Abstracts of Invited Talks

Knut Klingbeil,
Leibnitz Institut for Baltic Sea Research Warnemünde:
The problem of numerically-induced mixing

In this lecture talk numerical mixing of water masses will be presented as one of the most challenging problems in ocean models. It is caused by the truncation errors of numerical advection schemes and can easily dominate over the physical mixing due to well-calibrated turbulence parameterisations. An analysis method for the local quantification of numerical mixing will be explained. Finally, strategies to reduce numerical mixing by smart vertical meshes will be outlined.

Piotr Smolarkiewicz,
ECMWF
An important characteristic of the atmospheric dynamics is that it constitutes a relatively small perturbation about dominant hydrostatic and geostrophic balances established in effect of the Earth gravity, rotation, stably-stratified thermal structure of its atmosphere and the incoming flux of solar energy. Given this specificity, it is compelling to formulate the governing partial differential equations (PDEs) in terms of perturbation variables, defined with respect to an arbitrary "ambient" state of the atmosphere that already satisfies these dominant balances. The role of ambient states is to enhance the efficacy of numerical solution–e.g. by simplifying the initial and boundary conditions and/or improving the conditioning of elliptic boundary value problems–without linearising the system.

This talk presents select perturbation forms of nonhydrostatic PDEs that govern dynamics of all-scale global atmospheric flows. There can be many alternative perturbation forms for any given system of the governing PDEs, depending on the assumed ambient state about which perturbations are taken and subjective preferences in the numerical model design. All such forms are mathematically equivalent, yet they have different implications for design of effective numerical integrators of the governing PDEs. Arguments are presented in favour of perturbation forms that enhance the efficiency and accuracy of the numerical solution procedure. The different options are implemented in the global all-scale high-performance Finite-Volume Module of ECMWF's Integrated Forecasting System [1-3]. The presented implementation assumes a class of ambient states of reduced complexity, to verify the theoretical developments, and it provides an effective tool for further study. Numerical simulations of the planetary baroclinic instability, epitomising global weather, illustrate the accuracy of the perturbation equations.

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Dmitr Kuzmin
University Dortmund

Recent advances and new trends in the design of bound-preserving finite element schemes for transport problems

In this talk, we present three approaches to enforcing preservation of local bounds in continuous and discontinuous finite element discretizations of transport problems with steep fronts. The first approach is a predictor-corrector method which constrains the difference between the high and low-order solutions using a flux-corrected transport (FCT) algorithm. The new features to be discussed include the design of localized element-based limiters for arbitrary high-order Bernstein finite elements. The second approach constrains the difference between the residuals of high and low-order space discretizations using nodal limiters to tune monotonicity-preserving artificial diffusion coefficients. This correction technique leads to a nonlinear algebraic system which must be solved iteratively. The third approach combines the high and low-order finite element bases using a continuous piecewise-linear limiter function. This low-level limiting strategy represents a new partition-of-unity approach to hp adaptivity. The local order of approximation is adjusted in a continuous manner while keeping the number of degrees of freedom fixed. Extensions to hyperbolic systems will also be discussed in this talk. Numerical examples will be shown for scalar transport equations and 2D shallow water models.

Carsten Eden
University Hamburg

Energetically consistent models

The energy transfers between the three dynamical regimes -- small-scale turbulence, internal gravity waves and geostrophically balanced motion -- are fundamental to the energy cycle of both the atmosphere and the ocean. Nonetheless, they are poorly understood and quantified, and their representation in state-of-the-art Earth system models is unsatisfactory.

Since the interactions of the dynamical regimes ultimately link the smallest scales to the largest scales by a variety of complex processes, understanding these interactions is mandatory to construct atmosphere and ocean models and to predict climate. The current lack of understanding is reflected by energetically inconsistent models with relatively large biases, but also paralleled by inconsistencies of a numerical and mathematical nature.

Recent efforts to overcome these deficiencies to understand the dynamical interactions, and to improve the consistency of ocean and atmosphere models are described.

Abstracts of Presentations

1) An anisotropic mesh adaptation framework for coastal simulations

N. Barral, J. Wallwork, S. Kramer, A. Angeloudis, G. Gorman, M. Piggott, Imperial College, UK

Many ocean-based engineering applications require the modelling of a large geographic area, while the quantity of interest is very localized (e.g. tidal stream or range based power generation structures, the impact of tsunamis on a city or sea defence, etc.). The large extent of the domains involved and the accuracy required in specific locations tend to result in highly computationally intensive simulations. Mesh adaptation has proven to be an efficient approach to increase numerical simulations accuracy while reducing computational costs by better controlling the distribution of the degrees of freedom. In particular, anisotropic mesh adaptation makes full use of the flexibility of unstructured meshes and optimizes both the location and the orientation of mesh elements. The generation of the adapted meshes is driven by metric fields, which are derived from a certain error estimation in the model. The construction of the error estimators is of particular importance in a mesh adaptation method. In this work, we consider Hessian-based multi-scale metrics, that are able to capture the different scales of the ocean dynamics and the engineering applications of interest. The efficacy of error estimators can be greatly increased by adopting a ``goal-based'' point of view which is a capability also under development: by taking the adjoint of the solution into account in the error model, only the physical phenomena that influence a certain target quantity are accurately meshed and resolved, while all the others (e.g waves moving to the open boundary and away from a target location of interest in tsunami modelling) are coarsely meshed and dampened. The use of the appropriate adjoint formulation ensures that no ``useful'' phenomenon will be ignored. In this work, we present our implementation of mesh adaptivity in our coastal code, Thetis, taking advantage of its underlying PETSc integration. Applications to the modelling of tsunami propagation and tidal range and stream renewable energy generation structures are considered.

2) Towards Model Adaptivity - Localized nonhydrostatic wave modeling

Jörn Behrens, Anja Jeschke, Leila Wegener, University Hamburg

Long wave modeling is often performed with linear or non-linear shallow water wave theory, implemented in corresponding hydrostatic computer models. However, for more realistic features, in particular wave dispersion, nonhydrostatic approaches implemented by Boussinesq-type equations are used. Another approach utilizes nonhydrostatic correction terms to augment the hydrostatic model - the nonhydrostatic projection method. In order to compute these corrections, additional equations need to be solved that are usually of elliptic character and thus require the solution of large linear systems of equations. In order to alleviate the computational requirements arising from the linear system solve, we propose to use nonhydrostatic corrections only locally, obtaining a hybrid hydrostatic-nonhydrostatic model. In this preliminary study, we present first results obtained with a 1D discontinuous Galerkin (DG) implementation of the nonhydrostatic projection method. In order to determine the area, in which to use the (expensive) nonhydrostatic projection a criterion needs to be found that can be derived from the simpler hydrostatic computation. Additionally, care needs to be taken to interface nonhydrostatic with hydrostatic regions.

3) Gravity wave noise in adaptive vertical grids
Reiner Bleck, NOAA

Numerical models of low-Rossby number flow are generally able to mimic the geostrophic adjustment process, but details of the emerging quasigeostrophic equilibrium depend on the discretization errors in the model equations. Consequently, temporal changes in spatial resolution taking place in adaptive vertical grids will perturb this equilibrium. Using a "gravity wave noise meter" based on the 2nd time derivative of bottom pressure, we shed light on the extent to which vertical coordinate movement acts as a source of gravity waves that continually perturb the QG equilibrium the model is trying to maintain. The tool used in this study is the atmospheric global weather model FIM developed at NOAA-ESRL. FIM is laid out on an icosahedral horizontal grid and uses coordinate surfaces that can be chosen to be either fixed in space or near-isentropic adaptive. Results illustrate that gravity wave excitation is a possible negative side effect to the well-understood advantages of isentropic/ isopycnic vertical coordinates in atmosphere/ocean modeling.

4) Grid modes on triangular meshes
S. Danilov, A. Kutsenko, AWI, Jacobs University Bremen

Spurious numerical modes are common to shallow water equations discretized on triangular meshes. We demonstrate using the simplest discretizations as an example that in many cases these modes can be traced back to grid modes of triangular meshes, related to the lack of translational invariance for the discrete degrees of freedom located at cells or edges. The grid mode creates a possibility of decoupling between quantities defined at the nearest cells or edges. This is seen as spurious numerical modes in the framework of linearized shallow water equations. Dissipative operators based on smallest stencils suppress the manifestation of grid modes in solutions. Their ability of
detecting the grid mode is of key importance.

5) What is the optimal mesh layout for unstructured C-grid ocean models?
D. Engwirda, Columbia University

The generation of high-quality staggered grids for unstructured C-grid ocean models is a challenging task; meshes are required to satisfy a number of often competing constraints, including: pair-wise orthogonality, conformance to complex coastal boundaries and user-defined resolution constraints, and tight bounds on grid-cell quality and regularity. In this talk, I analyse the numerical characteristics of a typical unstructured C-grid discretisation scheme and assess the impact of grid irregularity on its performance and accuracy. I argue that unstructured grids based on 'conventional' Delaunay triangulations and Voronoi tessellations are not necessarily optimal for such formulations, and instead advocate for the use of a generalised 'weighted' mesh layout, based on so-called 'Regular' triangulations and their dual 'Power' diagrams. I describe a new coupled mesh optimisation strategy for the generation of such grids and discuss implications for various global and coastal ocean modelling applications using the Model for Prediction Across Scales (MPAS-O) and the COastal Model for Prediction Across Scales (COMPAS).

6) Cross-scale oceanography in the Adriatic Sea

Christian Ferrarin, Silvio Davolio, Debora Bellafiore, Michol Ghezzo, Francesco Maicu, William Mc Kiver, Oxana Drofa, Georg Umgiesser, Marco Bajo, Francesca De Pascalis, Piero Malguzzi, Luca Zaggia, Giuliano Lorenzetti, and Giorgia Manfe, ISMAR

The oceanographic forecast capability in coastal seas is often limited by the capacity of the numerical models in correctly reproducing the complex morphology of the coastline and the exchange processes between the shelf and the open seas. In the marginal Adriatic Sea this task is of uppermost importance due to the presence of several coastal water bodies and rivers. We present here a new oceanographic system, based on the unstructured grid model SHYFEM and representing the whole Adriatic Sea together with the lagoons of Marano-Grado, Venice and Po Delta. The innovative aspect of the oceanographic system for the Adriatic Sea presented in this study is that it accurately addresses land-sea, air-sea, and coastal-offshore interactions. These processes are taken into account in the forecasting system by adopting adjourned discharge for most of the rivers, by forcing the hydrodynamic model with high-resolution meteorological fields, and by resolving the lagoon-sea and the river-sea continuum using a very high-resolution, up to 10 m, numerical mesh. The presented results highlighted the capacity of the developed system in simulating the general circulation in the Adriatic Sea, as well as several relevant coastal dynamics, such as tidal dynamics, saltwater intrusion, storm surge and riverine waters dispersion.

7) Generation of operational forecasts on demand: the OPENCoastS platform

A.B. Fortunato, A. Oliveira, J. Rogeiro, J. Teixeira, A. Azevedo, J. Gomes, M. David, J. Pina, LNEC

Short-term forecasts of coastal dynamics are used for a variety of purposes, such as harbor management, search and rescue operations and response to extreme events. However, the generation of such forecasts remains a complicated procedure, which requires specialized human resources with expertise in both information technologies and modeling of coastal processes, as well as dedicated computer power. This presentation will describe a new Web platform that aims at generating on-demand coastal forecast systems with minimal user intervention. Denoted OPENCoastS (https://opencoasts.ncg.ingrid.pt), this platform is applicable to the European coastal waters and guides the user through seven simple steps towards the generation of an operational forecast system at his/hers coastal region. The user only needs to provide an unstructured grid of the study area, and river flow climatology (if needed). The platform includes the definition of ocean boundary conditions, selected from the options available, the model parameterization of the simulations and the choice of the online stations for model validation, identified by default by the platform. The platform also includes interfaces for the visualization of the results and the management of the forecasts. CPU resources for the forecasts are provided through the European Open Science Cloud, in the scope of the H2020 EOSC-Hub project. Presently, forecasts are generated with the community model SCHISM.

8) FESOM-C: coastal dynamics on mixed unstructured meshes

V. Fofonova, A. Androsov, I. Kuznetsov, S. Danilov, S. Harig, N. Rakowsky, D. Romanenkov,V. Zinchenko, K.H. Wiltshire

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

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Jacobs University, Bremen, Germany

Understanding the impact of climate change on shelf dynamics requires an accurate representation of physical environment in a coupled ocean shelf - open ocean modeling system. We utilize the unstructured mesh approach and augment the existing global sea ice-ocean model FESOM with a coastal branch FESOM-C. The newly developed FESOM-C is intended to work on smaller scales than FESOM, taking into account physical and dynamical processes commonly not accounted in the large-scale models. FESOM-C shares the part of the infrastructure with the global FESOM. It works on hybrid unstructured meshes composed of triangles and quads, which combine geometrical flexibility and numerical efficiency. The overview of FESOM-C and aspects of the hybrid mesh applications are the main focuses of this presentation.

9) A practical test case for modelling intertidal areas

David Greenberg Fisheries and Oceans Canada Bedford Institute of Oceanography, Canada
Florent Lyard LEGOS, Université de Toulouse, CNRS, IRD, CNES, UPS Toulouse, France

We have prepared a mesh to test drying algorithms for unstructured triangular grid models. The mesh defines a square bay with 50 km sides, driven on the one open boundary by a uniform tide of 4.0 m. The bottom shallows from 45 m on the open boundary to -6 m at the inner end of the bay. There are three different deviations from the constant shelf: 1) There is a narrowing deep channel that will not dry. It narrows to a width where there is a single node connected to the deep water and all other surrounding nodes will dry when the tide recedes. 2) There is a flat area at mean sea level which extends out beyond the 0 m isobath of the constant slope. This will flood from all sides and slowly drain on its sloping boundaries. 3) There is a tide pool that will be isolated with trapped water when the tide recedes. We have tested the mesh with T-UGOm, FVCOM, Quoddy and SCHISM. Our principal purpose for including drying in our models is not to accurately reproduce the intertidal hydrodynamics, but to faithfully reproduce the dynamics in the deeper parts of the model. Having said that, in a test case with accurate bathymetry (LIDAR) in a high resolution model, a model can reproduce the advance of the tide through the intertidal area very well.

10) Comparing different approaches to ocean model horizontal resolution distribution for unstructured meshes with FESOM2

Ozgur Gurses, Nikolay Koldunov, Dmitry Sidorenko, Sergey Danilov, AWI

When designing horizontal ocean model grids one should find a balance between the realistic reproduction of ocean dynamics necessary to solve specific scientific tasks and the computational resources. An increase in the computational resources allows to make less compromises on the total grid size, however model configurations that resolve mesoscale ocean dynamics over most of the globe are still not feasible for the majority of the modelling groups. Ocean grid resolution alters the simulated ocean dynamics in two major ways: it determines if eddies will be explicitly simulated and specifies how well the bathymetry will be rendered.

Unstructured meshes are flexible tools compared to standard rectilinear grids and can have arbitrary resolution distributions over the world oceans. This allows for the creation of global, dynamically consistent setups with increased resolution over particular regions, oceans or straits. However, when interested in the global ocean dynamics one has to make a decision on how to best use the unstructured mesh flexibility to distribute resolution on the global scale.
In this study we will compare simulations performed with the Finite-volumE Sea ice–Ocean Model (FESOM2) on four unstructured meshes. Two meshes have non-uniform resolution distributions based on the observed sea surface height variability (mesh HR) or resolve the Rossby radius with two grid points (mesh XR). Another two meshes have uniform resolution distributions that are similar in size to their non-uniform counterparts. The uniform resolution meshes are based on well known structured meshes (ORCA25 and STORM).
The performance of the four different meshes are compared with respect to basic ocean diagnostics. In particular, temperature and salinity biases in the deep ocean, SSH variability and AMOC strength are investigated. Furthermore, main reasons for differences between the simulations are studied. Information on computational performance and stability of the meshes are presented and recommendations on which meshes to use for which purposes are given.

11) A 3D model to simulate dissolved oxygen dynamics in the Elbe Estuary
Ingrid Holzwarth, Kai Wirtz, BAW Hamburg

An estuarine oxygen minimum zone regularly develops in the Elbe Estuary, impacting its ecology and biogeochemistry. The dynamics of dissolved oxygen is mainly due to the interaction of phys-ical and biogeochemical factors, but a detailed process understanding to track cause and effect relations is lacking. This gap is especially relevant when assessing anthropogenic influences. Therefore, we developed an integrated hydrodynamic-biogeochemical model consisting of Un-trim and D-Water Quality, and a tailored model configuration for the simulation of dissolved oxygen dynamics in the Elbe Estuary. Due to the subgrid bathymetry included in the hydrody-namic model component Untrim, the model is able to precisely represent water volume and wa-ter surface area. This characteristic is of particular benefit when studying the effects of man-made bathymetric modification on dissolved oxygen. For two bathymetries which reflect a 40 year difference in man-made modification, we find the difference in dissolved oxygen to be small, especially when compared to a change in riverine nutrient and phytoplankton load. Despite the considerable depth difference in the two bathy-metries, dissolved oxygen concentrations are only slightly reduced in the higher impacted ba-thymetry. However, the impact of the maintenance needed to preserve the higher impacted ba-thymetry still remains to be studied. Considering the combined effect of bathymetric change and maintenance may point to a greater impact on dissolved oxygen concentrations than pure geo-metric change.

12) Influence of estuarine and coastal morphology on tidal characteristics of adjacent coastal waters (ALADYN –C)
Krischan Hubert, NLWKN

Tide gauges along the German coastline record the tidal dynamics of the North Sea since up to over 150 years. Trend analysis of such long time records show a general increase of characteristic tidal values, ranging from several centimeters up to a few decimeters for the past century. In addition to global contributors like sea level rise, changes of the tidal regime also mirror effects on local scales. The interaction of the tidal wave with the coastline bathymetry is influenced by nonlinear hydrodynamic effects. Anthropogenic interventions of the past 120 years heavily modified the estuaries of the rivers Ems and Weser, causing a drastic change of the local tidal regimes. Whether these interventions additionally influence the tidal regime of adjacent coastal waters, thus effecting the aforementioned trends of coastal gauge stations, is analyzed using a numerical model on unstructured grids (SCHISM). Tidal signals from simulations with bathymetry of the estuaries prior to the major interventions are compared to such signals from simulations with the present morphological state. A cross-scale approach bypasses prerequisite model nesting. While resolving the wadden sea and estuaries up to the tidal barriers with high resolution, the model domain is extended well above the German Bight and covers the Greater North Sea and further parts of the North-East Atlantic. Validation against observations shows, that the model sufficiently reproduces the tidal characteristics across the model domain. According to the first results, effects from morphodynamics within the inner estuaries remain notable up to the outer reaches. This project is funded by the German Federal Ministry of Education and Research (ALADYN-C, funding reference 03F0756C)

13) German Bight Estuaries: An inter-comparison study from the perspective of numerical modeling

Benjamin Jacob, HZG

The Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), which is an unstructured-grid model, coupled with a 3D sediment model was established for the German Bight and its estuaries. The horizontal resolution of the model ranges from ~50 m in the estuaries to ~400 m in most of the open sea. Validation against tidal gauge data, fixed station data, and FerryBox data demonstrated that the model adequately simulated tidal dynamics in the entire area as well as the salinity fronts and estuarine turbidity maxima in the Ems, Weser and Elbe Estuaries. Comparisons with experiments with constant density confirmed the role of density control, which appeared to be strongest in the ocean-ward reaches of the limnic parts of the estuaries. There, the magnitude of the density effect on the sea level oscillations was comparable to the M4 tide amplitude, demonstrating its importance in shaping the tidal asymmetry in the estuaries. Although the three estuaries, which are only ~100 km apart, were driven by similar tidal and atmospheric forcings, they exhibited different extensions of tidal fronts as well as vertical stratification, mainly due to different river runoff conditions. Although the Ems and Weser Estuaries were of the strain-induced periodic stratification (SIPS) type most of the time, the Elbe Estuary was partially mixed and transitioned during certain situations into the SIPS type. At intra-tidal time scales, the dependencies between sea surface height and sea surface salinity varied considerably from estuary to estuary, and the largest flood asymmetry appeared in the Elbe Estuary. Wind acted as the dominant factor driving the longer-term estuarine variability; the correlation between zonal wind magnitude and SSH appeared to be very strong. The simulated suspended particular mater (SPM) dynamics and position of the estuarine turbidity maxima (ETM) were in agreement with observations. Secondary ETM appeared at different locations depending on the grain size, providing an illustration of the sediment sorting. Water density played the dominant role in the positioning of the ETM and occurrence of secondary maxima.

14) Simulating the Columbia River estuary and plume with Thetis

Tuomas Kärnä, Stephan Kramer, Lawrence Mitchell, David Ham, Matthew D. Piggott, António Baptista, Imperial College,UK

Unstructured grid models are attractive for modeling coastal areas and river-estuary-plume systems. However, many models tend to be diffusive and/or expensive to run which limits their applicability. The Columbia River estuary is a strongly stratified system with complex dynamics driven by the tides and river discharge; the plume is also strongly affected by coastal winds. Capturing horizontal density gradients and a sharp pycnocline is crucial for the correct representation of the estuarine circulation, plume dynamics, and biogeochemistry. As such this system is an excellent benchmark for assessing the skill of numerical circulation models. The three-dimensional Thetis model (http://thetisproject.org/) uses discontinuous Galerkin discretization and a split-implicit time integration scheme. In addition, Thetis implements the generic length scale turbulence closure model where the turbulent quantities are represented with a P0 field. We present a set of baroclinic test cases to demonstrate that numerical mixing in Thetis is well-controlled, being similar or lower than in established circulation models. The lower numerical mixing has a significant impact in the Columbia River plume application: Thetis is able to retain sharp density gradients and vertical stratification in the plume far better than a legacy circulation model (SELFE). Moreover, compared to the legacy model, the plume can be represented with a coarser mesh which decreases computational cost. Overall Thetis delivers superior modeling skill that is not attainable with the legacy model.

15) Sea-ice modeling on unstructured meshes

N. Koldunov, S. Danilov, D. Sidorenko, Q. Wang, N. Hutter, MARUM, Bremen University, AWI, Jacobs University, Bremen

We present an sea-ice model based on elastic-viscous-plastic (EVP) solver and its modified and adaptive versions. The dynamical part of the model is based on continuous P_1 elements and triangular meshes, and transport equations are solved with a variant of flux corrected method. As is well known, sea-ice dynamical equations, based on viscous-plastic rheology, lead to a stiff problem, which is dealt with by an EVP solver through subcycling. Since small time steps are explicit, they need to satisfy certain stability criterion, which becomes prohibitive as mesh resolution is refined. For example, at resolution of several km an EVP sea-ice model can be same expensive as a full 3D ocean circulation model. Furthermore, EVP solutions have to converge to those of VP equations, which imposes additional requirements on the number of substeps. The modified and adaptive versions of the EVP solver adjust the procedure of solution so that its stability does not depend on the number of substeps, which only govern the convergence. It turns out that in practice full convergence is not necessarily needed and practically appropriate solutions can be obtained with much reduced numbers of substeps provided the numerical procedure remains stable.

In a series of numerical simulations with FESOM using a global mesh with a 4.5 km refinement in Arctic we demonstrate that appropriate solutions for sea-ice distributions can be obtained with modified and adaptive versions of EVP solver at a fraction of cost compared with the traditional EVP solver. The solutions demonstrate a rich structure of linear kinematic features (leads and cracks) which are absent if measures on stability are not maintained in the process of solution.

16) Hydrodynamic and biogeochemical esturine modelling with precompiled FlexSem

Janus Larsen, Aarhus University

The modeling framework FlexSem is a fast, flexible and user friendly tool specifically targeted towards scientific and management challenges of the complex biogeochemical processes in coastal zone ecosystems. FlexSem is a modular marine modeling framework, containing a full HD module, a simplified formulation of estuarine hydrodynamics (HDLite) or it can be forced by an external hydrodynamic model. Setups can include complex descriptions of pelagic and benthic biogeochemical processes. http://marweb.dmu.dk/Flexsem/

17) A new non-hydrostatic pressure 2D/3D solver for the T-UGOm model

Florent Lyard (LEGOS, Toulouse) Cyril Nguyen (LA/LEGOS, Toulouse)

The T-UGOm model has been mostly specialized to solve for the ocean high frequency dynamics, namely tsunamis, tides and storm surges, at global and regional scales. However, during the past ten years, it has been more and more used in very high resolution configurations such as estuaries and deltas, where surface waves can be a critical sea surface variations contributor, as well in terms of mean level (wave setup) and instantaneous sea level. The coupling with a dedicated, spectral wave model such as WW3 tends to be problematic and relatively inefficient in the near shore sections of the domain. In consequence, a quick and robust non-hydrostatic pressure solver has been implemented in T-UGOm to allow for simulating explicitly surface waves (phase-resolving simulations) simultaneously to tides and storm surges in wetting/drying applications. It can also be used in 3D tides simulations to investigate the possible transfer of energy from internal tides toward solitary waves. Contrary to most available non-hydrostatic solvers, the additional computational cost is very low, typically 25%, compared to the hydrostatic solver. We will briefly describe the mathematical and numerical basis of the non-hydrostatic pressure solver and present academic and realistic test cases.

18) The Model for Prediction Across Scales, MPAS-Ocean

Mark Petersen, Los Alamos

MPAS-Ocean is the ocean component of the U.S. DOE's new Energy, Exascale, Earth System Model (E3SM). Version 1 was released in April 2018 and CMIP6/DECK simulations are mostly complete. I will describe our experiences in developing a completely new IPCC-class climate model over a three-year development cycle. E3SM's purpose is to create a model that is tailored to DOE's high performance computing platforms, where all components are variable resolution, for scientific study and impact assessment at regional to global scales. Validation of E3SM ocean and sea ice diagnostics compare well against observations. E3SM and MPAS are now open source and open development; see https://github.com/MPAS-Dev/MPAS-Model and https://github.com/E3SM-Project/E3SM. We put great effort into improved software engineering practices, so that all parts of the workflow are standardized and automated. This includes the creation of initial conditions, nightly regression testing, and the visualization and analysis of simulation data. In this talk, I will provide an overview of our path from ocean model to coupled climate model, and highlight some of our new capabilities such as ocean cavities below ice shelves and Lagrangian particles.

19) Adaptive vertical discretization techniques for baroclinic flows in estuaries

Balthasar Reuter (Applied Mathematics I, Friedrich-Alexander University Erlangen-Nürnberg) Vadym Aizinger (Alfred-Wegener-Institute, Bremerhaven and Applied Mathematics I, Friedrich-Alexander University Erlangen-Nürnberg)

Traditional vertical discretization techniques based on vertical coordinates employed in most 3D models of flow and transport in estuaries suffer from a number of shortcomings related to transport and mixing of species. We develop a novel vertical discretization technique that allows for a flexible choice of the vertical mesh structure and thus facilitates a more accurate vertical discretization. This approach is less intrusive than conventional ALE formulations, easier to implement and comes at reduced cost within an unstructured, adaptive numerical scheme. It captures the most important flow features using locally adapted vertical grids in a 3D prismatic mesh and is based on the ability of the discontinuous Galerkin method to efficiently utilize grids of very general geometry and connectivity without any negative effects on stability, accuracy, and conservation properties of the numerical scheme. We integrate this technique into UTBEST3D, a fully featured coastal and regional ocean simulator.

20) The Finite Volume Sea Ice-Ocean Model (FESOM 2.0) with the arbitrary Lagrangian Eulerian (ALE) vertical coordinates: possibilities, performance and scaling

P. Scholz, S. Danilov, D. Sidorenko
Alfred Wegener Institute, Bremerhaven, Germany

We present first results regarding the second version of the Finite-Element Sea Ice-Ocean Model (FESOM 2.0), with the dynamical core using finite volumes instead of finite elements and prismatic instead of tetrahedral elements. To ensure the same functionality in FESOM 2.0 as in the previous version, such as a full free surface and the possible use of a terrain following vertical discretization, we introduced arbitrary Lagrangian Eulerian (ALE) vertical coordinates. ALE provides the opportunity to incorporate a variety of different types of vertical coordinates (z-, sigma-, hybrid-coord.) and effects (linear-free surface (linfs) mode, full-free surface (zlevel, zstar) mode, partial cells, floating sea ice), with an only minor expansion of the code.
In our work we will present the main adaption of the numerical core and the largely improved computational efficiency of the finite-volume approach, due to a more efficient structuring of the data. Further, we will give an outlook of the general possibilities, performance and scaling of the new numerical core.

21) How to select ocean model resolution for global climate simulations?

Dmitry V. Sein, Nikolay V. Koldunov, Sergey Danilov, Dmitry Sidorenko, Claudia Wekerle, William Cabos, Thomas Rackow, Patrick Scholz, Tido Semmler, Qiang Wang, Thomas Jung
Alfred Wegener Institute, Bremerhaven, Germany

We discuss the performance of the Finite Element Ocean Model (FESOM) on locally eddy-resolving global unstructured meshes. In particular, the utility of the mesh design approach whereby mesh horizontal resolution is varied as half the Rossby radius in most of the model domain is explored. Model simulations on such a mesh (FESOM-XR) are compared with FESOM simulations on a smaller-size mesh, where refinement depends only on the pattern of observed variability (FESOM-HR). We also compare FESOM results to a simulation of the ocean model of the Max Planck Institute for Meteorology (MPIOM) on a tri-polar regular grid with refinement towards the poles, which uses a number of degrees of freedom similar to FESOM-XR. The mesh design strategy, which relies on the Rossby radius and/or the observed variability pattern, tends to coarsen the resolution in tropical and partly subtropical latitudes compared to the regular MPIOM grid. Excessive variations of mesh resolution are found to affect the performance in other nearby areas, presumably through dissipation that increases if resolution is coarsened. The largest improvement shown by FESOM-XR is a reduction of the surface temperature bias in the so-called North-West corner of the North Atlantic Ocean where horizontal resolution was increased dramatically. However, other biases in FESOM-XR remain largely unchanged compared to FESOM-HR. We conclude that resolving the Rossby radius alone (with two points per Rossby radius) is insufficient, and that careful use of a priori information on eddy dynamics is required to exploit the full potential of ocean models on unstructured meshes.

22) FESOM: Global ocean simulation on variable-resolution triangular meshes

D. Sidorenko, S. Danilov, Q. Wang, P. Scholz, V. Aizinger, D. Barbi, O. Gurses, S. Harig, N. Koldunov, D. Sein, M. Smolentseva, T. Rackow, N. Rakowski, T. Semmler, C. Wekerle, T. Jung
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FESOM (Finite Element/volumE Sea ice - Ocean Model) is developed for global large-scale multi-resolution simulations, for example, on meshes with local eddy-resolving refinement embedded in an otherwise coarse global mesh. It is a component of AWI Climate Model (AWI-CM), where FESOM is coupled with the atmospheric model ECHAM6. AWI-CM is used in the on-going CMIP6 project, which is the major achievement, as for the first time an unstructured-mesh model is employed in CMIP simulations.
FESOM is run on variable-resolution unstructured triangular meshes. Starting from version 2, its dynamical core is changed from Finite-Element to Finite-volumE discretization (no change in the model name), which grants at least three-fold increase in numerical efficiency. The ALE discretization is used in the vertical direction instead of less general z-sigma coordinate of the earlier versions. FESOM contains the finite-element sea ice model FESIM as one of its components. It is run on the same mesh and partition as the ocean, coupled at each time step, and based on a modified Elastic-Viscous Plastic (EVP) solver. The latter allows much better computational efficiency than the standard EVP. The model demonstrates excellent parallel scalability. Its throughput approaches that of traditional structured-mesh models.
Future FESOM development plans include generalization to hybrid meshes made of triangles and quads and extension of the ALE functionality beyond z*. New faster climate model configurations are also coming soon (ECHAM6-FESOM2 and IFS-FESOM2), intended for post-CMIP6 applications.
Practical FESOM configurations include global setups intended for climate simulations on variable-resolution meshes with equivalent resolution from 1 to 1/10 degree, and setups with regional focus, for example, on the Arctic Ocean, resolved at 4.5 km to 1 km.
The global mesh of 1km-Arctic configuration contains about 11.5M 2D vertices (more than the number of wet surface cells in the global NEMO 1/12 degree setup).

23) Two-layer inter-basin exchange. Unstructured-grid approach

Emil V. Stanev, HZG

In this paper, we use the unstructured grid model SCHISM to simulate the dynamics in inter-connected ocean basins on the example of Black Sea-Mediterranean and Baltic Sea-North Sea. The model shows a good skill in simulating the horizontal circulation and vertical profiles of temperature, salinity, and currents. The magnitude and phases of the seasonal changes of circulation are consistent with earlier observations. Mesoscale and sub-basin-scale circulation features are also realistically simulated, as well as the timing and magnitude of the major inflow events in the Baltic Sea during 2014-2015. The superiority of the simulations compared to earlier numerical studies is demonstrated with the example of model capabilities to resolve the strait dynamics, gravity currents originating from the straits, high-salinity bottom layer on the shallow shelf, as well as the intermediate and deep-water intrusions from the straits. One novel result is that the seasonal intensification of circulation affects the inter-basin exchange, thus allowing us to formulate the concept of circulation-controlled inter-basin exchange. The short-term variability of the strait transports is largely dominated by the anomalies of wind. The two-layer flows in the connecting straits show different dependencies upon the net transport. We show that the blocking of the surface flow can occur at different net transports, thus casting doubt on a previous approach of using simple relationships to prescribe (steady) outflow and inflow. Analysis on the impact of resolution in the area of Danish Straits indicates that the performance of the model changes depending on whether the narrow parts of the straits are resolved with a resolution of 500 m or 100 m. With this ultra-fine resolution, gravity flows and variability of salinity in deep layers is generally more adequately simulated. One major conclusion from this research is that modeling the individual basins separately could result in large inaccuracies because of the critical importance of the straits transport, which is not sufficiently resolved in structured grid models.

24) Dynamics of the Baltic Sea Straits via Numerical Simulation of Exchange Flows
Emil V. Stanev, Johannes Pein, Sebastian Grashorn, Y. Joseph Zhang, Corinna Schrum, HZG

The Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), which uses unstructured grids, is set up for the area of North Sea and Baltic Sea. With a resolution of ~100 m in the narrow straits connecting the two basins, this model resolves accurately the inter-basin exchange. Validation against observations in the straits shows a good skill of the model in simulating the transport and vertical profiles of temperature, salinity and currents. The timing and magnitude of the major inflow in 2014-2015 is also realistically simulated. The analysis is focused on the two-layer exchange, its dependence on the atmospheric forcing, and dominant physical balances. The two-layer flows in the three connecting straits show different dependencies upon the net transport. The spatial variability of this dependence is also quite pronounced. The three-strait system developed specific dynamics, with time lags and differences between currents in the individual straits during inflow and outflow conditions. Analysis on the impact of resolution indicates that the performance of model changes depending on whether the narrow parts of the straits are resolved with resolution of 500 m or 100 m. With this ultra-fine resolution, gravity flows and variability of salinity in deep layers is generally more adequately simulated. The paper identifies the needs for more profound analysis of the coupled dynamics of Baltic and North Sea with a focus on the Danish straits.

25) The HAMburg Ocean Carbon Cycle model in the icosahedral general ocean circulation model ICON-O
I. Stemmler, T. Ilyina, J. Maerz, P. Korn, H. Paulsen, K. D. Six, MPI-M

The ICON (Icosahedral non-hydrostatic general circulation model) modelling system is a joint initiative of the Max Planck Institute for Meteorology (MPIM) and the German Weather Service (DWD) aiming at a unified framework for climate simulations and weather forecast. The new Earth System Model of MPIM (ICON-ESM) is based on ICON. The HAMburg Ocean Carbon Cycle model (HAMOCC) was implemented into the ocean component of ICON (ICON-O). Here, we present features of the biogeochemistry of the new ICON-HAMOCC setup in stand-alone ocean and coupled atmosphereocean simulations. HAMOCC encompasses marine carbonate chemistry, an extended NPZD-type ecosystem model, airsea gas-exchange, and a sediment module (see references in Ilyina ea 2013, Paulsen ea 2017). In addition to the formulation in Ilyina e.a. 2013, alkalinity includes the contributions from silicic and phosphoric acid systems. All parameters used in air-sea gas-exchange and in the solution of the carbonate system are updated according to the recommendations of the biogeochemical protocol for the CMIP6 OMIP (Orr et al. 2016).
ICON-O runs on the unstructured triangular horizontal grid R2B6 (approx. 40km). The stand-alone ocean simulations are driven either by a constant climatological (OMIP) or a transient (NCEP, 1948-2018) forcing. In the coupled atmosphere-ocean simulation the atmosphere model runs on the horizontal grid R2B4 (approx. 160km). HAMOCC is started from basin-scale uniform distributions for most tracers and an empty sediment, an approach that has been used in previous spin-up simulations. Phosphate, silicate, oxygen, and nitrate are initialized using gridded climatological data (WOA 2013). The model uses climatological Ndeposition and Fe-deposition data as atmospheric boundary conditions. The standalone ocean simulation with OMIP forcing and the coupled simulation use constant preindustrial CO2 mixing ratios, whereas the NCEP simulation uses transient historical data. Spatial distributions of major state variables, i.e. nutrients, oxygen,

dissolved inorganic carbon, and alkalinity are used to illustrate the performance of the model in comparison to recent climatological observational data products (WOA13, GLODAPv2). Furthermore, the dynamical behaviour of the model is characterised by the intra- and inter-annual variability of key tendencies, such as CO2 surface fluxes and organic matter fluxes.

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26) Modeling tools for an Integrated River-Delta-Sea system investigation: the Pan-European Research Infrastructure DANUBIUS-RI

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ISMAR

The DANUBIUS Research Infrastructure (DANUBIUS-RI) is a new initiative to address the challenges and opportunities of research on large river- sea (RS) systems. DANUBIUS-RI is a distributed pan-European RI that will provide a platform for interdisciplinary research. It will deal with RS investigation through facilities and expertise from a large number of European institutions becoming a 'one-stop shop' for knowledge exchange in managing RS systems, ranging from freshwater to marine research. DANUBIUS-RI will provide, among a number of other facilities concerning observations, analyses, impacts' evaluation, a modeling node that will provide integrated up-to-date tools, at locations of high scientific importance and opportunity, covering the RS systems – from source (upper parts of rivers – mountain lakes) to the transition with coastal seas. Modeling will be one of the major services provided by DANUBIUS-RI, relying on the inputs from the whole RI. Currently, different model applications are made for the different geographical domains, and also for subsets of the processes. The challenge for the modeling of river – sea systems is (1) the integration of models for the geographical domains, (2) the integration of physical, chemical, ecological and socio-economical processes and (3) the exploration and application of new data sources. The modeling strategy that is starting to be shaped within DANUBIUS-RI will provide relocatable tools and suitable techniques to be efficiently applied in the different geographical areas, integrating the DANUBIUS-RI modeling skills and showing high performance modeling solutions for the investigation of RS systems. Moreover, a technological advanced platform for modeling services, in terms of software and shared data will be created. A preliminary sketch of the organization of the DANUBIUS modeling node and examples of field of action for RS systems investigation will be provided.

27) A numerical study of the estuarine plume in the Congo River

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With the second largest river in the world by discharge volume of water, the Congo River strongly affects the sea surface salinity in the Eastern Atlantic Ocean. The Congo River estuary is also the location of several vulnerable ecosystems (e.g. Mangroves National Park). Despite its importance, there are very few published studies about the dynamics of the area. The river estuary is characterized by a very deep canyon that directly connects the river to the the deep sea. This unique feature strongly impacts the plume dynamics and the shelf circulation. From a numerical modelling perspective, the variation of the water column depth over a wide range of values and the steep slopes require flexible vertical coordinates and multiscale horizontal resolution. Modelling the baroclinic circulation along the Congo river-to-sea continuum therefore represents a very challenging test case for any numerical ocean model. In this study, we show that the multi-scale coastal ocean model SLIM (http://www.climate.be/slim/) correctly represents the main features of the shelf and estuarine dynamics. SLIM solves the hydrostatic equations under the Boussinesq approximation on a single unstructured multi-scale mesh with the Discontinuous Galerkin finite element method. Beside assessing the model skill and its ability to capture the multi-scale processes that drive the estuarine circulation, we analyse how the horizontal mesh anisotropy can help improve the model results. Our results compare very favourably with in-situ data on the shelf and in the estuary and show the ability of the multi-scale coastal ocean model SLIM 3D to reproduce the exchange flow in the Congo River estuary. The Constituent-oriented Age and Residence time Theory, CART (http://www.climate.be/cart/), further helps to evaluate the fate of riverine and oceanic waters in this complex ecosystem. In particular, the renewing water age gives the spatial and temporal variability of the estuarine waters ventilation time. Due to a high stratification and a low tidal mixing, vertical mixing is expected to be small, hence restricting the supply of oxygen from the surface waters to the more saline bottom waters. The renewing water age helps understand the hypoxia observed in the bottom of the submarine canyon.

28) Adjoint-based calibration of an unstructured mesh regional tidal model, with an application to storm surge simulation

Simon Warder, Imperial College, UK

Regional shallow water tidal models typically contain a tunable bottom friction parameter, which can be calibrated to produce model outputs with the best possible agreement to real world observations. Adjoint methods are a powerful tool for data assimilation, and can be used to automate the process of model calibration by assimilating observation data into the model, thereby determining the optimal bottom friction parameter, which can be allowed to vary spatially. Here, we use the Thetis finite element coastal ocean model in its two-dimensional mode, and its adjoint, to assimilate tide gauge elevation time series data into a model of the Severn Estuary. Due to the small number of observation locations compared to the number of degrees of freedom in the bottom friction parameter, this problem is under-constrained; approaches to solve this problem are presented, including the addition of a regularisation term in the misfit functional. The Thetis model is also applied to the simulation of storm surges in the North Sea, with the December 2013 surge taken as a case study. The UK operational forecast model underestimated the maximum surge height at the tidal barrier at Hull during this surge; we seek to improve on this model using Thetis, with promising preliminary results.

29) Eddy properties and dynamics in Fram Strait: a comparison of two high resolution simulations with FESOM1.4 and ROMS

Claudia Wekerle, Tore Hattermann, Laura Crews, Qiang Wang, Sergey Danilov and Thomas Jung AWI

Fram Strait, located between Greenland and Svalbard, is the deepest gateway to the Arctic Ocean. It is a place where two contrasting water masses meet: Warm and salty waters of Atlantic origin are carried northward in the West Spitsbergen Current, whereas cold and fresh Polar Water is carried southward in the East Greenland Current. Moreover, this region is strongly influenced by eddy dynamics.

For realistic simulations of the Fram Strait ocean dynamics, a very high spatial resolution is required. This is due to the very small Rossby radius (around 4-6 km), an indication for the scale of eddies. In this study we compare two “eddy-resolving” configurations of sea ice-ocean models, ROMS_S800 and FESOM_1km, with mesh resolutions of 800 m and 1 km in Fram Strait, respectively. Both models differ in many aspects such as numerical discretisation, vertical mesh resolution, parameterisations, global vs. regional setups.

An eddy tracking method is used to study the properties of eddies. In particular, the distribution of eddies, their polarisation, size, lifetime and travel pathways are investigated. Furthermore, the generation mechanism of eddies, such as baroclinic and barotropic instability, is analysed. This comparison shows that both models are consistent in simulating the Fram Strait eddy dynamics, which increases the fidelity in numerical solutions.

30) Salt intrusion under sea level rise

Y.J. Zhang, Virginia Institute of Marine Science

We present an idealized case study for salt intrusion under rising sea level. An idealized rectangular estuary with deep channel and shallow shoal that are separated by a linear slope is used in an unstructured-grid model (SCHISM) that realistically captures the slope without any bathymetry smoothing. We show that under modest sea-level rise (SLR), the change in salinity exhibits nonlinear behavior, with more salt water intruded into the channel and less on the shoal, especially so with a steep slope. This behavior is ‘overwhelmed’ by a large SLR, under which more salt water intrudes into both channel and shoal.

Poster Presentations

A nested structured grid application for barrier islands of the Southern German North Sea with Lagrangian particle tracking

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A high resolution nested numerical model for the Southern North Sea is presented. Using the COAWST-Framework (Warner et al., 2008) with two structured, spatial grids in a two-way nested application allows for simulations of current fields on a 1 km x 1 km coarse grid in the offshore region and refined resolutions in the region of the German East Frisian barrier islands with wetting and drying of tidal flats. Online computations of Lagrangian particles are used to investigate the exchange of particles between the islands and generate connectivity maps for real and analytical atmospheric forcing conditions, thus allowing studies of surface particle redistributions.
Refinement of spatial resolution in this model is needed to investigate tidal effects on the particle exchange between the regions of the tidal flats and the offshore regions of the islands, for which the channels between the islands must be resolved. Particles are released at different times in the tidal cycle and in deployment regions on the northern and southern side of the islands.
The influence of wind on surface drifting objects is estimated using GPS-drifter data and an offline Lagrangian particle model using reanalyzed wind fields from the German Weather Service and simulated current fields of our model.

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Arctic Sea Ice Decline Significantly Contributed to the Unprecedented Liquid Freshwater Accumulation in the Beaufort Gyre of the Arctic Ocean: Insight from Global Multi-resolution Model Simulations

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The Beaufort Gyre (BG) is the largest liquid freshwater reservoir of the Arctic Ocean. The liquid freshwater content (FWC) significantly increased in the BG in the 2000s during an anticyclonic wind regime and remained at a high level despite a transition to a more cyclonic state in the early 2010s. It is not well understood to what extent the rapid sea ice decline during this period has modified the trend and variability of the BG liquid FWC in the past decade. A global multi-resolution model (FESOM) with 4.5 km horizontal resolution in the Arctic region is used. Our numerical simulations show that about 50% of the liquid freshwater accumulated in the BG in the 2000s can be explained by the sea ice decline caused by the Arctic atmospheric warming. Among this part of the FWC increase, 60% can be attributed to surface freshening associated with the reduction of the net sea ice thermodynamic growth rate, and 40% to changes in ocean circulation, which makes freshwater more accessible to the BG for storage. Thus, the rapid increase of the BG FWC in the 2000s was due to the concurrence of the anticyclonic wind regime and the high freshwater availability. We also find that if the Arctic sea ice had not declined, the liquid FWC in the BG would have shown a stronger decreasing tendency at the beginning of the 2010s owing to the cyclonic wind regime. From our results we argue that changes in sea ice conditions should be adequately taken into account when it comes to understanding and predicting variations of BG liquid FWC in a changing climate.

Impact of Ocean-Atmosphere Coupling and resolution on the Ring-Shedding Processes from the Loop Current in the Gulf of Mexico

Bracamontes-Ramirez, J., Cabos-Narvaez, W.D., Sein, D.V., Martinez-Lopez, B.

In order to assess the impact of coupling and resolution on the simulation of the ring-shedding from the Loop Current in the Gulf of Mexico we analyse stand-alone simulations with Finite Element Sea ice Ocean Model (FESOM) and the same model coupled with the atmospheric model ECHAM6 (AWI-CM). Different configurations were used. These configurations differ in the spatial resolution of FESOM and ECHAM6 when the simulations are coupled. Additionally, we analyse results from a two-and-a-half layer model with thermodynamic driven by seasonal atmospheric forcing, and from uncoupled simulations with two other ocean models (HYCOM and MPIOM) with high spatial resolution. The skill of FESOM to simulate the ring separation from the Loop Current is highly sensitive to spatial resolution. The seasonality of the ring separation seems to be better reproduced by both increasing the spatial resolution and the coupling. Ocean models in stand-alone mode without a higher spatial resolution are not able to reproduce the seasonality of ring separation process and, contrary to observations, they simulate only ring separation intervals shorter than one year. The spatial pattern of variability across the Gulf of Mexico is well reproduced in both FESOM and HYCOM with the higher spatial resolution, but not in MPIOM. FESOM reproduces also the seasonality of the ring-shedding process, characteristic that is not well simulated in HYCOM.

Tidally imposed nutrient fluxes at the NW-European shelf

Richard Hofmeister Kay Logemann, HZG

The shelf break area is known to play an important role for nutrient and matter fluxes from the deep water to the surface waters and into the shelf seas because of the energetic motions and modulation of the tides. Tidal mixing of tracers is analysed in a cross-scale simulation of the north-west european shelf with the unstructured grid model SCHISM. A flexible model grid allows for resolution of coastal processes as well as the transition zone between the European shelf seas and the Atlantic Ocean. The seasonal variability of thermal stratification as well as vertical nutrient gradients results in a climatology of tracer fluxes. The results of the regional simulations are compared to global-scale simulations with a tide-resolving model in order to assess the importance of tides in earth system modelling.

Considerations towards an ocean model for the regional climate model ICON-CLM

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Coupled ocean-atmosphere models are essential tools for establishing climate projections to simulate long-term exchange processes between the ocean, atmosphere and sea-ice. Setting up such models on regional scale enables to focus on specific processes at finer resolution. In collaboration with the CLM-Community the regional atmosphere model ICON-CLM is currently established within the pilot project ProWaS to perform climate simulations for Europe. The aim is to regularly provide a federal forecasting and projection service for potential climate change impacts on German waterways and the coastal areas. The planned model system also holds a high demand to the coupled ocean model, which needs to represent the North Sea and the Baltic Sea. Here, we present the concept for a coupled regional climate model including ICON-O, the ocean component in the ICON model family of DWD and MPI-M as well as alternative approaches like the community ocean model NEMO for which applications for the North Sea and Baltic Sea exist. Regional adaptation for these marginal seas holds different challenges. These include scientific challenges, e.g. potential drying areas in coastal regions as well as technical challenges, such as different stratification sources for which various mixing schemes can be considered. We will discuss different aspects and implications for the model setup.

Cross-scale seamless Mediterranean-Black sea model nested in Atlantic Ocean: towards an operational forecasting system

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The present work shows the development and implementation of a 3D-thermo-hydrodynamic fully-baroclinic pre-operational forecasting system (i) covering the entire Mediterranean and Black Sea with a unique-continuum-seamless grid and (ii) solving with appropriate resolution different oceanographic scales, from the regional to the shelf-coastal scale. The system is based on the unstructured-grid finite-element SHYFEM model (Umgiesser et al., 2004; Federico et al., 2017). The model domain extends in a large Atlantic box (similar to the one described in Oddo et al., 2009) with a lateral open boundary nested into high-resolution global ocean circulation model (Iovino et al., 2016). The horizontal resolution is optimized on the local bathymetry, coastline and expected solutions (relevant dynamics and coastal scale features), and ranges from 4-5 km in open-ocean to 1km-500m in shelf-coastal seas to 50-60m in narrow straits (Dardanelles and Bosphorus). The model has been run both in hindcast and forecast mode, simulating different seasonal conditions. Preliminary comparisons with satellite observations and in-situ coastal observations show promising features of the system. The system is a valuable tool (i) for process study focused on the coastal areas of the entire Mediterranean and Black seas, (ii) to assess the impact of straits (Gibraltar-Sicily-Dardanelles-Bosphorus-Kerch) on the dynamics and exchanges of interconnected basins, (iii) to provide high-resolution coastal operational forecasts.

Landslide modelling using a DG-FE based multi-layer non-hydrostatic model

Wei Pan, Stephan C. Kramer, Matthew D. Piggott, Imperial College

A submarine landslide model is developed based on the multi-layer non-hydrostatic version of the discontinuous Galerkin finite element (DG-FE) model, Thetis. This is accomplished using the PDE solver framework, Firedrake, which is used to automatically produce the code for the discretised model equations in a rapid and efficient manner.

The landslide motion is described as a viscous granular flow governed by the depth-integrated non-linear shallow water equation (NSWE), while tsunami wave generation is simulated by our newly developed DG-FE multi-layer non-hydrostatic model which can make use of relatively small numbers of vertical layers in order to accurately represent wave dispersion. The interaction between the lower-layer viscous slide motion and upper-layer water flow with a free surface is also taken into account.