MASTS Numerical Hydrodynamic Modelling Workshop,

Grassmarket, 86 Candlemaker Row, Edinburgh, EH1 2QA

Friday 11th March 2016.

Report

Summary

- The workshop was attended by 30 people, representing seven MASTS partner institutes (including Heriot-Watt University, Marine Scotland Science, the University of St. Andrews, the University of the Highlands and Islands, the University of Strathclyde, the University of Edinburgh and the University of Dundee) and SEPA.

- The workshop was funded by the MASTS Numerical Hydrodynamic Modelling Forum.

- Thirteen oral presentations were given (see programme below). Subjects ranged from numerical methods for hydrodynamic models to direct application of models to issues such as tidal energy, water quality and deep sea eddies, the Scottish Shelf Model, and coupled bio-physical modelling of biological dispersal. Thus a range of aspects of marine science, either directly focussed on or related to hydrodynamic modelling, were presented. This is a key objective of the Forum, to both promote HD modelling and to facilitate uptake of model outputs by other marine scientists.

- The workshop brought together a diverse group of Scottish marine scientists, younger and more experienced, with enough shared interest to make the event a useful networking opportunity. The event was attended by a number of post-graduate students, giving them opportunity to make contacts and discuss modelling issues with more experienced researchers.

- Three e-posters were also on display for viewing during coffee and lunch breaks.

- Abstracts from all the presentations are included below.

Programme

9:00-9:30	Coffee & Registration
9:30-9:40	Welcome and opening remarks: Philip Gillibrand
Session 1	*Chair: Ted Schlicke*
9:40-10:00	Mark Williams: Modelling and Data Analysis to understand Dissolved Oxygen Impacts in the Forth Estuary.
10:00-10:20	Susana Baston: Modelling energy extraction at the Pentland Firth.
10:20-10:40	Philip Gillibrand: A mass-conserving advection scheme for offline ocean scalar transport models.
10:40-11:00	Magda Carr: A combined Lagrangian advection method for modelling geophysical fluid dynamics.
11:00-11:30	**Coffee Break**
Session 2	*Chair: Rory Murray*
11:30-11:50	Ted Schlicke: Modelling of Marine Environmental Quality.
11:50-12:10	Paul Tett: What do marine community ecologists need from hydrodynamic models?
12:10-12:30	Ana Rodriguez: Shellfish restoration: Marine protected areas and built structures.
12:30-1:30	**Lunch Break**
Session 3	*Chair: Angus Creech*
1:30-1:50	Alejandro Gallego: An FVCOM unstructured-grid hydrodynamic model of Scottish shelf waters – the Scottish Shelf Model.
1:50-2:10	Rory O'Hara Murray: Maximizing the tidal stream energy potential of the Pentland Firth using a 3D hydrodynamic tidal model.
2:10-2:30	Dima Aleynik: Modelling Eddy Influence on Abyssal Currents in the Tropical Pacific with Application to Plumes Generated by Deep-Sea Mining.
2:30-3:00	**Coffee Break**
Session 4	*Chair: Dima Aleynik*
3:00-3:20	Angus Creech: Modelling tidal flows: a non-hydrostatic approach.
3:20-3:40	Alan Fox: A particle tracking modelling study of the inter-annual variability of connectivity in Lophelia pertusa reefs in Scotland’s marine protected area network.
3:40-4:00	Michael Bedington and Tom Adams: Applications of Lagrangian hydrodynamic models in biology: a matter of life and death.

Talks are 15 mins plus 5 mins for questions and switch over.

E-Posters

Philip Gillibrand: Eddy Generation and Shedding in a Tidally Energetic Channel

Charles Greenwood: The Simulation of WECs with Boussinesq and Spectral Wave Models

Heng Lu: Modelling of a new type of wave maker for tsunami research.

Applications of Lagrangian hydrodynamic models in biology: a matter of life and death

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Finite Volume hydrodynamic modelling has opened up new possibilities for modelling dispersal of biological organisms in coastal marine environments. We describe a recently developed suite of models of the coastal waters of the west coast of Scotland, which have been applied in two specific biological scenarios.

Firstly, modelling cetacean carcase drift, which is of interest both for determining the origin of stranded carcases and predicting the stranding site from potential mortality sites, in this case tidal stream turbines. The effect of carcase buoyancy and the combination of forcing fields is considered.

Secondly, the model was used to predict the spread of parasitic sea lice larvae between Salmon aquaculture sites. Analysis of temporally variation in “connectivity” allows insight into the adequacy of spatial management protocols.

Modelling Eddy Influence on Abyssal Currents in the Tropical Pacific with Application to Plumes Generated by Deep-Sea Mining

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Intensification of abyssal currents is of interest to engineers designing deep sea mining systems as well as to those interested in the environmental impact of such activities. To study the dilution and dispersion of particulate plumes resulting from proposed manganese nodule mining activities, a combination of direct current measurements and high resolution non-hydrostatic numerical modelling (MITgcm) was used. Three Acoustic Doppler Current Profilers (Teledyne RDI Workhorse Sentinel, 600 kHz) were mounted near the sea-bed in spring 2013 in the German license area of the north-eastern Clarion-Clipperton Fracture Zone (CCZ) of the central Tropical Pacific. This is an area of generally weak background flow over smooth topography with unevenly distributed underwater hills and troughs with mostly gentle slopes. The current speed was sampled hourly for 13 months at 10-17.5 m above the seabed. The spectral densities of the horizontal velocities $E_{u,v}$ approximately followed f^{-1} in the frequency subrange between the inertial frequency (f_i=0.017 cph, equivalent oscillation period T_i=58.4 hours) and the buoyancy frequency N at the measurement depth (~4100 m), which was derived from nearby CTD profiles (N=0.24 cph, T_N=4.2 h). Prominent spikes in power spectral density are found at tidal M_2, S_1 frequencies and at a frequency which is slightly higher than inertial (f_o~0.026 cph, T_{fo}~42 h); therefore wind-induced near-inertial abyssal currents here are as energetic as the tidal currents.

Modelled plume spreading mostly followed the slow near-bottom east-south-east residual current (3.1±1.5 $cm \cdot s^{-1}$). However, during the first four weeks a stronger mean northward flow (4.6±1.1 $cm \cdot s^{-1}$) was detected by all three instruments with the observed maximum absolute current speed of 17.6 $cm \cdot s^{-1}$. Rotary coherence estimates between a time series of surface velocity from satellite altimetry (Mean Absolute Dynamic Topography provided by AVISO) and daily-averaged currents measured near the seabed are statistically significant above a 90% threshold with a co-rotation delay period of about 10-15 days. It is known that the influence of large ocean eddies can penetrate to abyssal depths in this region. The eddy induced low-frequency signal therefore might propagate from the surface toward the sea-bed with a lag and its vertical (downward) phase speed can be defined as 300-400m per day (0.003-0.005 $m \cdot s^{-1}$). A large surface eddy passed over the mooring sites in April 2013 and was traced back over 318 days to its origin. Surprisingly that leads to the conclusion that there is a significant impact of the strong offshore winds through the gaps in the Central American mountains on abyssal currents more than 4000 m below the surface and as far as 3500 km from the coast.

Using the model the influence of that signal on the advection and dispersion of the plume was determined at distances of several km from the source, at hundreds of meters in horizontal scale and tens of meters in vertical in the lower part of water column. The modelled horizontal spreading of the plume matched well the realistic mean flow transport. The dilution rate in the plume core was enhanced 3-5 times in mixing hot-spots associated with topographic features, where modelled vertical turbulent diffusivity was enhanced compared to less turbulent sites nearby. The study was funded by EU FP7 MIDAS Grant N^{o} 603418.

Modelling energy extraction at the Pentland Firth

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The Pentland Firth and Orkney Waters (PFOW) is the first Marine Energy Park in Scotland and second for the UK [1]; which promotes the Highlands and Islands of Scotland as a marine energy hub. This site holds the world's first commercial scale leasing round for marine energy. So, agreements for lease have been awarded to developers for 11 sites in the area. In this context, Marine Scotland as a regulator has developed an FVCOM model for the region, implemented a tidal turbine module within the open source code and assessed different farm layout configurations.

In this work, a comparison of the PFOW FVCOM model with the commercial package MIKE 3 has been undertaken. Because of the absence of large arrays in the water, so far it is not possible to validate models of tidal energy extraction against measured data. Thus inter-model comparisons are one way to gain confidence in the approaches used. Tidal energy extraction in FVCOM has been implemented following the momentum sink approach, which consists in adding a volumetric momentum sink term to the momentum equations [2] . This approach is the same used by MIKE 3, and therefore, similar results are expected. Results will show the comparison for a baseline scenario without turbines and for a couple of different scenarios including farms of tidal turbines.

[1] 'What Does Marine Energy Park Mean'. [Online]. Available: http://www.hi-energy.org.uk/whatdoes-marine.htm. [Accessed: 15-Dec-2015].
[2] Z. Yang, T. Wang, and A. E. Copping, 'Modeling tidal stream energy extraction and its effects on transport processes in a tidal channel and bay system using a three-dimensional coastal ocean model', *Renew. Energy*, vol. 50, pp. 605–613, 2013.

Modelling tidal flows: a non-hydrostatic approach

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Tidal models used in resource assessment generally use depth-integrated or sigma-layer approaches, which assume that the flow is essentially hydrostatic. Whilst these techniques are efficient enough to model large areas of sea with modest computational resources, observations of energetic tidal flow at proposed tidal energy sites show that this assumption does not always hold, with significant vertical turbulent mixing often present, and so realistic representation of anisotropic turbulence within tidal models give a more realistic representation of the flow conditions at energetic tidal sites. In a collaborative project between Edinburgh and the Scottish Association For Marine Sciences (SAMS), a fully three-dimensional, non-hydrostatic Large-Eddy Simulation model was developed and applied to the Sound of Islay, where 10 1 MW tidal turbines are proposed. The challenges of development the model and the initial findings are presented, as well as proposed future work.

A combined Lagrangian advection method for modelling geophysical fluid dynamics

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A combined Lagrangian advection method (CLAM) is used to numerically solve equations that describe two dimensional, inviscid, incompressible flow satisfying the Oberbeck-Boussinesq equations. These equations, while idealised, are representative of and applicable to many geophysical fluid dynamic problems. The numerical method uses a combination of contour advection and a pseudo-spectral method to solve for vorticity while contour advection alone is used to solve for density (buoyancy). Contour advection is highly effective for respecting material conservation of density, but it also works on evolving the vorticity field even though the vorticity equation has a source term proportional to the horizontal derivative of density. The scheme enables high effective Reynolds numbers to be reached at modest computational cost. The model is presented in the context of studying breaking internal solitary waves in the ocean and tidal flow over topography.

A particle tracking modelling study of the inter-annual variability of connectivity in *Lophelia pertusa* reefs in Scotland's marine protected area network.

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Modelled *Lophelia pertusa* larval dispersal from protected reefs off Scotland demonstrates intense inter-annual variability related to the North Atlantic Oscillation. A new network of marine protected areas in Scotland's continental shelf waters includes protection for *L. pertusa* reefs. While widespread, the reefs are geographically isolated, relying for their formation on a specific range of physical conditions. The reefs are connected through the production of pelagic larvae. Understanding this connectivity, and how it might change under changing climate, is important for management of the protected area network.

Daily mean velocity fields from a 40-year (1965-2004) of the POLCOMS Atlantic Margin Model were used, off-line, to drive a particle tracking model. Based on the best knowledge of *L. pertusa* larval behaviour, connectivity was found to be weak, with significant gaps between small groups of well-connected populations.

Inter-annual variability of larval dispersal was investigated by counting modelled larvae crossing a set of vertical sections. Movements of larvae off the shelf from East Mingulay reefs were correlated with years of negative March North Atlantic Oscillation (NAO) index. Larvae from sites on the Wyville Thomson Ridge and the shelf break North-West of Shetland follow two principle routes: along the continental shelf break across to Norway, or onto the shelf and south into the North Sea. The number of larvae entering the North Sea is strongly positively correlated to the March NAO index.

Although predictions of NAO under climate change are uncertain, this work demonstrates some possible effects on the connectivity of populations of important, habitat forming cold-water corals, with implications for Scottish marine protected area management.

An FVCOM unstructured-grid hydrodynamic model of Scottish shelf waters – the Scottish Shelf Model

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The complex characteristics of Scottish shelf and inshore waters pose particular challenges for the more traditional regular-grid hydrodynamic modelling approaches . Unstructured grid models, on the other hand, can have increased resolution in areas of particular interest or complexity, while allowing for coarser resolution elsewhere, resulting in a unified model across scales with higher computationally efficiency. Here we provide a general outline of an implementation of the Finite Volume Community Ocean Model (FVCOM) to Scottish shelf waters, which we refer to as "The Scottish Shelf Model (SSM)". The SSM was commissioned by the Scottish Government to CH2M HILL and the National Oceanography Centre – Liverpool. Marine Scotland Science defined and oversaw the project and has also carried out, in-house and collaboratively, additional model development. We present the characteristics of the SSM (larger domain and finer scale sub-domain models), and show some results from the initial simulations already available, including some derived indices. We also outline our vision of a "community model" of choice in Scottish waters and how we propose to make this project a truly open and participative initiative, of wide use and applicability within science and society."

A Mass-Conserving Advection Scheme for Offline Ocean Scalar Transport Models

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We present a flux-form semi-Lagrangian (FFSL) advection scheme designed for offline scalar transport simulation with coastal ocean models using curvilinear horizontal coordinates. The scheme conserves mass, overcoming problems of mass conservation typically experienced with offline transport models, and permits long time steps (relative to the Courant number) to be used by the offline model. These attributes make the method attractive for offline simulation of tracers in biogeochemical or sediment transport models using archived flow fields from hydrodynamic models. We describe the FFSL scheme, and test it on two idealised domains and one real domain, the Great Barrier Reef in Australia. For comparison, we also include simulations using a traditional semi-Lagrangian advection scheme for the offline simulations. We compare tracer distributions predicted by the offline FFSL transport scheme with those predicted by the original hydrodynamic model, assess the conservation of mass in all cases and contrast the computational efficiency of the schemes. We find that the FFSL scheme produced very good agreement with the distributions of tracer predicted by the hydrodynamic model, and conserved mass with an error of a fraction of one percent. In terms of computational speed, the FFSL scheme was comparable with the semi-Lagrangian method and an order of magnitude faster than the full hydrodynamic model, even when the latter ran in parallel on multiple cores. The FFSL scheme presented here therefore offers a viable mass-conserving and computationally-efficient alternative to traditional semi-Lagrangian schemes for offline scalar transport simulation in coastal models.

Maximizing the tidal stream energy potential of the Pentland Firth using a 3D hydrodynamic tidal model

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It is estimated that Scotland's marine area contains 25% of Europe's tidal resource, and the Scottish Government has identified 10 broad areas of search for future tidal stream energy exploitation (The Scottish Government, 2015). One of these areas is the Pentland Firth and Orkney Waters Strategic Area (PFOW), as it contains the highest tidal stream energy resource in Scotland (Black & Veatch, 2005). To date six sites in and around the Pentland Firth have been leased by The Crown Estate to developers for commercial tidal stream energy development within the PFOW. Together, these sites have an aspirational energy generating capacity of approximately 1 GW. In order to harness more energy from the Pentland Firth, careful marine spatial planning will be required, since any single development has the potential to change the flow within the Pentland Firth region to an extent (Adcock et al., 2013; Draper et al. 2014; Vennell, 2015). This work explores tidal stream energy extraction in the Pentland Firth region, beyond the 1 GW currently leased to developers, and aims to quantify the upper limit of energy extraction and some of the changes that may occur in the tidal stream.

A 3D hydrodynamic model of the northern isles of Scotland has been developed using the Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2006). Potential tidal stream energy scenarios are represented within the model using a momentum sink, following the approach of Yang et al. (2013). A number of scenarios were explored based on recommendations from previous work (Adcock et al., 2013; Draper et al. 2014; Vennell, 2015), and the results used to investigate the realistic limits to the potential of tidal stream energy extraction in the region.

This work is part of a wider study, the EPSRC-funded EcoWatt2050 project, aiming to model a realistic 2050 marine energy scenario, in order to better understand the potential, far field, environmental consequences of very large scale marine energy extraction in Scottish waters.

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Yang, Z., T. Wang and E. Copping (2013), Modelling tidal stream energy extraction and its effects on transport processes in a tidal channel and bay system using a three-dimensional coastal ocean model, Renewable Energy 50, 605-613, 2013.

Shellfish restoration: Marine protected areas and built structures

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Shellfish beds were once widespread and formed extensive beds throughout the North Sea. The European Oyster (*Ostrea edulis)* and the Horse Mussel (*Modiolus modiolus)* were among the dominant shellfish species and as ecosystem engineers produced habitat for entire ecosystems. Through their filter feeding behaviour they contributed to maintain good water quality, supported coastline defence and increased secondary production. In addition, the European Oyster has provided civilizations with food for millennia and has fuelled costal economies for centuries. Currently, these two ecosystems are identified throughout the NE Atlantic as threatened and declining, their beds having been decimated to a large extent by harmful fishing activities. They are flagged as priorities for conservation and are the focus of Marine Protected Areas (MPAs) in the UK. This project seeks to study the restoration potential of these two shellfish habitats. Suitable potential restoration sites will be considered within a network of MPAs and marine renewable energy development sites, because these sites offer protection from the principal fishing pressure. In addition, larval dispersal and settlement behaviour will be investigated for both species, as well as the community development and biodiversity associated with European Oyster beds. Finally, hydrodynamic models will be used to provide insight into whether the selected restoration sites could promote connectivity and resilience and whether they could seed-out fishable stocks.

Supervisors:

Dr. Bill Sanderson (CMBB, Heriot-Watt University)
Dr. Mark James (St. Andrews University)
Dr. David Donnan (Scottish Natural Heritage)

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Modelling of Marine Environmental Quality

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Numerical Hydrodynamic Modelling (NHM) has a number of important applications within SEPA, including: predicting water levels for flood-forecasting; assessing the dispersion and dilution of pollutants; and driving water quality models to quantify the parameters key to life. As such, NHM is an invaluable tool for helping SEPA understand Scotland's environment, one of its corporate values. Results from numerical models also help SEPA fulfil its regulatory duties by helping set consent limits for industrial discharges and informing strategic investment to ensure compliance with the Water Framework Directive.

SEPA has worked closely with Scottish Water and its consultants to develop and run a numerical model of the Clyde estuary. The Clyde has been subject to extensive morphological change over the centuries and, while this helped its economy (notably the ship-building industry), it had a detrimental effect on water quality in the estuary. Encouragingly, oxygen levels have been increasing in recent decades and modelling has been used in conjunction with data analysis to quantify the various factors contributing to this improvement.

SEPA has started to apply NHM methods to enhance the assessment of the environmental impacts of the aquaculture industry, including far-field benthic impacts and the cumulative effects of multiple fish-farms. This will be crucial for ensuring that the expansion of the industry is environmentally sustainable. With more and more numerical models being developed, particularly the Scottish Shelf Model, Oceanmet is keen to collaborate with fellow modellers to maximise the benefits of NHM.

What do marine community ecologists need from hydrodynamic models?

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In the case of plankton ecologists, the simple answer is: the depth of the euphotic zone, the illumination therein, and rates of exchange with deeper water and with adjacent waters. That is, we need accurate simulations of the density structure and horizontal and vertical exchanges of water columns, taking into account the effect of freshwater as well as thermal buoyancy. For some purposes we also need reliable climatologies, allowing the identification of ecohydrodynamically different sea-areas. This will be illustrated with two coupled physical-biological models: ACExR-LESV, a 3-layer model of fjords (Gillibrand et al., 2013; Tett et al., 2011), and GETM-ERSEM, a 3D model of the North Sea (van Leeuwen et al., 2015).

Gillibrand, P.A., M.E. Inall, E. Portilla and P. Tett, 2013. A box model of seasonal exchange and mixing in restricted exchange environments: application to two contrasting Scottish inlets. Environmental Modelling and Software, 43, 144-159. DOI 10.1016/j.envsoft.2013.02.008

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van Leeuwen, S., Tett, P., Mills, D. and van der Molen, J., 2015. Stratified and nonstratified areas in the North Sea: Long-term variability and biological and policy implications. Journal of Geophysical Research: Oceans, 120(7), pp.4670-4686. DOI: 10.1002/2014JC010485.

Modelling and Data Analysis to understand Dissolved Oxygen Impacts in the Forth Estuary

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Numerical Hydrodynamic Modelling (NHM) is utilised by SEPA to drive water quality models to assess the dispersion and dilution of pollutants and to investigate the risks posed by these to the marine environment.

A Delft3D model of the Forth estuary was used to provide an initial indication of the extent to which the discharge of organic wastes containing a high Biological Oxygen Demand (BOD) into the middle estuary contribute to low Dissolved Oxygen (DO) levels in the upper estuary. This was part of a wider study involving the analysis and visualisation of SEPA’s monitoring buoy data using Spotfire to better understand the processes controlling DO to place the BOD inputs within the wider environmental context.

The model simulations indicate that there is likely to be a detectable influence of anthropogenic BOD upon DO in the upper estuary. Spotfire analysis identified two sources of DO reduction; one influenced by high concentrations of sediment and warm river water originating from upstream, and the second influenced by sediment and industrial BOD originating from downstream. This highlighted that during periods of low DO in the summer DO reduction due to industrial discharges is overshadowed by DO reduction due to processes.

E-poster

Eddy Generation and Shedding in a Tidally Energetic Channel

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The Pentland Firth in northern Scotland, and its subsidiary channel the Inner Sound, are currently under scrutiny as the first tidal energy farm in the world is installed. The tidal flows in the channel and sound have been intensively observed and modelled in recent years, and the turbulent nature of the flow, with features of eddy generation and shedding, is becoming increasingly well known. Turbulence and eddies pose potential risks to the turbine infrastructure through enhanced stress on the blades, while understanding environmental effects of energy extraction also requires accurate simulation of the hydrodynamics of the flow.
Here, we apply a mixed finite element/finite volume hydrodynamic model to the northern Scottish shelf, with a particular focus on flows through the Pentland Firth and Inner Sound. We use an unstructured grid model, which allows the open boundaries to be far removed from the region of interest, while still allowing a grid spacing of ~40m in the Inner Sound. The model employs semi-implicit techniques to solve the momentum and free surface equations and semi-Lagrangian methods to solve the material derivative in the momentum equation, making it fast, robust and accurate and suitable for simulating flows in irregular coastal ocean environments [1, 2]. Estimation of tidal energy potential is a challenge that the model is particularly well-suited to address [3, 4].
We present numerical simulations of tidal currents in The Pentland Firth and Inner Sound. Observed velocities in the Inner Sound, measured by moored ADCP deployments, reach speeds of up to 5 m s-1 and the model successfully reproduces these strong currents. In the simulations, eddies are formed by interactions between the strong flow and the northern and southern headlands on the island of Stroma; some of these eddies are trapped and remain locked in position, whereas others are shed and transported away from the generation zone. We track the development and advection of eddies in relation to the site of the tidal energy farm, and we compare the simulated locations of eddies with observed seabed sediment distributions in the Inner Sound.

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E-poster

The Simulation of WECs with Boussinesq and Spectral Wave Models

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Comparative simulations explores the realms of validity of DHI's Mike21 Boussinesq (BW) and Spectral Wave (SW) models with respect to diffraction and incident sea state. Alternative methods for simulating WECs are introduced that allow the frequency dependent absorption in the BW and SW models. This work highlights the importance of the inclusion of diffraction and directional spreading when assessing the far-field wave-device interactions in Spectral wave models.

Additional work focuses on the interaction of wave and tides at high energy sites around Orkney. The ongoing development of a coupled wave and tidal model will be supplemented with high resolution wave, current and turbulence measurements using broadband acoustic sensors, X-band radar and additional state of the art instruments. This will deepen the insight into complex hydrodynamic processes in support of engineering design development of tidal turbines.

E-poster

Modelling of a new type of wave maker for tsunami research

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In this study, a new type of wave maker is designed and investigated, which aims at becoming a better tsunami wave model than solitary wave. Analytical solutions from linear wave theory are used to do a first prediction. For more rigorous theoretical investigation, a numerical model based on the weakly nonlinear and weakly dispersive wave theory is built. A high-order shock-capturing finite volume method, such as UNO2 (Dutykh and Kalisch, 2013) and WENO5 (Li and Raichlen, 2002), is applied to solve these equations numerically. As a result, the theoretical results can fit the experimental results, and confirm that the new wave maker can generate longer waves than the corresponding solitary waves with same wave amplitude.