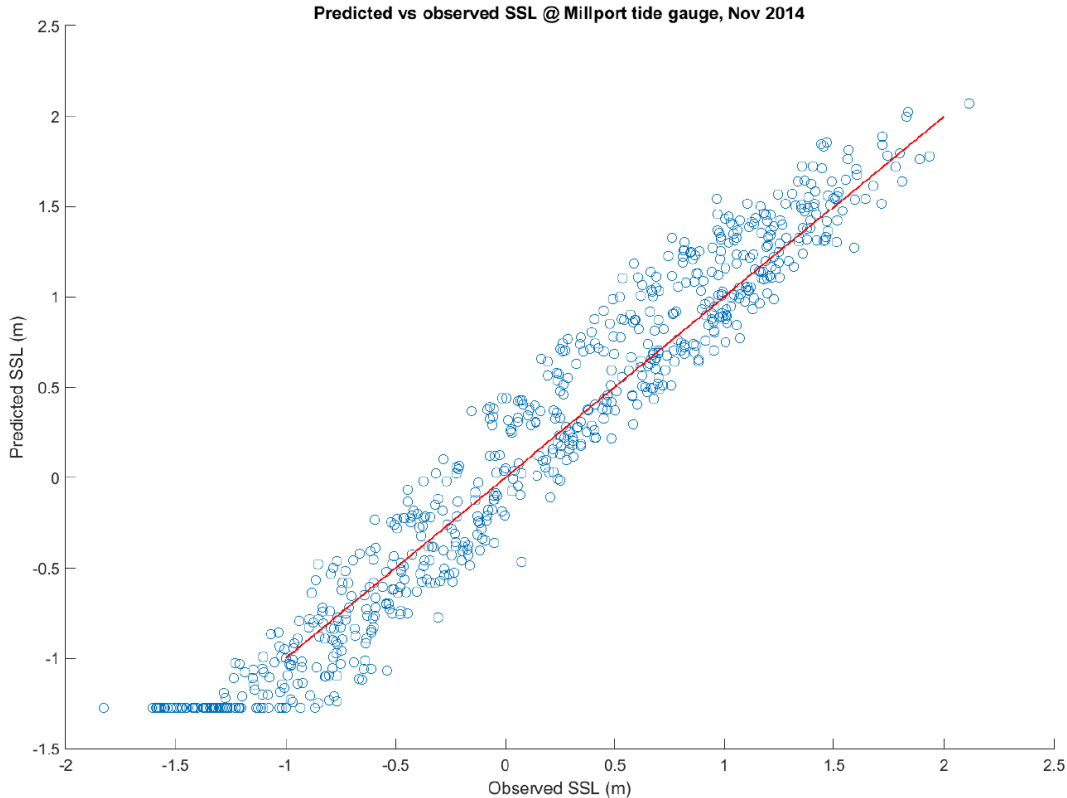Predicted vs observed SSL @ Millport tide gauge, Nov 2014

Figure 7: Scatter plot comparing predicted and observed values for sea surface level at Millport over the month of November 2014. All elevations are relative to mean sea level. Red line represents a 1:1 relation.

Figure 8 and Figure 9 show predicted vs observed velocity distributions over a month from two locations. The Gob A Barra site uses measurements from a proposed fish farm location, submitted to SEPA as part of its application for consent. There is a poor match, in that the model predicts velocity magnitudes of up to 0.2 m s^{-1} in two main directions, while the observed speeds rarely exceed 0.05 m s-1. One possible explanation for this discrepancy is that the proposed fish farm location is close inshore, and that it may be protected by the shore from wind and/or tidal influences.

The Carradale South site (Figure 9), in which predictions are compared to ADCP observations kindly provided by Mowi Scotland Limited (formerly Marine Harvest), shows a much better match, with a broad agreement on both magnitudes and directions. However, when we examine a time series from this location (Figure 10) we see that while the model is generally in phase with observations and – as the hodograph shows – produces a good distribution of amplitudes, it does not always correctly predict *which* speed peaks will be the faster and which the slower. Given the slow tidal velocities in this area, it is tempting to conclude that this is due to the use of

wind forcing, which is supplied on a 0.7° grid (approx. 45-75 km in this area) and hence is likely to be inaccurate for any precise measurement location. However, it is the shallow layer that shows the best match and the deep layer the worst, which is the opposite to what we would expect if this were the correct explanation.
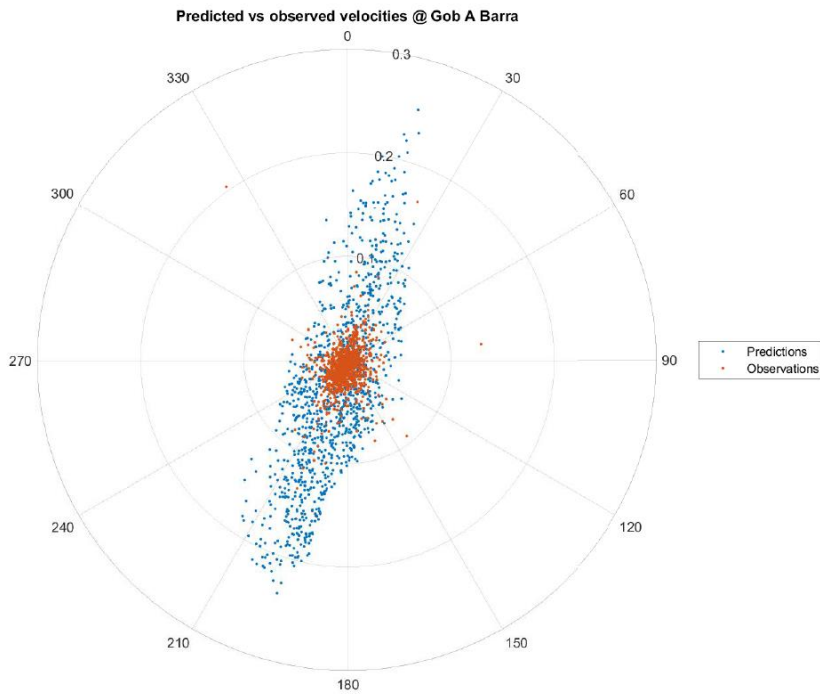

Figure 8: Hodograph showing predicted vs observed velocity distributions at location of Gob A Barra current meter during November 2014. Speeds (radial axis) are in m s-1. For station location, see Figure 6.

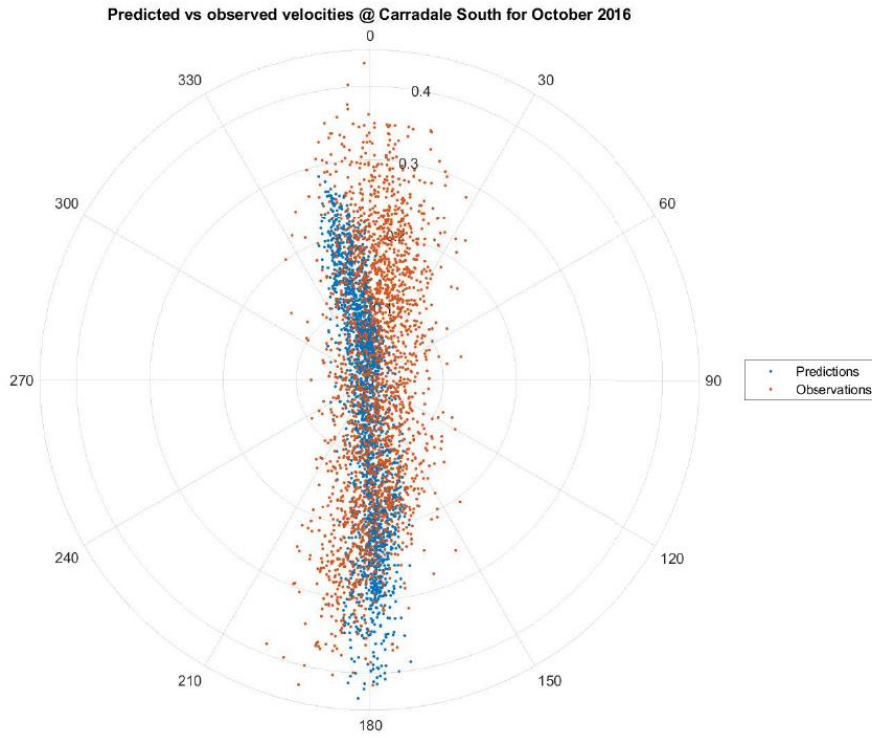Predicted vs observed velocities @ Carradale South for October 2016

Figure 9: Hodograph showing predicted vs observed mid-layer velocity distributions at location of Carradale South current meter during October 2016. Speeds (radial axis) are in m s-1. For station location, see Figure 6.
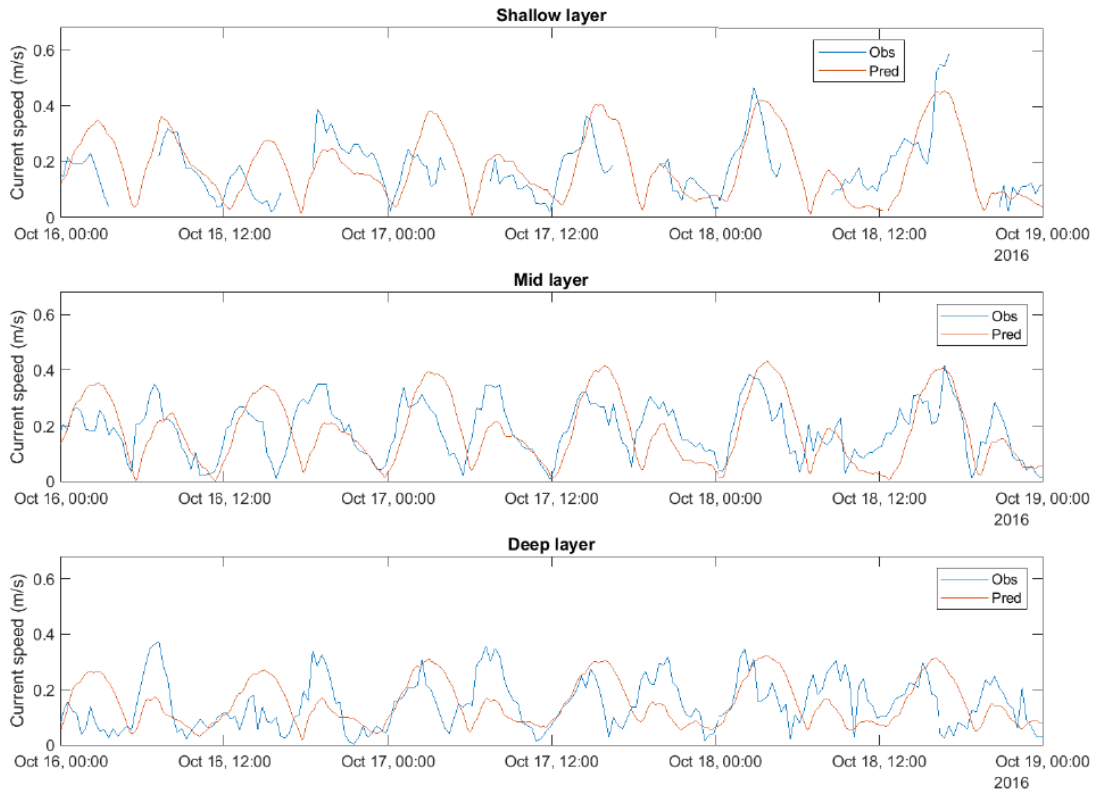
Figure 11 shows temperature and salinity profiles at three stations within the Clyde Sea during November 2014. The match here is encouraging, in that the changes in temperature and salinity with depth are well represented, including a clear thermocline at Station 473. The model does appear to be running about 2°C too warm, and it is clear that there is a difference between mesh and observed depths at Station 471. It is important to remember that for reasons of practicality only one month of model spin-up was allowed before the month in which these predictions were made, so temperature and salinity are likely to still be partially influenced by the initial conditions.
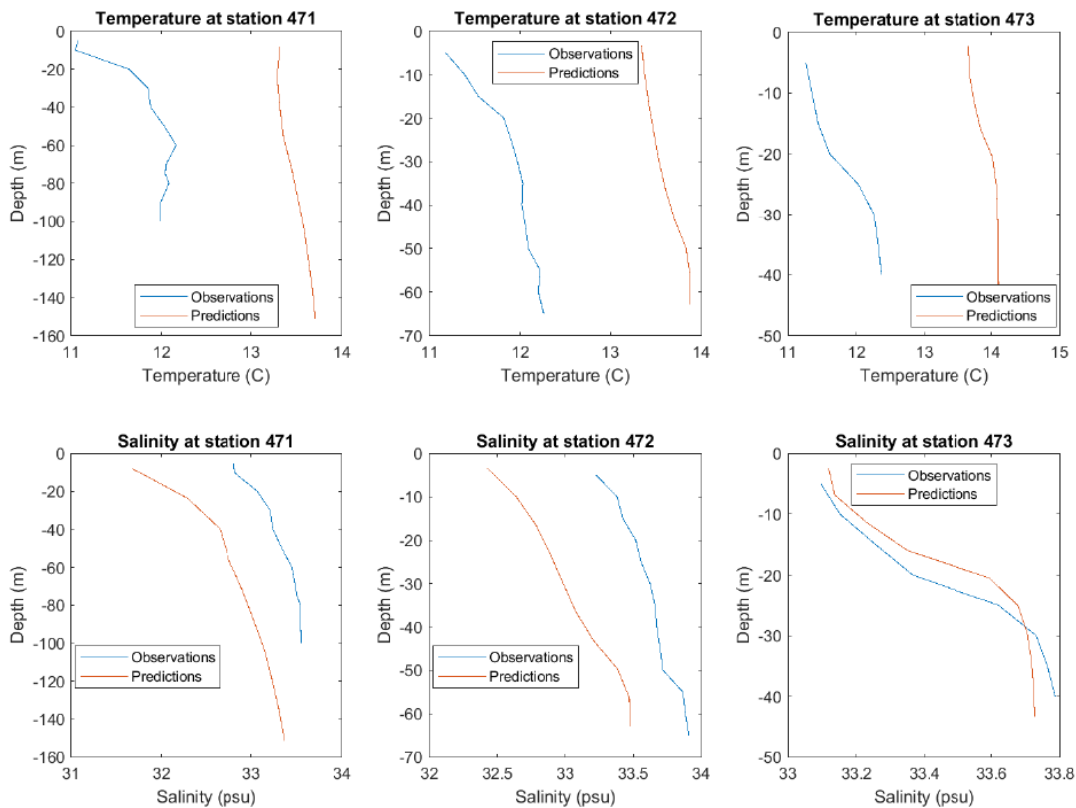
Figure 11: Comparison of temperature and salinity profiles at three stations at an arbitrary instant during November 2014. For station locations, see Figure 6.

Discussion and Future Work

At this point, with the relatively limited validation data available, we appear to have developed a model which correctly predicts the broad patterns and characteristics of water structure and circulation in the Clyde, and may give useful predictions for understanding the typical behaviour of the flow in a given area, but cannot yet be fully relied upon for predictions of specific points in time.

The area covered by this model includes narrow channels and steep-sided hills and mountains. Much of the area has extremely slow tidal velocities, and hence advection is heavily influenced by the wind, which in turn will be influenced by the topography. However, meteorological forcing is currently provided by the 0.7° grid of the ERA-Interim reanalysis – a resolution of approximately 45-75 km in this area. This may explain to a considerable extent the mixed validation results, although it is unlikely to account for all discrepancies.

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There are a number of improvements which should be considered for this model when future resources allow:

- Use of seasonally varying river temperatures. At present all rivers have fixed temperature and salinity. It would be relatively trivial to replace these with (for example) monthly varying values on a global basis if information could be obtained on the appropriate temperatures to use.
Because some of the rivers in this model come from mountainous areas with snow melt, and others do not, it might also be beneficial to specify different temperatures for different rivers if these data were available.
Salinity for the rivers should also be adjusted if appropriate data can be acquired. The current fixed value of 0 PSU is sure to be an underestimate, as the larger rivers enter this model well downstream of their tidal limits.
- Solar heating is not currently enabled in the model. Enabling this is recommended, and should improve accuracy.
- Open boundary forcing is based on hourly data. While this is more than sufficient for temperature and salinity values, an hourly frequency for tides means that the real peaks may be missed. More frequent forcing data, where available, would improve accuracy but would lead to considerably larger input files.
- As mentioned above, advection is heavily influenced by the wind, which is likely to vary on small spatial scales, but meteorological forcing is currently based on a low-resolution dataset. The use of finer resolution data or the output from of a dedicated atmospheric model for the region, such as a fine resolution implementation of the Weather Research and Forecasting (WRF) model (Michalakes et al., 2001), which would take topography into account, would undoubtedly improve accuracy.
- The recently-released ERA-5 reanalysis has a significantly better resolution than ERA-Interim. It is recommended that forcing of the standalone model should be converted to use this product, and that any future atmospheric model used should use ERA-5 (or similar resolution forcing) as its input.

Additional validation data is, of course, always desirable, and would allow a better assessment of the strengths and weaknesses of the model. Due to the relatively weak influence of tides and the strong effects of wind in the area of interest, harmonic analysis has proved to be of relatively little value in comparing measurements and predictions of velocities from different dates. Hence, while many historic current meter records are available in the region, they are of limited use when they predate the start of

AMM7 forcing availability in 2013, although harmonic analysis could still be used to extract the tidal harmonics from these records to carry out a tidal comparison. It would be of great value to obtain further modern current meter or ADCP records of suitable length in the area of interest, especially in more open water locations.

Acknowledgements

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Appendix A

Data Required for Standalone Use

- AMM7 instantaneous model output (i.e. not daily means) for sea surface height, currents, temperatures, and salinities. AMM7 data is available as "NORTHWESTSHELF_ANALYSIS_FORECAST_PHYS" on the Copernicus service at http://marine.copernicus.eu/.
- Meteorological reanalysis and forecast data from ECMWF (ERA-Interim is described here, but replacement with ERA-5 is recommended). For detailed instructions on what to download, see the Word document "Atmospheric forcing – what fields to download" in "preprocessing/4_MetForcing/" in the model directory.
- Either the commercial Grid2Grid river climatology data, or the "rivernodes.mat" file, distributed with the model, which contains the information required to generate river forcing files for this model for any given date.

Setting up for Standalone Use

1. Build FVCOM. This will not be covered here. Inspect the sample "make.inc" file that is included with the model files to check that the correct compile-time flags are enabled.
2. Work through the MATLAB scripts in the subfolders under the "pre-processing" folder in numerical order.
   \\svm-ml\Shelf_Model\FOC\Clyde_SW2_baroclinic\preprocessing
   1_Mesh and 3_bottomroughness can be skipped if these aspects of the model have not changed, but it will be necessary to run the other scripts to generate open boundary conditions, met forcing, river forcing and initial conditions for the desired dates. To generate initial conditions, first run the model for a single timestep at the desired start date with a cold-start and with a restart file saved immediately. Then use the script in 6_InitialConditions to insert the initial conditions for a hot-start into this restart file.

Data Required for Nested use within the SSM

- Wider SSM input and output files for the dates desired
- Either the commercial Grid2Grid river climatology data, or the "rivernodes.mat" file, distributed with the model, which contains the information required to generate river forcing files for this model for any given date.

Setting up for nested use

The scripts provided for nested use can be found under "FOC_1.03_Climatology".
\\svm-ml\Shelf_Model\FOC\FOC_1.03_Climatology

However, if the SSM has been run for a real period rather than a climatology then the same approach can be used to run the Clyde model for a real period as well.

1. Build FVCOM. This will not be covered here. Inspect the sample "make.inc" file that is included with the model files to check that the correct compile-time flags are enabled.
2. Work through the MATLAB scripts in the subfolders under the "pre-processing" folder in numerical order.
   \\svm-ml\Shelf_Model\FOC\FOC_1.03_Climatology\preprocessing
   1_Mesh and 3_bottomroughness can be skipped if these aspects of the model have not changed, but it will be necessary to run the other scripts to generate open boundary conditions, met forcing, river forcing and initial conditions for the desired dates. To generate initial conditions, first run the model for a single timestep at the desired start date with a cold-start and with a restart file saved immediately. hen use the script in 6_InitialConditions to insert the initial conditions for a hot-start into this restart file.

Appendix B

Node Numbers for Interface between New Mesh and SSM Mesh

The following nodes, which form a line across the mouth of the Clyde Sea, coincide exactly with nodes of the wider SSM. It is envisaged that this will be the boundary of the area that is used for output.

37200 37348 37494 37639 37784 37926 38062 38198 38344 38495
38653 38812 38964 39116 39266 39409 39553 39554 39552 39692
39691 39830 39968 40105 40242 40269 40409 40542 40544 40545
40543 40541 40540 40539 40538 40537 40536 40535 40534 40533
40532 40531 40530 40407 40387 40250 40133 40002 40001 40000
39999 39998 39867 39868 39731