Numerical Simulations of the Effects of a Tidal Turbine Array on Local Bed Shear Stress

Philip A. Gillibrand[1], Roy A. Walters[2] and Jason McIlvenny[1]

[1] *Environmental Research Institute, North Highland College UHI, Thurso – philip.gillibrand@uhi.ac.uk*
[2] *Ocean-River Hydrodynamics, Victoria, British Columbia, Canada*

Area being submitted to: 2) Numerical Hydrodynamic Modelling

Preferred presentation medium: (i) oral or (ii) e-poster format.

Are you a student?: No

Abstract

The extraction of energy from the coastal ocean by arrays of tidal turbines has the potential to impart a variety of environmental effects. A primary area of interest for marine energy has been the Pentland Firth in the north of Scotland, and its subsidiary channel the Inner Sound, where tidal current speeds regularly reach 5 m s^{-1}. One of the potential impacts of energy extraction is on local sediment dynamics Accurate sediment transport modelling is inhibited by a lack of detailed knowledge of local sediment deposits and transport in the area, but information on local sediment distributions in the Inner Sound is gradually being accumulated through multibeam [1] and sidescan sonar surveys [2,3]. Sediment banks are known to lie to the south of the island of Stroma but the local sediment dynamics, and the potential impacts of tidal energy extraction on the deposits, are only beginning to be understood. McIlvenny et al. [2] suggested that the local sediment banks in the Inner Sound have been locked in place for a significant period of time, with rates of sediment erosion and deposition expected to be low over the period. The tidal current velocities and the bed shear stress fields calculated by [2] using a 2D hydrodynamic model were largely consistent with the observed sediment distributions, with sediment banks lying adjacent to the main flow through the Inner Sound. However, depth-averaged modelled velocities, as used by [2], cannot be considered ideal to calculate bed shear stress fields.

In the current absence of real world commercial arrays, accurate and robust hydrodynamic models are an important tool to predict potential effects on the ambient environment prior to array development. In this presentation, we apply a three-dimensional (3D) hydrodynamic model [4] to consider the potential effects of energy extraction by an array of tidal turbines on the ambient flow and local bed shear stress in the Inner Sound of the Pentland Firth. Bed shear stress is a key parameter in the erosion of seabed sediment. Building on the 2D modelling work reported by [2], we extend the modelling study to 3D, thereby resolving the vertical structure of the flow and leading to better estimates of near-bed velocity and local bed shear stress during flood and ebb tides, and allowing better predictions of the potential changes to bed shear stress following the installation of tidal turbines.

The model solves the Reynold-averaged Navier-Stokes equations on an unstructured mesh using mixed finite element and finite volume techniques. Individual tidal turbines are represented through an additional form drag term in the momentum balance equation. The thrust imparted and power generated by the turbines is velocity dependent, with appropriate cut-in and cut-out velocities.

In the presentation, we describe the model, its application to the Inner Sound, and present some numerical predictions of the effects of introducing a tidal turbine array into the area.

Acknowledgements

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Numerical Hydrodynamic Modelling of the Clyde Estuary

Ted Schlicke, Gunda Wieczorek, Alan Hills

Oceanmet Unit, Scottish Environment Protection Agency – ted.schlicke@sepa.org.uk

Area being submitted to (delete as appropriate): 2) Numerical Hydrodynamic Modelling

Preferred presentation medium (delete as appropriate): (i) oral

Are you a student? (Delete as appropriate): No

Numerical Hydrodynamic Modelling is used within SEPA to help fulfil its regulatory duties and to meet its corporate goal of protecting and improving Scotland's environment. This typically involves using hydrodynamic model output to drive Water Quality models for predicting concentrations of Dissolved Oxygen and/or contaminants.

Development of a Delft3D model of the Clyde Estuary was funded by Scottish Water to help inform its investment program and ensure that the estuary meets the classification required under the Water Framework Directive. The model has subsequently been utilised by SEPA to better understand the hydrodynamic processes affecting water quality in the estuary and to investigate options for further improvements. Factors considered in this study include the effect of the location of sewage discharges, the impact of dredging and the role of river flow in flushing the estuary.

A new, higher-resolution MIKE3 model of the inner estuary is currently being developed to investigate the environmental conditions around the tidal weir that can lead to fish kills. Data analysis suggests that stratification of the estuary contributes to stagnation and the formation of pools of anoxic water during periods of dry, warm weather, which can pose a threat to the fish population, especially if followed by spills from storm overflows. This model will be used to investigate these processes in more detail, the possibility of changing the weir operation to improve flushing, and to help predict adverse environmental conditions in advance.

Three-dimensional characteristics of the tidal currents at the Pentland Firth

S. Baston & R.E. Harris

ICIT, Heriot-Watt University Orkney Campus. – S.Baston@hw.ac.uk

Area being submitted to (delete as appropriate) 2) Numerical Hydrodynamic Modelling; 3)

Preferred presentation medium (delete as appropriate): (i) oral

Are you a student? (Delete as appropriate): No

The Pentland Firth is the focus of the marine renewable development in Europe. Mainly because it has been identified as one of the more important areas for tidal energy extraction, but also because the first commercial array of tidal turbines has been consent at the Inner Sound.
Due to its complex hydrodynamic characteristics For the benefit of a successful development of this new economic sector, it is important to accurately predict the energy resource and sea conditions. In this work a three-dimensional SUNTANS model for the Pentland Firth is presented. Comparison of the Harmonic Analysis of the result with the Gardline ADCP shows a good correlation. Analysis of the velocity profiles indicates that at the Pentland Firth they fit better a $1/5^{th}$ law than the widely assumed $1/7^{th}$, which may have implications for the energy available at layers closer to the seabed.

The Pentland Firth is the focus of the marine renewable development in Europe. Mainly because it has been identified as one of the more important areas for tidal energy extraction in the UK (Carbon Trust and Black & Veatch, 2005), but also because the first commercial array of tidal turbines has been consent at the Inner Sound (MeyGen website, 2013).

Modelling hydrodynamics of the Pentland Firth is not easy because combination of fast tidal races and large waves coming from the Atlantic Ocean implies the presence of non-linear processes. Many attempts of modelling this channel have been done in order to assess its energy resource (Easton et al., 2012; Adcock et al., 2013; Draper et al., 2014; Martin-Short et al., 2015), but all of them are 2D, i.e. they are not resolving velocities through the water column.

In this paper a three-dimensional 30 days simulation using the SUNTANS model is presented. SUNTANS stands for Stanford Unstructured Non-hydrostatic Terrain-following Adaptive Navier-Stokes Simulator, a code developed by Stanford University (Fringer, 2007). Rationally behind this model choice will be explained. Principal axis variance (PAV) and comparison of velocity through the water column between ADCP data and model outputs show that the model is able to reproduce tidal stream characteristics at the Pentland Firth accurately. Looking at variations of tidal currents with depth, it is noteworthy that velocity profiles in this energetic channel are not following the $1/7^{th}$ law, it was founded that they fits better to a $1/5^{th}$ law.

Discussion of the results will focus on the sensitivity analysis of the bottom friction coefficient, which was not undertook in this work. Proposed future work is the implementation of the non-hydrostatic capability of the model in order to resolve more precisely the vertical accelerations, which are presumed important at the Pentland Firth given the presence of pits on the seabed.

Acknowledgements: This work was funded by the SFC SRDG (MReDS, 2007-2013[G1]). Main author is now involved in a Knowledge Transfer project funded by EPSRC.

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West Scottish Coastal Ocean Modelling System and Environment Impact Studies

Dmitry Aleynik[1]
[1] *Physics and Technology Department, Scottish Association for Marine Studies (SAMS)* – Dmitry.Aleynik@sams.ac.uk

Area being submitted to: 2) Numerical Hydrodynamic Modelling

Preferred presentation medium: (i) oral format.

Are you a student? No

The encounter between economy growth and continuously changing global ocean takes place within a narrow (~100 km wide) stripe along the coastline. Reliable hydrodynamic predictions with adequate resolution of the shelf and coastal sea along the West Scottish coast, which is densely indented with multiple sea-lochs, fjords, thousands islands and mountainous terrain is possible with flexible and scalable unstructured grid modeling approach that we developed and run at SAMS on massively parallel computer architectures. The West Scottish Coast Modeling System (WSCOMS)[1] seamlessly fills the linkage gaps between coastal, shelf and deep ocean models and includes the operational forecast with Atmospheric (WRF[2]) and the hindcast Ocean (FVCOM[3]) dynamic core components capable to predict flows at the unprecedented high (up to tens of meters) resolution in the key areas (Fig.1). WSCOMS is a fundamental tool for Environmental Impact Assessment related to natural hazards such as heavy storms accounted as 15% of time annually (Fig. 2), Harmful Algae Blooms affecting the shellfish[1] farms, sea-lice dispersal with implications on both natural habitat and finfish[4] aquaculture sector, sea-animals protection measures associated with renewable energy constructions[5] (tidal and waves turbines), as well as urgent response to marine pollution risks in a result of spontaneous sea-traffic incidents (Fig. 1).

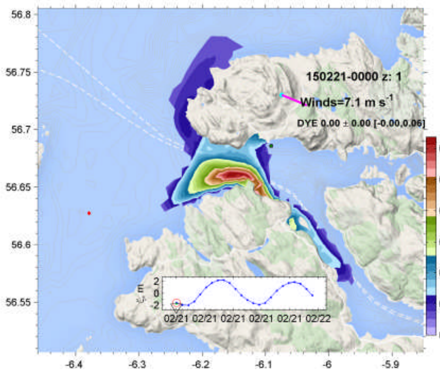

Fig.1. Diesel spill forecast with WSC-FVCOM, 'Lysblink Seaways' grounded in Sound of Mull, 02.18 - 02.23, 2015.

Acknowledgements

The development and maintenance of the West coast modeling system is currently supported by BBSRC/NERC Grant #BB/M025934/1, and EU HORIZON 2020 Aquaspace Project #633476.

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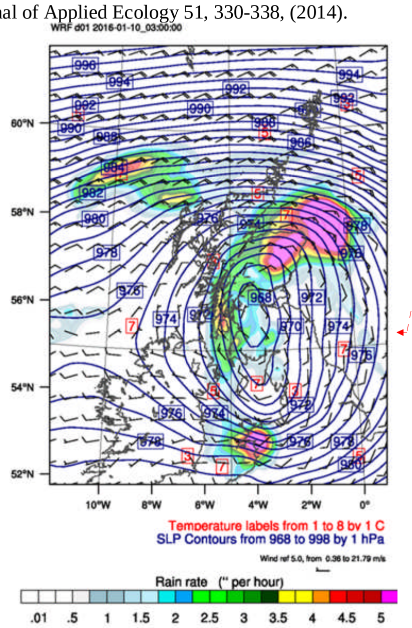

Fig. 2. SAMS Weather Research Forecast model example.

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Interaction between surface buoyancy filament and a deep vortex

Jean N. Reinaud[1], David G. Dritschel[2] and Xavier Carton[3]

[1] *School of Mathematics and Statistics, University of St Andrews. – jean.reinaud@st-andrews.ac.uk*
[2] *School of Mathematics and Statistics, University of St Andrews. – david.dritschel@st-andrews.ac.uk*
[3] *Laboratoire de Physique des Océans, Université de Bretagne Occidentale. – xcarton@univ-brest.fr*

Area being submitted to (delete as appropriate): 2) Numerical Hydrodynamic Modelling

Preferred presentation medium (delete as appropriate): (i) oral

Are you a student? (Delete as appropriate): No

Modern satellite imagery and sea surface altimetry are providing an increasingly accurate picture of the dynamics of the ocean surface. Details of the dynamical structures evolving at depth are less observable. Nevertheless, nonlinearity implies that the dynamics of the surface and the interior are coupled.

We investigate the interaction of a buoyancy anomaly distribution at the surface of the ocean and of a potential vorticity distribution in the interior of the ocean. The work is performed within the framework of the quasi-geostrophic model which is a well-established and accurate model for the oceans mesocales. The governing equations are solved using a version of the Contour-Advective Semi-Lagrangian algorithm (CASL), where buoyancy and potential vorticity are advected explicitly in a Lagrangian manner, while the inversion procedure to obtain the advecting velocity field is done on an Eulerian grid. In this presentation we propose the study of a surface buoyancy filament and a single spherical vortex at some depth. The filament has an elliptic distribution of buoyancy leading to a continuous velocity field. The maximum buoyancy is b_m, and the width of the filament is denoted a. The internal vortex consists initially of a sphere of radius r of uniform PV anomaly q, located at a horizontal distance of 2r from the axis of the filament and at a depth of 2H. The interaction between the two structures depends on the ratio of two time scales associated with the flow L $= b_m/(qa)$ as well as the relative separation both in the horizontal and in the vertical directions between the filament and the vortex.

The filament and the vortex induce shear onto one another. Depending on the relative sign of the buoyancy anomaly and the potential vorticity anomaly, the shear may be in the same direction (cooperative shear) or in opposite direction (adverse shear). One of the first features of the interaction is that buoyancy anomaly tends to be expelled from the region at the surface lying above the vortex in adverse shear cases, whereas some buoyancy anomaly accumulates in this region in the cooperative shear cases. This is due to the nature of the Kelvin-Helmholtz type instability that the filament undergoes. It is shown that the filament breaks up in all cases as a result of its unstable characteristic, producing a plethora of small scale structures and thinner filaments at the surface. It is also shown that an intense filament may shear out the internal vortex. Adverse shear is significantly more destructive than cooperative shear, as illustrated in figure 1.

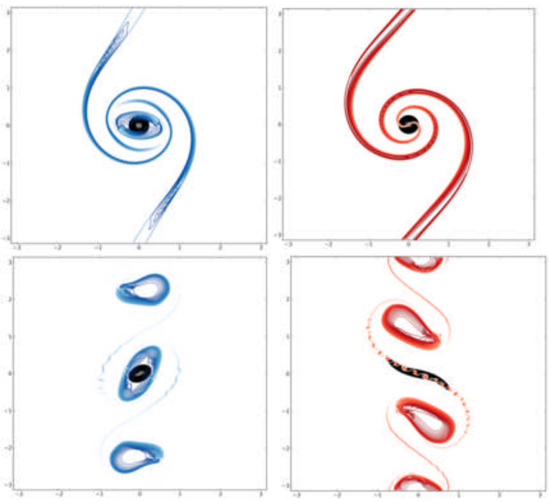

Figure 1: Top view on the surface buoyancy filament (blue for cooperative shear, red for adverse shear), and deep vortex (black) with q=2p, r=0, H/a=2, and r/a=1. From left to right: L =0.04 at t=600, L=-0.04 at t=600, L =4 at t=17.5, L =- at t=17.5.

Numerical investigation of the effects of tidal energy extraction in the Goto Islands, Japan

Simon Waldman[1], Soichi Yamaguchi[2], and David Woolf[1]

[1] *International Centre for Island Technology, Heriot-Watt University (Orkney campus) – smw13@hw.ac.uk*
[2] *Department of Earth System Science and Technology, Kyushu University, Japan*

Area being submitted to (delete as appropriate): ; 2) Numerical Hydrodynamic Modelling;
Preferred presentation medium (delete as appropriate): (i) oral
Are you a student? (Delete as appropriate): Yes ~~/ No~~

The Goto Islands, in south-west Japan, experience strong tidal currents through four parallel channels (Figure 1). Work is in progress to set up a marine energy test centre there similar to, and advised by, EMEC in Scotland. Two of the channels have been designated by the government for full-scale tidal energy development, and the first turbine is due to be installed in 2018 (Shankleman / Bloomberg, 2016).

Kyushu University previously developed a hydrodynamic model of these isles using the FVCOM modelling software. This model represents the existing flow well (see Figure 2, also Sun *et el.*, (2014) and Garcia Novo & Kyozuka, (in press)), but it does not include representation of tidal turbines.

This talk will relate the outcomes of collaborative work being conducted this summer on a MASTS-funded research exchange in Japan. The Goto Islands model has been updated to run in the latest version of FVCOM, and code developed by Marine Scotland Science has been used to successfully implement large-scale tidal energy extraction. Upcoming work will simulate tidal arrays in single and multiple channels in the archipelago, investigating both their effects in the channels containing turbines and the effects in other channels.

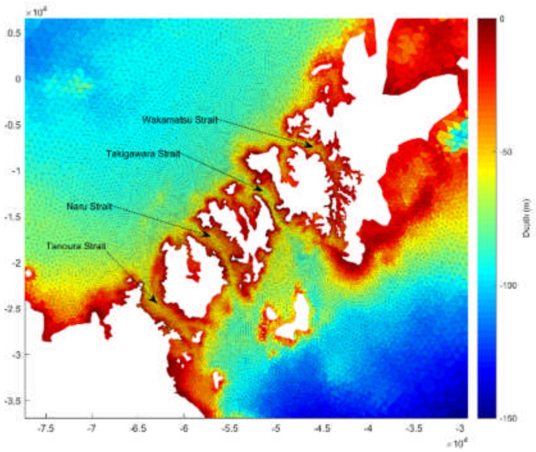

Figure 1: Detail of the central part of the FVCOM model showing the bathymetry, the computational mesh and the layout of the four tidal channels. Figure: Authors.

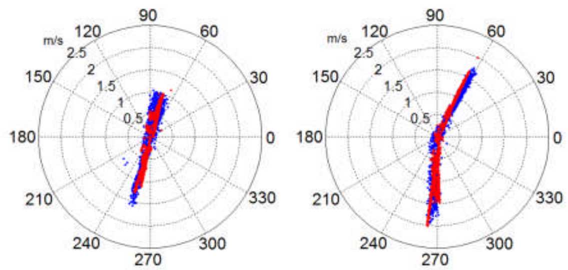

Figure 2: Sample hodographs showing validation of model through comparison of bottom (left) and surface (right) layer velocities in the Wakamatsu Strait. Red represents model predictions and blue shows measurements. Figure: Garcia Novo & Kyozuka (in press).

Results will be presented showing the interactions between the parallel channels, and providing a new estimate for the energy potential of the islands at different levels of exploitation.

Acknowledgements

This work was made possible by the MASTS PECRE research exchange scheme. We thank Prof. Changhong Hu of Kyushu University for hosting the exchange and acknowledge Dr. Huihui Sun, formerly of Kyushu University, whose model was used as a starting point. Further thanks are due to Rory O'Hara Murray of Marine Scotland Science for permitting the use of his code for energy extraction in FVCOM.

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Modelling for regulation in aquaculture

Andrew Berkeley[1]

[1]OceanMet Unit, Scottish Environment Protection Agency - andrew.berkeley@sepa.org.uk

Area being submitted to: Numerical Hydrodynamic Modelling

Preferred presentation medium: oral

Are you a student? No

The growth of the aquaculture industry in Scotland over the past couple of decades has resulted in increased pressures on the marine environment and challenges for environmental regulation. In particular, established forms of regulatory modelling for the aquaculture industry have proved too simple to deal with many of the environmental and operational complexities and are unable to address questions pertaining to waterbody-scale impacts and the potential for interaction between discharges from multiple sources.

In order to address these challenges SEPA is adopting a wider range of modelling technologies and approaches. These include the use of a newly re-developed version of the particle tracking model *AutoDepomod*, which contains a number of improvements over its predecessor and is considered primarily suitable for understanding seabed impacts in the immediate vicinity of aquaculture sites. In addition, the use of numerical hydrodynamic modelling (NHM) techniques is a significant new step in the regulation of the aquaculture industry. SEPA has started to apply NHM methods to strategic policy questions and to develop requirements and guidance for the use of NHM in obtaining discharge licenses in the aquaculture sector specifically. This step will improve SEPA's ability to assess risks to the wider marine environment, including "far-field" benthic impacts and the cumulative effects of multiple farms operating the same water body. The adoption of NHM techniques will be crucial for ensuring that the expansion of the industry is environmentally sustainable.

Modelling Atlantic salmon (*Salmo salar*) post-smolt dispersal from Scottish shores

James Ounsley[1], Alejandro Gallego[3], Graeme Ruxton[2], David Morris[3] and John Armstrong[3]

[1] *Department of Biology University of St. Andrews – jpo2@st-andrews.ac.uk*
[2] *Department of Biology University of St. Andrews*
[3] *Marine Scotland Science*

Area being submitted to 2) Numerical Hydrodynamic Modelling;

Preferred presentation medium (i) oral 2-3 minute pitch

Are you a student? No

Wild Atlantic salmon populations have recently experienced substantial decline across their range (Boisclair 2004). Salmon support fisheries, contributing substantially to the rural economy, and are of high conservation importance, protected under the EU Habitats Directive. Mortality is believed to be largely density-independent during the post-smolt period, when individual salmon move from their natal river habitats into the open-ocean, and hence directly influences fisheries and numbers of spawners. The sustainable development of coastal industries, including aquaculture and marine renewable energy, requires an understanding of potential effects on salmon populations. A fundamental requirement is greater understanding of the migratory behaviour and marine distribution of Atlantic salmon smolts both as a component of impact assessments and to facilitate effective marine spatial planning.

Detailed data on the migratory behaviour of Atlantic salmon are hard to obtain given the difficulty (e.g. due to their small size) and high cost of tracking and sampling populations at sea. However numerical modelling approaches offer the potential to leverage sparse data in order to make general inferences about the geographical distribution of migratory species (Moriarty 2016). We aim to use an agent based biophysical model to identify plausible migratory paths for populations of salmon migrating from multiple origins around the Scottish coast. Our approach will utilise the recently developed Scottish Shelf model (SSM) – an unstructured grid, high resolution hydrodynamic model of Scottish waters. Within this system, we will track the spatial-temporal distribution of notional salmon modelled as simulated agents. The movement of each agent will be jointly influenced by both its dispersion behaviour and the complex forcing of the SSM. For robustness a range of different hydrodynamic and behavioural scenarios will be considered.

Existing empirical data on salmon swimming speeds and data from tracking studies will be used to parameterise and validate the model. In addition it may be possible to test some of the model predictions through targeted field experiments and surveys.

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Optimal-detail circulation models for fjords and sea lochs

Soizic Garnier[1], Neil Banas[2]

[1] *Department of Mathematics and Statistics, University of Strathclyde, Glasgow, UK – soizic.garnier@strath.ac.uk*
[2] *Department of Mathematics and Statistics, University of Strathclyde, Glasgow, UK*

Area being submitted to Numerical Hydrodynamic Modelling

Preferred presentation medium oral

Are you a student? Yes

A new fast and flexible numerical circulation model for estuaries with fjord-like geometry is being developed. The approach involves a compromise between the simple box model, which allows fast simulation although poor detail, and the three-dimensional simulation which grants high resolution of the estuary topography but is computationally expensive. In order to resolve the vertical and longitudinal structure of the dominant physical processes, the model includes a fixed Cartesian grid. It averages the momentum equation and salinity conservation over the channel cross-section and the tidal cycle to improve speed-efficiency.
The momentum equation is solved analytically with a quasi-steady condition on the circulation velocity used by Hansen and Rattray (1965). However, the solution for the salinity conservation is numerically computed and takes in to account the adjustment time for the salinity as developed by MacCready (2007). This reflects the regional dynamic conditions and climate variabilities of the estuarine circulation . This implementation allows the evolution of estuaries over multi-decadal time-scales to be studied realistically, efficiently and is easy to adapt to different scenarios. This circulation model will also provide a physical base which can be coupled with a biochemical model to answer marine ecological questions concerning fjords. A first application to the Puget Sound, Washington, USA will help discern the reasons driving the large decline of wild salmon in this estuary. Moreover because of its flexibility, future plans include applications to nutrient loading in Scottish sea lochs.

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Biophysical modelling of fjords and sea lochs

Hoa T. T. Nguyen[1], Neil S. Banas[2], and Nicholas A. Kamenos[3]

[1] *Department of Mathematics and Statistics, University of Strathclyde, Glasgow G1 1XH, Scotland* – nguyen-thi-thai-hoa@*strath.ac.uk*
[2] *Department of Mathematics and Statistics, University of Strathclyde, Glasgow G1 1XH, Scotland*
[3] *School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, Scotland*

Applied biophysical modelling to understand responses of regional ocean ecosystem to global change such as climate change and ocean acidification is crucial for future predictions and adaptation planning. Numerous biophysical models have been being developed, and although all these models were built based on the same theoretical backgrounds and frameworks, they are widely different in number of state variables as well as parameters and therefore results interpretations. This study takes advantage of recent advances in estuarine physical modelling to conduct unusually comprehensive sensitivity analyses of two problems in marine biogeochemistry of fjord-like geometries:

(1) Trends in primary production in Puget Sound, USA. Wild salmon in Puget Sound have shown a long-term decline, and their marine survival correlates with decadal climate patterns, but for unknown reasons.

(2) Experiments in Loch Sween, Scotland suggest that coralline algae are highly responsive to dissolved CO2, but it is unclear to what extent their nutrient cycling could drive trends in carbon chemistry (pH, corrosiveness to calcium carbonate) that are significant relative to circulation trends and variability.

Based on fast-running, easy to build and refine physical model, hundred of thousands of variants of a common planktonic nutrient-cycling model for each application will be run with variation of both internal and physical drivers parameters. Then, by carrying out parameter identification procedures which include parameter sensitivity analyses, parameter estimation and parameter identifiability analyses, processes and parameters that are not constrained by observations will be removed. By this, simple model and nearly optimal parameter combinations will be achieved, and allow the study to answer question "Given the limited types of data available to constrain such models, which unmeasured state variables/fluxes should be regarded as robust predictions, and which are essentially unconstrained?"

Area being submitted to : 2) Numerical Hydrodynamic Modelling;

Preferred presentation medium : (i) oral (short 2 – 3 minutes)

Are you a student? : Yes

Comments on submission: I know that the session – Numberical Hydrodynamic Modelling to which I would like to submit the abstract, has a different emphasis. However, my work will be based on output of numerical circulation model will be developed from the project titled "Optimal-detail circulation models for fjords and sea lochs" (Soizic Garnier's work). And I would think that, if Soizic Garnier's and my abstract are both accepted, and if my talk comes after Soizic's, it would provide a broad view of our project as well as a valuable multi-discipline case study.