# JONSMOD 2016

18th Joint Numerical Sea Modelling Group Conference

# Book of Abstracts

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# About JONSMOD

The JONSMOD acronym dates from the mid 1970s. At that time the acronym stood for Joint North Sea Modelling Group. The modelling formed part of the initiative centered around a few North Sea projects active at the same time 40 or more years ago. JONSMOD quickly developed into an "informal forum" of interested parties for countries that border the North Sea. The notion of JONSMOD as an "informal forum" thus has its roots in these early days, and certainly describes the present JONSMOD with accuracy. In 1981 Professor Phil Dyke from the Plymouth University was asked to take over the vacancy as Chairman after Professor Jaques Nihoul from the University of Liège, who had acted as Chairman of JONSMOD since 1973. Under Professor Dyke's Chairmanship there have been biennial JONSMOD conferences since 1982. When he resigned as Chairman in 2010 the JONSMOD Conferences have continued as a "relay" in which the local host of JONSMOD has acted as Chairman before giving the relay stick onward to the next local host. The 2012 JONSMOD was chaired by Dr. Pierre Garraud from IFREMER, Brest, and the 2014 JONSMOD by Dr. Patrick Luyten from the Royal Belgian Institute of Natural Sciences, Brussels, Belgium. In 2016 a Steering Committee was established in order to continue promoting and organising future JONSMOD Conferences and Professor Lars Petter Røed from the Norwegian Meteorological Institute and University of Oslo was asked to organize the 2016 JONSMOD.

Figure 1: Professor Phil Dyke, the long time Chairman of JONSMOD (1981-2010), with his wife and daughter at the 2006 JONSMOD organized by him in Plymouth, UK.

No systematic funding has ever existed or been sought for JONSMOD. This has sometimes been irritating, but it has given the JONSMOD research community a freedom to follow research directions unfettered by the demands of funding bodies. This also helps in another respect. Delegates are able to present work that is still in progress rather than a fait accompli, which gives a more dynamic feel to the sessions. Longer than normal time for presentation (25 or 30 min) and lively question-and-answer sessions always conducted in a positive atmosphere have helped maintain JONSMOD.

For further reading about JONSMOD and what it has achieved the reader is referred to Dyke, P., 2007: The history of Jonsmod 1981-2006, *Ocean Dynamics*, **55**, pp. 239-244. DOI 10.1007/s10236-007-0107-4.

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## Session 1: Tides

### Simulating the tidal regime the coastal zone of the Red River Delta

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The Red river delta (RRD) is located in the Northeast Vietnam which one of the two biggest river system release water and sediment to the East Sea over nine main river mouths, namely Bach Dang, Cam, Lach Tray, Van Uc, Thai Binh, Tra Ly, Ba Lat (main branch of the Red river), Ninh Co and and Day. The study area is dominated influence by a sub-tropical summer monsoon from the South and a winter monsoon come from the North East. With tidal amplitude maximum could reach to 4m, tidal oscillation is main factor that decide to hydrodynamics condition in the RRD coastal area. A good model for tidal currentsis also a prerequisite for solving problems such as hydrodynamics (current, wave, sediment transport), environment (water quality transport) or ecology. This study based on the new version of COHERENS (Coupled Hydrodynamical - Ecological Model for Regional and Shelf Seas, Ver. 2.9) model to simulation tidal regime study along the coastline of the Red River estuary. The model gird is a curvilinear grid with 607x502 grid cells and resolution size in range 10-1800m.The open sea boundaries condition include effect of 11 tidal constituents that based on FES2004 database. The river boundaries condition for the model are measured water discharge. Measured wind data at Hon Dau gauging station used for the surface boundary conditions. The model results validated with measured data in some tidal gauging station in the study area and showed a good agreement. The initial simulation results show that along the coast the tidal regime is conform to commonly known rule: diurnal waves (O1, K1) have maximum tidal amplitude while semi-diurnal waves (M2, S2) have a minimum amplitude. The amplitude of tidal diurnal waves decrease gradually from North to South. On the contrary, the tidal semi-diurnal waves increase from North to South. With these initial promising results, the model setup will be expanded to include waves, sediment transport, environmental processes (water quality transport) and ecology.

Acknowledgment: This work acknowledges the support from the CEBioS programme of the Royal Belgian Institute of Natural Sciences (RBINS), Belgium.

## Ocean self-attraction and loading (SAL) and internal tides dissipation implementation within an unstructured global tide-surge model

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In the context of the BASE-platform project (H2020), whose objective is to set up an online platform for up to date bathymetry data for the whole globe, Deltares is the partner responsible for the development of a global hydrodynamic model to correct depth data from different sources for dynamic variation of the sea level. The so called Global Tide Surge Model (GTSM) is a 2D depth-averaged, unstructured model with up to 5km coastal resolution. The transition from a regional model to a global model requires the consideration of two physical processes that are usually neglected at a regional scale: Self Attraction and Loading (SAL) and dissipation due to internal tides. The tide generated by the SAL potential (SAL tide) is significant and known to be around 10% of the tide triggered by the gravitational forces, and it is sometimes included in global models as a term reducing the pressure gradient by 10%. In addition, the dissipation due to internal tides constitutes the major dissipation mode of tidal energy in deep waters, accounting for almost a third of the total dissipation over the globe (≈1TW). Therefore it is expected to have a significant effect on tidal propagation. In the GTSM model, an efficient parameterization of the SAL potential is implemented. For the internal tides dissipation, a semi-empirical parameterization based on the Brunt-Väisälä frequency is implemented, which accounts for the stratification that the 2D model cannot reproduce. First tests including these two implementations show promising results. The SAL implementation reduces standard deviations and improves propagation significantly with a minor increase of computational time of the order of 3%.

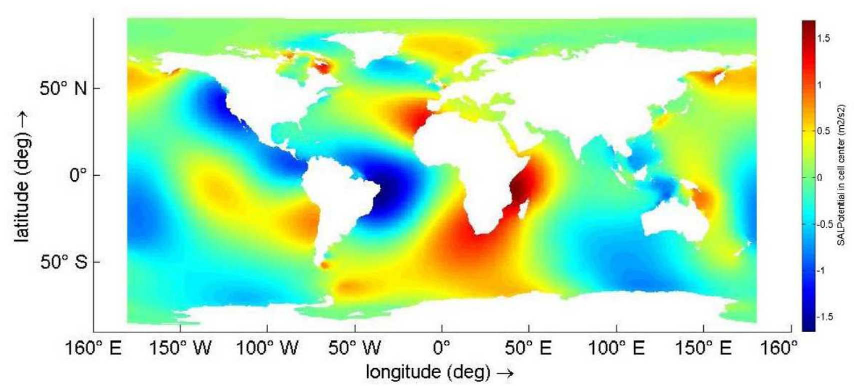


Figure 2: SAL Potential calculated by the GTSM ($m^2/s^2$).

The large impact of both SAL and internal tides dissipation in the global model response raises the question of how negligible these effects may be in a regional scale.

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## Simulating Saltstraumen: The highest tidal current of the world (?)

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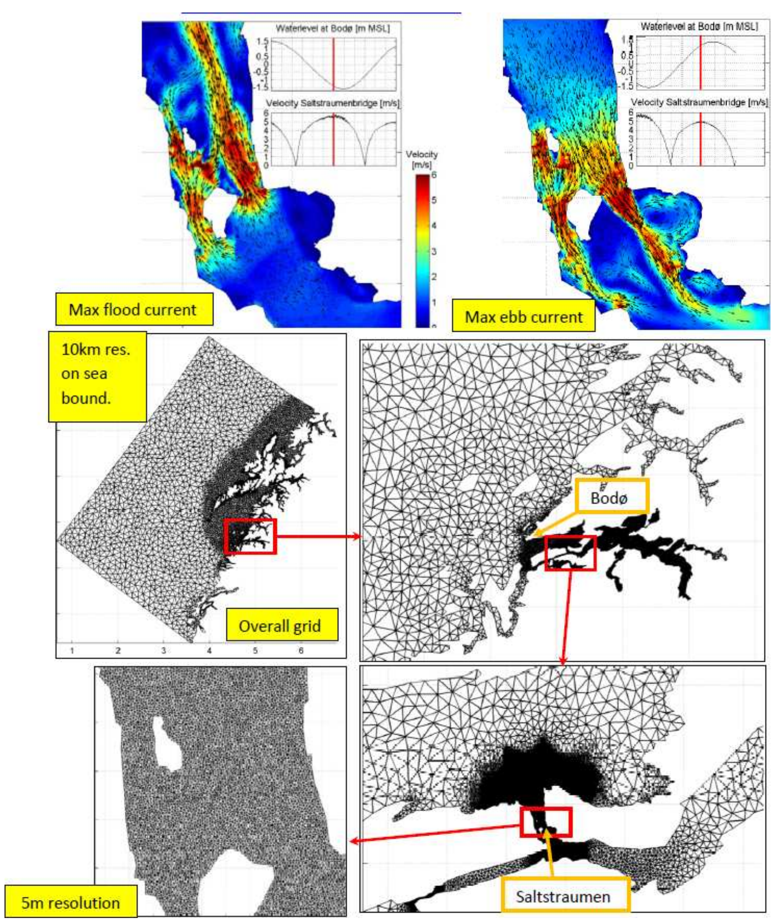
Saltstraumen, located in the northern part of Norway, connects the large Skjerstadfjorden with the sea. Large quantities of water flow in and out each tide through the 150m wide Saltstraumen. The velocities can get up to 10 m/s according to the tourist information and is therefore named the highest tidal current in the world. In this study we use the finite element model FINEL2d to simulate the currents in Saltstraumen. The model domain is around 400x600 km, with coarse resolution at sea (10km). The resolution is steadily refined to a final resolution of 5m in Saltstraumen. The triangular shaped mesh is especially suited to follow the rugged coastline of Norway and without complicated nesting techniques this refinement can be carried out easily. The study shows that the model is capable of simulating in high resolution the water motion and currents through Saltstraumen. Several sensitivities have been investigated. The conclusion is that 10 m/s is a myth: A maximum situation gives +/- 6 m/s. See for animation: www.damengineering.no/saltstraumen.html



## Adjusting global tidal forcing for use in high-resolution fjord models

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Tides are one of the dominant driving forces in coastal waters. Due to complex topography with narrow and shallow straights, the tides in the innermost parts of the Norwegian fjords are both shifted in phase and altered in amplitude compared to the tides in the open water outside the fjords.

In order to model the hydrography and currents in the fjords, accurate tidal forcing is crucial. The global tidal forcing has to be adjusted to fit the observed tides in the area. We have developed a simple method to do this adjustment. First, a high-resolution ocean model is run with the global tidal forcing on the open boundary. Time series of water level is then analysed and compared with observed water level. Based on the comparison a factor for the amplitude and a phase shift is computed and applied to produce adjusted tidal forcing. The same factor and phase shift is used on tidal current forcing as for tidal water level forcing. The model is then rerun with the adjusted tidal forcing.

The method is tested in the Reginal Ocean Model System (ROMS) on two different model areas in Norway; the Oslofjord and Saltstraumen. The Oslofjord is located in the eastern part of Norway with the main city of Norway in the innermost part of the fjord. Even though the mean total tidal elevation is less than 20 cm in the Oslo fjord, the tidal currents are up to 0.5 m/s due to the narrow straits and thresholds. Saltstraumen is a small straight with the world's strongest tidal currents. The difference between the water level before the narrow straight and after the narrow straight can be up to one meter, causing water speeds up to 11 m/s.

High-resolution, curvilinear grids are set up for both model areas. Both models are nested into a regional model (NorKyst800) covering the Norwegian coast with 800 meters resolution. Atmospheric and river forcings are also included.

The results show a promising improvement in modelled tides in both the inner and the outer parts of the fjords.

## Circulation generated by a tidal jet

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Tidal jets through narrow sounds generate circulations which do not obey geostrophic restrictions. Here we present an example of circulation in Grøtsundet and Tromsøsundet, generated by a tidal jet through Kvalsundet, modeled with a barotropic version of FVCOM. The model results are compared with measurements.

## On the modeling of vertical reference surfaces

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Different applications around the coast often make use of different vertical reference surfaces or vertical datums. For example nautical charts are expressed relative to Chart Datum (CD), which is often based on the Lowest Astronomical Tide (LAT). In addition applications like flooding by storm surges often require data with different reference systems. Although, accurate conversion is not a simple task, hydrodynamic models can play an important role in this process. In this presentation, we will present a number of examples and show how hydrodynamic models can contribute to the conversion of vertical referencing of bathymetric data.

Measurements of the bathymetry, either from a ship or from space, usually provide the local total water-depth which changes both in space and time, so that corrections are needed for the instantaneous sea-level. Other elevation data, e.g. from satellite radar or levelling often has a different datum and conversion to a common ground is needed to combine these sources.

In addition to regional hydrodynamic models, we will use a Global Tide Surge Model (GTSM v1.0) to compute fluctuations of the sea-level. The model is now running 4 times a day to provide near real-time results and forecasts for the next few days. The same numerical model can be used to compute the difference between LAT and the mean sea-level (MSL). With a different configuration the same model can also be used to compute the difference between MSL and the geoid (Slobbe et al. 2013).

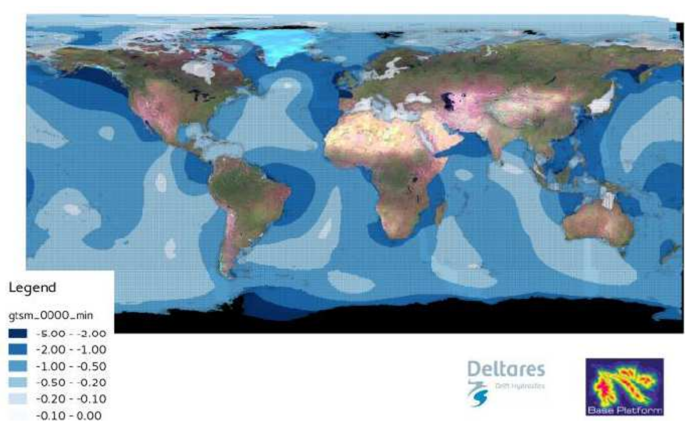


Figure 3: Lowest Astronomical Tide relative to Mean Sea Level

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## On the origins of annual modulation of $M_2$ and $M_4$ harmonic constituents

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Several recent studies (Gräwe et al., 2014, Müller et al., 2012, 2014) have found a seasonal modulation of the $M_2$ tidal constituent and its overtides, such as $M_4$. Along the Dutch North Sea coast these can change the $M_2$ range by more than 3% and the M4 range by more than 10%. Although several authors have suggested seasonal variations of the thermal stratification as the cause, the precise cause of these modulations is as yet unclear. For the increasingly accurate real-time operational prediction of water levels it becomes important to represent these modulations in the hydrodynamic tide-surge models used. In the Operational Dutch Continental Shelf Model, version 6 (DCSMv6), the tide representation has improved over the years, to the extent that at tide gauge location Delfzijl, in the Ems-Dollard Estuary, the satellites of $M_2$ responsible for the annual $M_2$ modulation now constitute the largest contribution to the tidal error.

To gain further insight in the origin of these modulations, monthly amplitudes and phases of $M_2$ and $M_4$ are determined based on a set of tide gauge data covering 19 years. Results show variation in $M_2$ and $M_4$ amplitude with annual and semi-annual periodicity. While the maximum $M_2$ amplitudes can be found in summer, the annual modulation has its maximum in spring.

Several tests are performed with the 3D barotropic DCSMv6 model. These show that the semi-annual modulation of $M_2$ ($\pm 2$ to 3% along the Dutch coast) is caused by the presence of the tidal constituent $MKS_2$, which itself is caused by non-linear interaction between $M_2$, $S_2$ and $K_2$.

However, contrary to the semi-annual modulation, the annual $M_2$ modulation is hardly present in the tidal potential, and consequently has to be generated to a large extent by other, non-gravitational phenomena with an annual periodicity. To further investigate the origins of the annual modulation, tests are performed with a three-dimensional, baroclinic Delft3D Flexible mesh model of the Northwest European Shelf.

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## Session 2: Processes: modeling and observations

### Numerical studies of density driven currents down a slope and in canyons

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A sigma-level numerical ocean model is applied to the Dynamics of Overflow Mixing and Entrainment (DOME) idealized density current problem. The focus in the present study is on sensitivity to the vertical resolution and to the bottom boundary condition. In a rotating system, there is a transverse flow normal to the main direction of the dense water flows. This flow is referred to as secondary circulation, and the role of the secondary circulation on mixing and entrainment is investigated. Sensitivity of the processes in the bottom boundary layer and in the interface between the plume and the ambient to the vertical grid size and to the bottom boundary condition is targeted. Canyons crossing the slope affect the steering of the plumes and mixing and entrainment. To address these effects, the numerical experiments are repeated with a wide canyon crossing the slope.

## Enhanced Ahead-of-Eye Cooling of Stratified Coastal Oceans and Feedback on Tropical Storm Intensity

Scott Glenn, Travis Miles, Greg Seroka, Yi Xu, Robert Forney, Fei Yu, Hugh Roarty, Oscar Schofield and Josh Kohut
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Enabled by the advances in global atmospheric models, tropical cyclone track forecasts have steadily improved over the last two decades. In contrast, improvements in tropical cyclone intensity forecasts have lagged, prompting research in regions of rapid intensification and rapid de-intensification. Here we use an advanced coastal ocean observatory to study the feedback loop between tropical cyclones and stratified coastal oceans in a region of rapid de-intensification.

Integrated ocean observations from Hurricane Irene (2011) reveal widespread and significant ahead-of-eye cooling (at least 5°C and up to 11°C) as it crossed the seasonally stratified continental shelf of the Mid-Atlantic Bight of North America. Buoys and gliders deployed in the storm allow the detailed evolution of the surface temperature to be examined at select points, revealing approximately 90% of the total cooling occurs before eye passage. A range of ocean models were used to diagnose the processes responsible for the observed cooling. In Irene, 1-D vertical mixing models generate only 17% of the total cooling ahead of eye, while deepwater 3-D models forced by Irene’s nearly symmetrical offshore windfield produce an approximately 50-50 split in the cooling between the front and back side. A 3-D coastal ocean model (ROMS) generates a wind-forced two-layer circulation in the stratified Mid-Atlantic not present in the 1-D and 3-D deepwater models. The resultant shear-induced mixing more accurately reproduces both the magnitude and timing of the surface cooling with respect to eye passage. Atmospheric simulations establish that this cooling was the missing contribution required to reproduce Irene’s accelerated reduction in intensity over the Mid-Atlantic Bight.

Historical buoys from 1985 to present show that ahead-of-eye cooling occurred beneath all 11 tropical cyclones that traversed along the Mid Atlantic Bight continental shelf during stratified summer conditions. The buoys also reveal that an average of about 75% of the cooling in these 11 hurricanes occurs ahead of eye, indicating a robust process in the Mid Atlantic. Similar to the Mid Atlantic Bight, the Yellow Sea have had 35 typhoons cross its shallow highly stratified waters in summer before making landfall in China or Korea. Typhoon Muifa (2011), whose intensity was also overpredicted, generated significant SST cooling (up to 7°C) in the Yellow Sea, and a Yellow Sea buoy array similarly revealed 85% of the cooling was ahead of eye. These findings establish that including realistic 3D coastal ocean processes in forecasts of landfalling storm intensity and impacts will be increasingly critical to mid-latitude population centers as sea levels rise and tropical cyclone maximum intensities migrate poleward.

## Analysing sea level rise in the Baltic Sea for the period 1950-2015

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The General Estuarine Transport Model (GETM) was applied to create a state estimate of the Baltic Sea for the period 1950-2015 with a horizontal resolution of 1 nautical mile. In the vertical 60 terrain-following layers were used, which during runtime automatically adapt to the highly variable stratification. This is associated with sporadicly inflowing bottom gravity currents of saline North Sea water, the seasonal thermocline and internal wave motions at the permanent halocline. These challenges need to be tackled by a model to correctly reproduce the mixing and entrainment of water masses in the Baltic Sea. The atmospheric forcing was taken from a regional reanalysis with a spatial resolution of less than 20 km and hourly values.

The analysis of the sea surface height (SSH) revealed a non-uniform absolute mean sea level (MSL) rise in the Baltic Sea. Lowest values are found in the western part with 1.4mm/year and highest values in the Gulf of Finland with values of 2.2 mm/year. This spatial heterogeneity is partially explained by an increase in the mean zonal winds but also by changes in air pressure. The warming trend of the sea surface temperature adds to the regional increase in SSH.

Analysing water level extremes, the simulations indicate a much faster rise in annual maximum SSH compared to MSL rise. This is well correlated with an increase in the annual maximum wind speed. The linear trends in annual maximum SSH are 2 mm/year in the western Baltic Sea and reach peak values of 6 mm/year in the Gulf of Finland. For the trends in annual minimum SSH we do not see any trend different from MSL rise.

As a further measure to quantify changes in extreme water levels, we computed the duration and intensity (duration times excess water height over 99 percentile). Whereas the mean duration does not change significantly, the model results indicate a significant increase in intensity.

To estimate the robustness of the results, their sensitivity to the atmospheric forcing was analysed for the period 1980-2005. For this, based on the global forcing from ERA40 and NCEP-NCAR, an ensemble of 4 regional atmospheric reconstructions was used and provided to GETM. Within the 4 ensemble members, we see a common response in MSL rise. Only for the extreme water levels we see differences. However, these can be partially explained by the different grid resolutions of the atmospheric models and thus a different representation of extreme winds.

## How to accurately predict salinity intrusion in the Rotterdam Waterway?

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The Rotterdam Waterway is an estuary in which saline water from the North Sea mixes with the fresh water from the lower branches of the Rhine and Meuse. Due to sea level rise and possible future measures in this Rhine-Meuse estuary, it is expected that salinity intrusion will increase in upstream direction. Consequently, the freshwater intake points are potentially affected. Since the drinking water criterion is very strict in The Netherlands with maximum chlorine concentrations of 0.25 g/l, it is evident that this criterion might be exceeded at certain periods throughout the year. This might be the case at dry periods, at which relatively low river discharges occur. Therefore, it is very important to accurately compute salinity intrusion in the Rotterdam harbour.

However, an accurate prediction of salinity intrusion in the Rotterdam Waterway is a very challenging task from numerical point of view. Large variations in prediction quality have been found for simulations with various vertical grid concepts, various modelling systems and various meteorological conditions.

For systems with strong tidal dynamics, often 3D models with $\sigma$-layers (with moving layer interfaces and ability to follow the bed) are preferred over Z-model layers (with fixed layer interfaces). The latter are designed for weakly-dynamic flows such as in lakes. However, is this still a good choice? Model simulations show promising results for salinity intrusion with Z-model layers in dynamic situations as well (see Figure 4), while the numerical drawback of $\sigma$-layers for salinity intrusion (overestimation of vertical mixing) usually has to be compensated with the so-called 'anti-creep' technique at the cost of extra computation time.

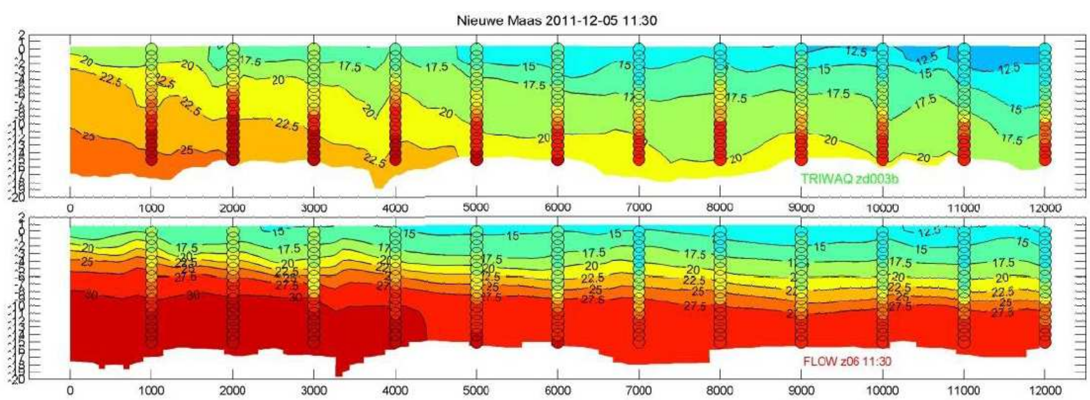


Figure 1: Data (dots) – model (contours) comparison for salinity in the Rotterdam Waterway for a σ-layer simulation (top, using Simona) and a Z-layer simulation (bottom, using Delft3D).

Figure 4: Data (dots) - model (contours) comparison for salinity in the Rotterdam Waterway for a $\sigma$-layer simulation (top, using Simona) and a Z-layer simulation (bottom, using Delft3D).

The results also depend on the applied software system. In the Netherlands, we have several hydrodynamic codes for 3D modelling (Simona, Delft3D 4 and Delft3D Flexible Mesh), which give slightly different model results as well. Next, while testing the various codes and techniques, we also found effects due to meteorological conditions. Under normal situations the various numerical models give adequate results. However, under storm conditions the agreement between model results and measurements shows strong differences between the various systems and approaches. In the presentation we will show results of various simulations and discuss the pros and cons of different numerical models and methods.

## Characterization of Wave-related Processes in the Upper Ocean Boundary Layer in the North Sea: OBLEX-F1[1] experiment

Mostafa Bakhoday Paskyabia and Ilker Fer
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Measurements of ocean currents, waves, and turbulence were carried out as part of a large-scale air-sea interaction experiment aimed to investigate the important role of wind and wave-induced circulations in the dynamics of ocean surface boundary layer. Observations made in the close vicinity of FINO1 research platform at a water depth of approximately 28 m of water for 5 months between June and early November 2015. In this study, we discuss the characteristics of circulations derived by the wave-related processes including wave breaking, Coriolis Stokes forcing, Langmuir turbulence, and mixing by nonbreaking waves from an observationalnumerical standpoint. It is shown how surface gravity waves contribute to: (1) elevation of vertical Turbulent Kinetic Energy; (2) modulation of turbulence anisotropy; and (3) variability in the skewness of vertical velocity as a combined effect of surface thermodynamic processes and wave-induced vortex force. We next use our measurements to assess the ability of the wave-modified and rigid-boundary ocean turbulence models to predict the full-depth variability of turbulence quantities, particularly in the presence of Langmuir circulation, in such a shallow water system.

[1] Offshore Boundary Layer Experiment Fino1 (OBLEX-F1)

## Examination of wave-current interactions over the eastern Canadian shelf under severe weather conditions using a coupled circulation-wave model

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This paper presents a numerical investigation on interactions between surface gravity waves and currents over the eastern Canadian shelf and adjacent deep waters of the northwest Atlantic Ocean under severe weather events. A coupled ocean circulation-wave model based on the third generation wave model and three-dimensional (3D) circulation model is applied to the study region with a horizontal resolution of 1/16$^o$. The circulation model uses the vortex-force formalism and wave-induced vertical mixing to account for effects of surface gravity waves on the 3D currents. The wave model uses the sea surface elevations and 3D currents generated by the circulation model to account for the effect of the circulation on the surface gravity waves. An external coupler is used to exchange information between the circulation and wave models. Analysis of model results demonstrates that the simulated significant wave heights (SWHs) and peak periods are significantly affected by the wave-current interaction (WCI) during and after the storm. For fast-moving hurricane cases, major contributions to the WCI include the current-induced modification of wind energy input to the wave generation, current-induced wave advection and refraction. In the slow-moving winter storm case, the effect of the current-induced advection differs significantly from that in fast-moving hurricane cases. The effect of the 3D wave forcing on the vertical mixing is significant over the Scotian Shelf. By comparison, the effect of wave-enhanced vertical mixing due to breaking waves is mainly significant in the fast-moving hurricane cases.

## Mean particle drift in long gravity waves at the interface between immiscible viscous fluids

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The mean drift in long waves at the interface between two layers of immiscible viscous fluids is investigated theoretically by applying a Lagrangian description of motion. The initial drift (inviscid Stokes drift + viscous boundary-layer terms) associated with the instantaneously imposed wave field does not generally fulfill the boundary conditions at the interface. Hence, transient Eulerian mean currents develop on both sides of the interface to ensure continuity of velocities and viscous stresses. Generally, the development of strong jet-like Eulerian currents increasing with time in this problem is related to the action of the time-independent virtual wave stresses at the interface. Very soon (after a few wave periods) the transient Eulerian part dominates the Lagrangian mean current near the interface, leading to a positive drift. Similar calculations are made for the case when the interface is covered by a thin inextensible film, and comparisons are made with the case of film influence on surface wave drift. In particular, for freely floating films, the virtual wave stresses promote transient drift currents near the interface that in a few wave periods may exceed the Stokes drift.

## Session 3: Advances in numerics

### Massive Ensembles and GPUs for Short Term Ocean Current Forecasts

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Today's oceanographic forecasts are based on highly complex numerical models that capture a lot of the relevant physical driving forces. Whilst these models can be accurate in a statistical sense, they often have high errors when it comes to short term ocean currents due to large uncertainties in initial conditions and forcing. An alternative is to run a simpler model with many different initial condition, and select those that match observations best for the forecast by using nonlinear data assimilation techniques. This approach requires a large number of runs, and thus high performance of the simpler model. In this talk we will give an overview of how one can use modern graphics cards to help achieve this goal.

Graphics cards, often referred to as GPUs, have become highly popular for numerical simulation over the last decade. The main reason is that these specialized processors are capable of performing around ten times the number of floating point operations per second as the traditional CPU. However, utilizing the GPU can be a significant challenge which requires insight into both the underlying computing hardware and the numerical algorithms. The reason for this is that GPUs are massively parallel, and requires algorithms that are designed to take advantage of parallelism. It has been shown that GPUs are highly suitable for simplified ocean models when using so-called explicit numerical schemes with compact stencils. These numerical schemes end up with taking a weighted average of a local neighborhood for each cell to advance the solution in time. This means that each cell in the computational domain can be advanced in time independently of its neighbors, making the algorithm embarrassingly parallel. We have implemented a simple GPU program for a simplified ocean model based on these principles. The result is a significant speedup over an existing (non-optimized) code, showing that GPUs can be used to realize the goal of simulating huge ensembles.

# An adaptive vertical coordinate system for a coastal flows discontinuous Galerkin finite element model

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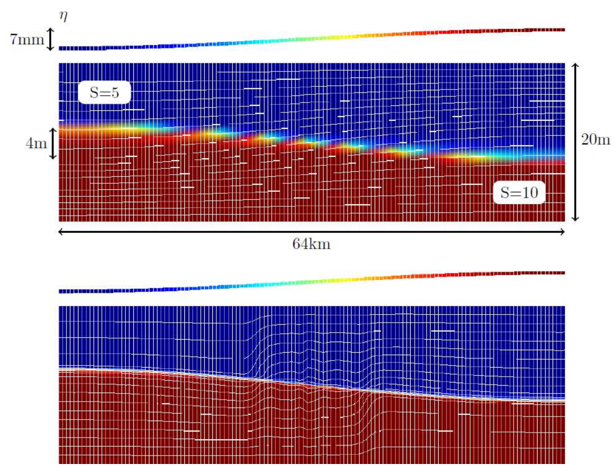
Unstructured-mesh models have shown their efficiency for coastal system modelling. For 3D models, the mesh is often built using a horizontal unstructured grid and a structured vertical column. The discretisation of this vertical column has a large impact on the results, as it has been shown for SLIM 3D, a baroclinic discontinous Galerkin finite element model [1]. For such flows, SLIM 3D exhibits numerical dissipation where strong density gradients occur, especially on the vertical direction. One way to tackle this problem is to adapt the mesh vertical resolution. For some applications when the region of interest varies in time, an adaptive vertical grid [2, 3] may be necessary, as in the internal seiche test case, for which we compare in the figure below a fixed mesh (top panel) and a vertical adaptive mesh (bottom panel).




During this presentation we will focus on the vertical discretisation of SLIM 3D. Different options will be presented: $\sigma$-layers, $\sigma$-layers on the bottom with z-layers on the top, and an adaptive vertical grid. This last option system will be studied in further details and its benefits and limitations will be shown.

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## CROCO (Coastal and Regional Ocean Community model)

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CROCO (Coastal and Regional Ocean Community model [1]) is a new oceanic modeling system built upon ROMS_AGRIF, the non-boussinesq kernel of SNH, gradually including algorithms from MARS3D (sediments) and HYCOM (vertical coordinates). The communication will put shed light on two among others (which will be briefly mentioned) original features of the numerical model which are being implemented and will be soon available not to say are already:

- The hydrostatic and even the Boussinesq assumption are both relaxed thanks to a local solver which has been proven to be more scalable. It goes one step beyond the traditional and well known correction pressure algorithm [2] that leads to a global 3D Poisson problem; what should be noticed is that both relaxations allows the propagation of pseudo acoustic wave in interaction of the barotropic mode.

- A major objective of CROCO is to provide the possibility of running true multi-resolution simulations as an alternative to unstructured strategy to tackle, up to a certain extent, coastal water problem. Our previous work on structured mesh refinement [3] allowed us to run two-way nesting with the following major features: conservation, spatial and temporal refinement, coupling at the barotropic level. In this presentation, we will expose the current developments in CROCO towards multiresolution simulations:

- connection between neighboring grids at the same level of resolution and

- load balancing on parallel computers.

Results of preliminary experiments will be given both on an idealized test case and on a realistic simulation of the Bay of Biscay with high resolution along the coast.

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# A compact high order (one-step) coupled time and space discretization to represent vertical transport in oceanic models

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Recent papers by Shchepetkin (2015) and Lemarié et al. (2015) have emphasized that the time-step of an oceanic model with an Eulerian vertical coordinate and an explicit time-stepping scheme is very often restricted by vertical advection in a few hot spots (i.e. most of the grid points are integrated with small Courant numbers except just few spots). The consequence is that the numerics for vertical advection must have good stability properties while being robust to changes in Courant number in terms of accuracy. An other constraint is the strict control of numerical mixing imposed by the highly adiabatic nature of the oceanic interior. The same applies for remapping schemes when ALE coordinates are used. We propose to examine in this talk the possibility of mitigating vertical CFL restriction, while avoiding numerical inaccuracies associated with standard implicit schemes (i.e. large sensitivity of the solution on Courant number, large phase delay, and possibly excess of numerical damping).

Several regional oceanic models have been successfully using fourth order compact spatial discretizations for vertical advection. In this talk we present a space-time generalization of compact schemes. In particular, we derive a generic expression for a fourth-order (one-step) coupled time and space compact scheme (see Daru & Tenaud (2004) for a thorough description of coupled time and space schemes). Among other properties, we show that this scheme is non dissipative, unconditionally stable, and has very good accuracy properties especially for Courant numbers smaller than 1 while having a very small computational cost. Furthermore, we show how this scheme can be made monotonic without compromising its stability properties. We emphasize that the scheme can be successfully used in number of different situations:

- as an unconditionally stable vertical advection scheme in an oceanic model with quasi-eulerian vertical coordinate (provided a degradation of time accuracy for large Courant numbers)
- as a scheme to compute the so-called "fractional ux" in a ux-form semi-lagrangian scheme a la Lin & Rood (1996) to provide a stable scheme even for large Courant numbers
- as a remapping scheme in an ALE framework following Dukowicz & Baumgardner (2000)

We illustrate the properties of the scheme and compare it to existing fourth-order accurate in time and space schemes using linear and nonlinear numerical experiments.

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## Implementation of a semi-implicit scheme using a multigrid solver into a regional ocean model

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The numerical solution of the momentum equations by explicit integration imposes a limit on the time step which is restricted by the CFL stability criterion. A common technique for partially removing this constraint is mode-splitting whereby the depth-averaged (2-D) equations are first solved for a number of small time steps, satisfying the CFL criterion, followed by an integration of the 3-D equations with a larger time step. Since the limiting time step is inversely proportional to the square root of the water depth, mode-splitting still remains CPU inefficient in deeper water.

The time constraint can be completely removed using a (semi-implicit) time integration scheme leading to an Helmholtz-type equation for the surface elevation. The discretised form of this equation results in a system of linear equations to be solved with an adequate solver. Several schemes have been proposed in the literature. Here, we discuss the implementation of a geometric multigrid solver in the COHERENS model. The method consists of applying a number of Jacobi or Gauss-Seidel iterations on the model (fine) grid to reduce the high-frequency (short-scale) error. The iterative process is repeated firstly on successively coarser grids and then in the reverse sense on successively finer grids. Interpolation is performed at each passage to a coarser/finer grid. The procedure is repeated after each (V- or W-) cycle until convergence is achieved. Although complex in form, the method proves very efficient in CPU time provided that, depending on the application, a number of numerical parameters are appropriately tuned. The efficiency of the method is discussed by a tidal shelf sea application.

## Session 4: Regional high-resolution modeling

### Resolving the spatial variability of environmental conditions in Norwegian fjords by a numerical ocean model

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The dynamics of the fjords and coastal regions are characterized by high spatial and temporal variability, and typically more stratified water masses compared to the ocean. The environmental parameters such as currents, salinity and temperature are dynamically linked through the physical conservation laws, as for the open ocean. For offshore ocean circulation models the spatial resolution is leading on whether the mesoscale dynamics are properly resolved or not. A fjord model will have additional constraints on how the bathymetry is resolved, e.g. to resolve straits and fjord heads that may have a strong influence on the main fjord dynamics and the fjord-coast water exchange. The topographical complexity of Norwegian fjords introduces essential challenges related to spatial (and temporal) resolution that squeezes our computational resources. In order to meet the increasing amount of public demands on detailed knowledge of environmental conditions in Norwegian fjords, e.g. related to water quality parameters, spread of early life history of fish (eggs/larvae) or patches of infectious agents being advected around, an ocean model system for the entire Norwegian coast and fjords is established, named NorFjords (Norwegian Fjords). The numerical current model used is the Regional Ocean Model System (ROMS, http://www.myroms.org). The horizontal resolution is usually 160m by 160m (can be finer), and vertically the model is normally using 35 terrain-following coordinate levels with higher density in the upper 30m. The internal time step of solving the equations of, among others, conservation of momentum, temperature and salinity, is about 10 seconds. Additional efforts must be made to apply detailed external forcing, most importantly high-resolution atmospheric modeling and realistic freshwater discharges from rivers with high resolution in time and space as well as open boundary conditions at the coastal ocean. The NorFjords system will be demonstrated where the main innovations are the generation and accuracy of the external forcing data and the streamlining of performing simulations quickly for a specific area and time period when required. We will present a short overview of the main technical details along with user products and validation results for some fjords. In addition, we will show how it is used as the main provider of environmental conditions in the national salmon lice monitoring leading to influence on aquaculture production.

# A high resolution ocean model for the Oslofjord

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We present a new high resolution ocean model for the Oslofjord area (FjordOs CL). The model is based on the Regional Ocean Modeling System (ROMS), and is developed as a part of the FjordOs project. It has a curvilinear grid with variable resolution between 50 and 400 meters, realistic river runoffs, adjusted tidal forcing from TPXO, and high resolution atmospheric forcing.

The Oslofjord is located in Southern Norway and is about 100 km long. Its width varies from about 25 km at the entrance ($\sim 59^{\circ}$N) to about 1-2 km in the Drøbak Sound and Drøbak area. The fjord is somewhat special among the Norwegian fjords from a physical as well as a societal perspective. The population surrounding it is by far the most populated area in Norway. It comprises about 40% of Norway's population, and the population is steadily growing. Moreover, no other Norwegian fjord has anything close to as high density of leisure boats. In addition the Oslofjord features two of Norway's national underwater parks, the Hvaler National Park and the Færder National Park. Thus, taking into account that the Oslofjord has the largest traffic density of commercial vessels of all the Norwegian fjords the risk of an accident resulting in a possible, unwanted contaminated effluent to the fjord is uncomfortably high.

The Norwegian Meteorological institute (MET Norway) uses ROMS as its main ocean model for modeling tides, storm surge, currents, temperature and salinity. MET Norway also has a national responsibility for running emergency models to predict drift paths for Search and Rescue (SAR), ships, and oil. The main motivation behind the development of this new Oslofjord model is to improve the predictions of drifting substances in the fjord by better resolving the small scales present. This includes a more detailed topography and coastline, and a better representation of islands and narrow sounds than present in our regional model which covers the entire Norwegian Coast (NorKyst800). Results from a trial hindcast run, along with comparisons with observations, will be presented.

## Modelling coastal circulation in Finnmark, Norway with the unstructured grid model FVCOM

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[2]*University of Athens, Greece*

We have setup the Finite Volume Community Ocean Model for Finnmark, northern Norway , with a resolution varying from 800 m at the open boundary to 50 m in narrow passages with strong tidal currents. The model is forced with output from a high-resolution atmospheric model (RAMS-ICLAMS) of the northernmost part of Norway. Open boundary conditions are provided by hourly output from NorKyst800m, the Norwegian 800 m resolution coastal model based on ROMS. These boundary conditions also include tides originally from TPXO. River runoff data are provided by the Norwegian Water Resources and Energy Directorate, and the model includes 1686 rivers. The smallest rivers (about 1500) are added to the precipitation for computation efficiency. The simulation is run for the two years 2013 and 2014. We show how the model results compare to available observational data and analyze the near shore and fjordal circulation patterns. The model results illustrate the importance of resolving narrow straits with strong tidal currents. The advection of the kinetic energy created at these locations together with the asymmetry in the circulation pattern for different flow direction causes strong mean flow in some of the modelled fjords.

## Three-dimensional circulation and hydrography over the Scotian Shelf, a numerical study using a multi-nested ocean circulation model

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A multi-nested coastal ocean circulation model was developed recently for the Scotian Shelf. The model consists of four submodels downscaling from the eastern Canadian Shelf to the central Scotian Shelf. The model is driven by tides, river discharges, and atmospheric forcing. The model results are validated against observations, including satellite remote sensing data from GHRSST and Aquarius and in-situ measurements taken by tide gauges, a marine buoy, ADCPs and CTDs. The simulated monthly-mean sea surface temperature and salinity have fair agreement with satellite remote sensing observations. The ocean circulation model is able to capture variations of sea levels, hydrography and the Nova Scotia Current on timescales of days to seasons over the central Scotian Shelf. Model results are also used in examining the effect of tidal mixing and wind-driven coastal upwelling in the formation of cold surface waters along the coast of Nova Scotia. It shows that cold water along the south shore of Nova Scotia is a result of wind-driven coastal upwelling. The formation of cold water in the Bay of Fundy and off Cape Sable is due mainly to tidal mixing and topographical upwelling.

# Session 5: Forecasting and assimilation

## On Meteorological Forcing in Ocean Modelling

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Numerical ocean models are in operational use at many institutions around the world. In this presentation, a particular issue related to an inherent discontinuity of operational meteorological forcing data will be examined. It will be shown, that a naïve implementation of an operational forecast process may lead both to discontinuous forcing data, and to a significant difference of the forcing's spectral components in, respectively, forecast/nowcast and hindcast modes. This difference may result in significant underprediction of forecast/nowcast errors of ocean models, compared to hindcast. The discontinuity problem is examined, and a straight-forward solution is proposed. The effects of the discontinuity on a particular ocean model are quantified, and results with and without use of the outlined solution are examined.

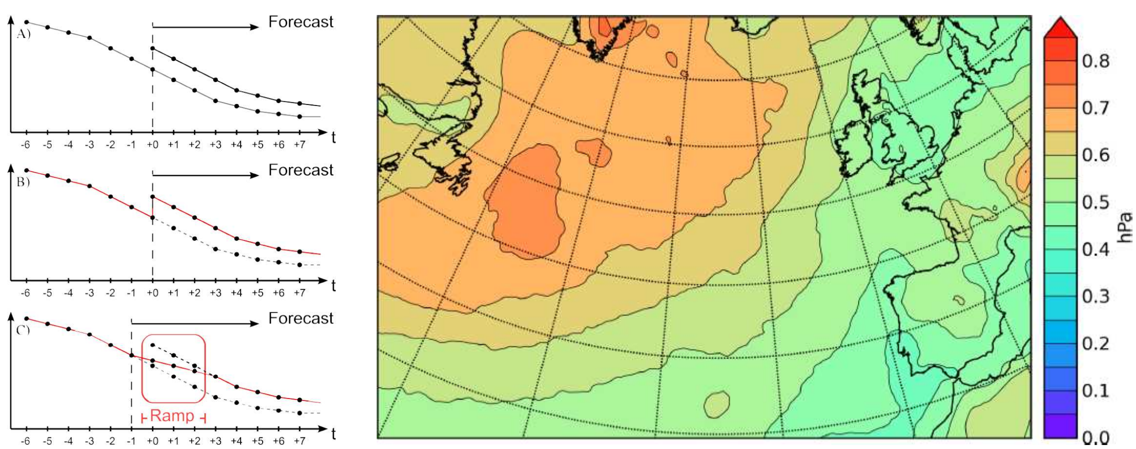


Figure 5: Left-hand figure shows a conceptual time series of meteorological data. Dots denote times, where data fields are available. The actual variable could be, e.g., pressure, temperature or wind. The dashed line denotes the start of the meteorological forecast. Panel A: Two consecutive meteorological forecasts: new (black line) and old (grey). Panel B: Meteorological forcing for ocean model with hotstart coinciding with the epoch; it is assumed that the ocean model uses linear interpolation between the available meteorological fields. Panel C: Meteorological forcing for ocean model with hotstart at -1H and three hours of meteorological ramping. Right-hand figure depicts the absolute sea level pressure change at the analysis time step averaged over all forecasts in 2010-2013.

In the left-hand panel of Figure 5 a conceptual data from two subsequent forecasts are shown. The difference between the forecasts at the analysis time is caused by assimilation of observations into the meteorological model. The epoch, or analysis time, is the first time step of the forecast typically temporally aligned to midnight UTC plus an integer times six hours. It may seem natural to choose the epoch as the start of an ocean forecast simulation, and write a new hotstart at +6 hrs for the next forecast cycle. This choice seems to be commonly used in operational ocean modelling. However, due to the data assimilation at the analysis step of the weather forecasts, the meteorological data from two consecutive forecasts are discontinuous exactly at the epoch (panel B). This discontinuity in the meteorological forcing, which could include instantaneous repositioning of pressure minima, generates non-physical waves, as the ocean model adapts to the sudden changes in forcing. Since this process is repeated every six hours (every epoch), the ocean model is in effect forced by data, which are discontinuous every six hours, and thus non-physical waves are generated every six hours back in time. These non-physical waves may continue to propagate around the model domain for the entire forecast.

To increase the uniformity of the meteorological forcing, it is possible to perform a so-called ramping process, in which a linear combination between old and new meteorological forecast fields are used to change smoothly from the old to the new forecasts (left-hand figure, panel C). The obvious disadvantage is that the ramping process sacrifices the accuracy of the first fields of the meteorological forecast, by replacing a significant part of the data with older and probably less accurate data from the previous forecast. Thus, the ramping is a delicate balance between smoothness and (temporally local) accuracy. As is the case in many other aspects of (ocean) modelling, the use of the most accurate (unfiltered) data is not implicitly ensuring the most accurate model results.

The magnitude of the discontinuity in sea level pressure has been investigated using four years of meteorological forecasts. The mean absolute change in sea level pressure corresponding to the +0 hrs in the left-hand figure is shown in the right-hand figure. The change is significantly larger than the average absolute change in sea level pressure over one hour. It is therefore not surprising that we find a significant effect of this discontinuity on the ocean model forecast.

## Application of Multi-Window Maximum Cross-Correlation to multi-sensor datasets and comparison with HF radar current measurements

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The Maximum Cross-Correlation (MCC) technique was known in oceanographic applications for about thirty years. In this period many authors have been working to improve its capability and reliability to provide useful and realistic results for ocean currents. However the progress done is limited by the accuracy and resolution of satellite sensors and by the number of satellite passes available to middle latitude.

In previous studies by our group an improved version, called Multi-Window Maximum Cross-Correlation (MW-MCC), was proposed, and its applications to synthetic imagery, obtained by a regional high resolution ROMS model, and to high resolution (about 1 km) MODIS images were discussed. The areas considered for these studies were the Tyrrhenian Sea, Ligurian Sea, and part of the Balearic Sea up to the Gulf of Lion. Due to the lack of systematic current measurements in this areas, it was not possible to perform an extensive error analysis of the MW-MCC results, although, a comparison between HF radar measurements and MW-MCC data was shown for a case study near Toulon.

The recent higher resolution (750 m, and 375 m) products obtained by the VIIRS sensor on the Suomi satellite allow now further developments of MW-MCC applications. In particular, the possibility to integrate the MODIS and the VIIRS datasets in order to increase the temporal resolution of images, gives an improvement both in the number of MW-MCC current maps and in their accuracy. For example, in the 2013 summer dataset of MODIS images, only about 15 pairs of images per month at the latitudes of Tyrrhenian Sea were suitable for MW-MCC applications, while considering also VIIRS images an increase of about 30% can be reached.

Moreover, the increased spatial resolution of the new images allows a significant increase in the accuracy of the current estimation by the MW-MCC technique.

Finally, since a new HF radar system is now operational in Tuscany, a more systematic error analysis of the MW-MCC results in this area can be done.

# On Ensemble Variability in Ocean Modelling

Bjarne Büchmann and Johan Söderkvist
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FCOO runs operational forecasts for the Danish waters. The NS1C model setup is a 1nm, 60-layer baroclinic model covering the North Sea - Baltic Sea area, see Büchmann et al., 2011. It is of concern that the uncertainty inherent to the stochastical nature of the model is unknown. It is well-known that the physical processes of hydrodynamics inherently are chaotic in nature. This does not mean that the processes are entirely unpredictable, but rather that the exact physical state cannot be predicted in advance. A numerical model of the system, should at least to some degree share the stochastic nature of the flow: on the chosen scale, the model must resolve each eddy. While a particular numerical result may be reproduced exactly by re-running the model, it is still so that the result should be seen as a single outcome of a stochastic process. If the simulation is perturbed just slightly, then it may result in a rather different end state. If the perturbation is small enough, then the overall stochastic process is unchanged, and the second simulation may be viewed as a second outcome of the same stochastic process. Thus, in a calibration scenario it may be difficult to state with certainty, that a particular model setup is changed (for better or worse), even though the computed model skill score is different.

To shed light on some of the inner workings of the model, we examine model uncertainties related to pure stochastical phenomena using ensemble model runs of the FCOO NS1C model setup. The initial conditions are perturbed by $\Delta S(x,y) = \epsilon_{salt} \cdot p(x,y)$, i.e., each water column is perturbed by a constant factor. Here $\epsilon_{salt}$ is PSU units, and $p(x,y)$ contains random values from the uniform distribution over $[-0.5, 0.5]$.

It is found (results omitted for brevity) that even the smallest actual change of the initial state leads to branching of the numerical model results. Changing as little as 1 mg of salt has led to simulation branching, and to large local differences of several PSUs within a few days of simulation. The model execution is fully repeatable, so the uncertainty is unrelated to e.g. random rounding effects taking place in the floating point computations.

Annual simulations with an ensemble, consisting of 20 independent perturbations of the initial conditions are made, where the salinity perturbation is $\mathcal{O}(10^{-12})$PSU, corresponding to a redistribution of about 10kg salt within the North Sea - Baltic Sea domain. The ensemble variability during the first five days is demonstrated here by showing the salinity variations at Drogden Sill in the Sound, see Figure 6. Initially, the variability corresponds to the applied level of perturbation. After a few hours, the ensemble variability grows exponentially, and increases roughly 10 orders of magnitude over a 34 hour period. It is postulated that the cause is simple time-stepping repetitions. After some time, the differences between ensemble members reach “physical” levels, which end the exponential increase.

After a few months the ensemble reaches a state with some limiting variability, which varies significantly over the modelled area. Spatially limited short-term periods with high ensemble variability occur intermittently. For example, after about nine months of simulation the surface salinity range is about 0.1PSU at a location in Skagerrak, see Figure 2. Due to the passage of a free eddy, the ensemble variability increases almost two orders of magnitude. On this occasion,

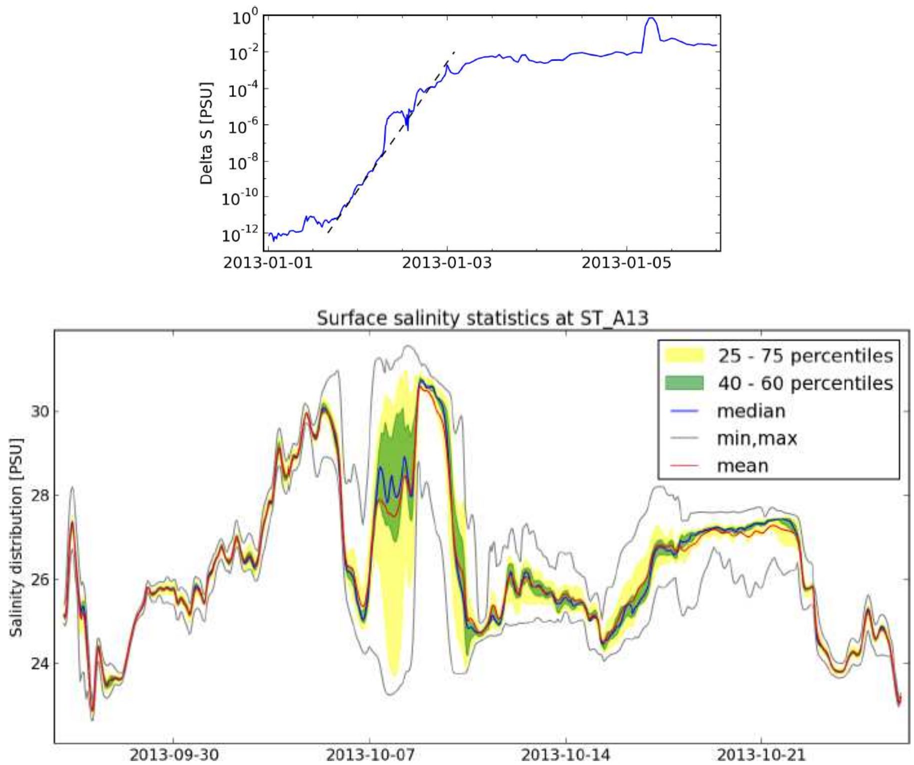


Figure 6: Upper figure shows time series of surface salinity range (max-min over all ensemble members) at the Drogden Sill (the Sound). Lower figure depicts time series of statistical properties over 20 ensemble members for surface salinity in eastern Skagerrak.

the 25-75 percentile band is very wide, so 50% of the ensemble members are very close to the extreme ends of the distribution. At other times, the majority of the ensemble members are close to the median value, corresponding to a narrow 25-75 percentile band. After some time, when the salinity front has passed this particular location, the range goes back to O(0.1PSU). The variation in the ensemble distribution could have adverse effects for data assimilation. It might be considered to use observational data to select between ensemble members rather than correcting the individual members in a data assimilation process. This procedure is known as a Particle Filtering Method or Sequential Monte Carlo Method (Liu and Chen, 1998), and is described in detail by e.g. van Leeuwen (2010).

## Forecasting the Ecology of the Red Sea using a Cluster of Regional 1D Marine Ecosystem Assimilative Models

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Marine ecosystem models are increasingly used to understand and predict the functioning of large-scale marine ecosystems. These models are based on a set of mathematical equations governing the ecosystem variability and dynamics, generally forced by the outputs of a hydrological model. Recently, the European regional seas ecosystem model (ERSEM) has been coupled to the MITgcm circulation model to simulate the Red Sea ecology. However, the complexity of such a 3D model makes it difficult to parameterize, tune, and assimilate, especially when not enough data are available, which is usually the case in many marginal seas. This contribution explores the possibility of partitioning the Red Sea into different distinct provinces, covering the major patterns of surface phytoplankton production. This is implemented using an unsupervised learning algorithm and remotely sensed chlorophyll (CHL) data. The idea is then to consider several (independent) 1D ERSEM models describing the ecosystem of the different identified regions of the Red Sea, which drastically reduces computational cost compared to a 3D ecosystem model. An ensemble Kalman filter is then applied to each regional 1D model for assimilation of satellite CHL data and forecasting, and for parameters estimations. Numerical experiments assimilating real CHL data are conducted to demonstrate the efficiency of the proposed approach.

## Optimize oceanographic observation networks to reduce ocean forecast uncertainty

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There is a growing demand for ocean observing data to support activities such as marine monitoring, ocean forecasts (from regional to coastal scales), maritime surveillance and safety, and all activities related to the so-called Blue Growth. Collecting data at sea is an expensive and difficult task, and a concept of long term sustainability should also involve the creation of sustainable observation networks, that can be achieved through a rational use of available resources. The design of observing systems can take great advantage from the identification of optimized sampling points (moorings, buoys Lagrangian, or autonomous marine vehicles) aimed at collecting information needed to Data Assimilation. This allows both to reduce costs, and to improve significantly the quality of ocean forecasts. In particular, the criteria may be established on the basis of the dynamic model properties (analysis of errors growth), in combination with criteria based on information theory.

In the present work we first introduce some experimental activities recently undertaken in the coastal area between the Ligurian and Northern Tyrrhenian seas, where a new observing and forecasting system have being installed as part of the SICOMAR project, in order to provide real time data at high spatial and time resolution and, possibly, reliable forecasts. Other test cases are based on conceptually simpler models, like the ocean double-gyre and a quasi-geostophic model. The performances of the data assimilation procedures depend on the particular dataset configuration, well beyond the background quality and the assimilation method in use.

In order to identify the dataset composition which is able to minimize the forecast error, a methodology based on Singular Vectors Decomposition (SVD) of the tangent linear model is proposed. Such a method can give strong local indication on the error dynamics. Model configurations are based on available ROMS routines, where a variational assimilation algorithm (4D-var) is included as part of the code These applications have provided encouraging results in terms of increased predictability and reduced forecast error, also improving the quality of the analysis to recover any real circulation pattern from a first guess even far from the real ocean state.

## EnKF vs. EnOIs for data assimilation in the Red Sea and Sensitivity to Atmospheric Forcing

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We present our efforts to build an ensemble data assimilation and forecasting system for the Red Sea. The system is composed of the MIT general circulation model (MITgcm) to simulate ocean circulation and of the Data Research Testbed (DART) for data assimilation. In this implementation, the MITgcm is configured with a horizontal resolution of 4 km and 50 depth-varying vertical layers. The model is forced with real time atmospheric products from the National Center for Environmental Prediction (NCEP) and the European Centre for Medium Range Weather Forecasts (ECMWF) Red Sea fields. DART has been configured to integrate all members of the ensemble Kalman filter (EnKF) in parallel, and for testing with an invariant ensemble, i.e. an ensemble Optimal Interpolation (EnOI). To deal with the strong seasonal variability of the Red Sea, the EnOI ensemble is seasonally selected from a climatology of long-term model outputs (dictionary). Observations of Sea surface height (SSH) and sea surface temperature (SST) are assimilated every three days. We examine the behaviors of the EnKF and EnOI and compare their performances. We further investigate the impacts of the different atmospheric forcings on the results of the assimilation system.

## Assessing an Ensemble Kalman Filter Inference of Manning's n Coefficients of a Storm Surge Model against a Polynomial Chaos-Based MCMC

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Bayesian estimation/inversion is commonly used to quantify and reduce such uncertainties in coastal ocean model, especially in the framework of parameter estimation. Based on Bayes rule, the posterior probability distribution function (pdf) of the estimated quantities is obtained conditioned on available data. This posterior pdf can be computed either directly using the sampling-based Markov Chain Monte Carlo (MCMC) approach, or by sequentially processing the data following a data assimilation approach, which is heavily exploited in large dimensional state estimation problems. The advantage of data assimilation schemes over MCMC-type methods arises from the ability to algorithmically accommodate a large number of uncertain quantities without significant increase in the computational requirements. However, only approximate estimates are generally obtained by this approach due to the restricted Gaussian prior and noise assumptions generally imposed in these methods. This contribution aims at evaluating the effectiveness of utilizing an ensemble Kalman based data assimilation method for parameter estimation of a coastal ocean model against an MCMC Polynomial Chaos (PC)-based scheme. We focus on quantifying the uncertainties of a coastal ocean ADCIRC model with respect to the Manning's n coefficients.

Based on a realistic framework of observation system simulation experiments (OSSEs), we apply an ensemble-based Kalman filter, the Singular Evolutive Interpolated Kalman (SEIK) filter, and the MCMC method employing a surrogate of ADCIRC constructed by a non-intrusive PC expansion for evaluating the likelihood, and test both approaches under identical scenarios. We study the sensitivity of the estimated posteriors with respect to the parameters of the inference methods, including ensemble size, inflation factor, and PC order. We present a full analysis of the solutions of these two methods and the contexts in which each algorithm applies, and make recommendations for realistic applications.

# Session 6: Transport in the ocean

## OpenDrift - an open source framework for ocean trajectory modeling

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We will present a new, open source tool for modeling the trajectories and fate of particles or substances (Lagrangian Elements) drifting in the ocean, or even in the atmosphere. The software is named OpenDrift, and has been developed at Norwegian Meteorological Institute in cooperation with Institute of Marine Research. OpenDrift is a generic framework written in Python, and is openly available at https://github.com/knutfrode/opendrift/.

The framework is modular with respect to three aspects: (1) obtaining input data, (2) the transport/morphological processes, and (3) exporting of results to file. Modularity is achieved through well defined interfaces between components, and use of a consistent vocabulary (CF conventions) for naming of variables. Modular input implies that it is not necessary to preprocess input data (e.g. currents, wind and waves from Eulerian models) to a particular file format. Instead "reader modules" can be written/used to obtain data directly from any original source, including files or through web based protocols (e.g. OPeNDAP/Thredds). Modularity of processes implies that a model developer may focus on the geophysical processes relevant for the application of interest, without needing to consider technical tasks such as reading, reprojecting, and colocating input data, rotation and scaling of vectors and model output. We will show a few example applications of using OpenDrift for predicting drifters, oil spills, and search and rescue objects.

## Long-term dispersion of radioactive technetium-99 from Sellafield: the impact of resolution

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The controlled discharge of radioactive technetium-99 from Sellafield between 1994 and 2004 is a great opportunity for studying large-scale transport of a passive tracer in the North Atlantic. Technetium-99 is a highly soluble radionuclide, so it can be assumed to be entirely dissolved in sea water, following the currents with a passive tracer behavior. In addition, the concentration of technetium-99 downstream of the source has been closely monitored at a number of obervation stations up until the present. In this study, the fate of the Sellafield discharges has been simulated with flow fields from the global FOAM model at 0.25 deg. horizontal resolution and from a regional ROMS model at 4km resolution. The FOAM fields have a temporal resolution of 1 month whereas ROMS fields with either 1 day or 1 hour resolution have been used. Transport and dispersion was estimated using the off-line Lagrangian dispersion model TRACMASS. The model concentrations have been compared with timeseries of seaweed and seawater samples taken at Norwegian and British monitoring stations.

Model results show good general agreement with observations in light of sampling errors. But the hourly ROMS fields gives the best prediction. In particular, because of highly energetic tidal currents in the Irish Sea, a net northward wave-induced drift appears in the model runs that use hourly circulation fields. When the tides are filtered out there is a stronger southward transport in the southern Irish Sea. This feature suggest that inclusion of tides are required for correct Lagrangian dispersion simulations in the Irish Sea. This process also strongly impacts the flow out of the Irish Sea, so the run that use hourly fields has a better correlation with the observations at greater distances as well. The study also points to problems with using regional models. In this case challenges were experienced as the regional model boundary is too near the source. In the runs with daily model fields, the lack of tidal motions thus causes a too high flux of particles out of the southern model boundary. This artifact is not present in the runs with hourly circulation fields (because of the northward wave-induced drift) and in the global model.

## Dispersion of land-derived substances in the coastal environment

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Land derived substances affect the coastal ecosystem. One example of this is the phenomena ocean darkening due to increased input of organic matter and particles in general, which greatly reduces the available light for marine plankton.

Here we demonstrate the possibilities a combination of modelling tools and satellite products may give. The study area is the outer Oslofjord where the river Glomma has its outlet. First we look at the amount of matter in the river water, based on the RID program, the TEOTIL model and we also look at the possibility of the INCA model.

Next step is to compare dispersion in the Hvaler archipelago and beyond using satellite products and results from the FjordOs model (www.fjordos.no). With the use of the USGS satellite, Landsat-8, the relative distribution of particles can be calculated with a spatial resolution of 30 m. Within the repeat cycle of 16 days, two different orbits pass the Glomma outflow. These satellite data can help mapping how far the dispersion of the outflow can reach and also the magnitude of the dispersion

## Changes in drift pathways of fish egg along the coast of Norway

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Observational evidence from the past decades show that while spawning of fish egg and larvae off the coast of Norway at MÃ¸re has declined dramatically, the corresponding spawning in the Lofoten region to the north has not undergone a similar change. It is not fully understood if this shift is due to changes in environmental (climatic) conditions, or if it can be attributed to increased pressure from commercial fisheries, or if it can be attributed to increased pressure from commercial fisheries removing the largest individuals.

These hypotheses can be tested by combining egg survey data with drift models. If the drift of the eggs are well represented we can estimate the spawning intensity at the different spawning ground. In such a way it is possible to extend the data with several decades and hence get a better basis for separating the two hypotheses.

We present early results from simulations which are designed to shed light on changes in drift from two selected spawning sites, using the ROMS ocean model. We examine three different means by which advection of eggs are represented: (1) as particles represented by "floats" in the numerical model; (2) as tracer concentration advected and diffused in the model; (3) as particles in the off-line advection and diffusion model LADIM. Seasons from two years will be investigated in this context, using a combination of a 800m configuration and a 4km configuration.

Our discussion will focus on two topics:

1. How results depend on the method used for representing fish egg in numerical simulations
2. Differences of results between the two years, with emphasis on contrasts between the two spawning sites, to investigate the impact from environmental conditions versus spawning stock demography on drift pathways.

## Suspended sediment transport in Red River Delta coastal area

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The Red River Delta estuarine and coastal zone is located in the north east of Vietnam, western of Tonkin Gulf. This area is directly impacted by the Red-Thai Binh river system. Sedimentation at the Red River estuarine and coastal zone is an important influence on erosion in coastline and deposition in biggest port in the North Vietnam. Due to the influence of a tropical monsoon climate, water discharge and sediment flux to the Red River estuarine and coastal zones are concentrated in the rainy season (Apr. - Sep.). This area is largely affected by a diurnal tide with a maximum amplitude up to 4 m. This paper presents results of a three dimensional numerical model to simulate hydrodynamic and suspended sediment transport in the study area. The model (based on Delft3D system model) was setup with five vertical layers in Sigma coordinates. River data of water discharge and suspended sediment concentration were collected and systematically and homogeneously processed in order to create open river boundary conditions (time-series) for the model. Tidal constituents analyzed from tidal gauge data measured in near the coast, FES2004 and WOA13 were used for sea boundaries condition. two stations were used at the open sea boundaries. There was a fair match between model results and measured data of water elevation, currents, and suspended sediment concentration-SSC and between model data and satellite data of suspended sediment concentration in the surface layer. Results of the dry and rainy simulation show the temporal distribution and spatial variation of hydrodynamics and sediment transport change in time with a high dependence on tidal oscillation. Alongshore net sediment transport has a tendency to move to the South West of the studied zone.

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## Using ocean modelling to structure salmonid farming in Norway

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Salmonid farming is a large industry in Norway. The management objective from the government is to obtain environmentally sustainable growth in the industry. The largest environmental problem is presently the salmon lice situation, which is used as an indicator of sustainability. To manage this it is proposed to set up production domains, management units for regulating the production volume.

Salmon louse is a copepod. After an initial planktonic phase it lives as a parasite on salmonid fish. It is infectious between 50 and 150 degree days. A combination of coastal modelling and particle tracking is used to model the transport of the planktonic stages. The results are summarised in an influence matrix, showing the infection pressure from any fish farm upon all others. Cluster analysis is then used to produce a subdivision of the fish farms into domains that balances minimising cross infection of salmon lice while keeping the domains infectively connected.