IMUM2010 – Submitted talks – Presenter in bold and underlined
(arranged alphabetically by first author surname)

1. **Robert C. Beardsley** and Changsheng Chen - *NECOFS: a FVCOM-based regional coastal and local inundation forecast tool*

2. M.J. Berger, D.L. George, R.J. LeVeque, and **K.T. Mandli** - *Using Adaptive Mesh Refinement to Model Ocean Flows*

3. **Mustafa Kemal Cambazoglu**, Cheryl Ann Blain, Kendra Dresback, Randall A. Kolar - *Modeling 3D Density-Driven Flow in a Complex Two-Strait, Three-Sea System*

4. **V. Carey** and D. Estep - *Adjoint-based error control and sensitivity analysis for shallow water models*

5. **Changsheng Chen** and Robert C. Beardsley - *A Global-to-Wetland Scale FVCOM System: A New Unstructured-grid Model Tool to Resolve Multi-scale Ocean Processes*

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7. **Andrea Cucco**, Christian Ferrarin, Aaron Roland, Debora Bellafiore, Marco Bajo, Francesca De Pascalis, Michol Ghezzo and Georg Umgiesser - *SHYFEM, a numerical tool for investigating environmental processes in coastal seas and lagoons*

8. **Haiyang Cui**, J.D. Pietrzak and Guss S. Stelling - *A non-hydrostatic two-dimensional unstructured finite volume model for tsunami waves*

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11. **Mike Foreman**, Roy Walters, Mike Tarbotton - *Circulation Models for the Discovery Islands, British Columbia*

12. **S. Funke**, C. Pain, S. Kramer and M. Piggott - *A new wetting and drying algorithm using a combined pressure/free-surface finite element method*

13. **Shiva Gopalakrishnan**, Frank Giraldo and Jim Kelly - *Development of a Coastal Inundation Model using a Triangular Discontinuous Galerkin Method*

14. **O. Gourgue**, J. Lambrechts, E. Deleersnijder, V. Legat and E. Wolanski - *A fine sediment module for the two-dimensional component of SLIM*

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16. **Patrick J. Haley, Jr.** and Pierre F. J. Lermusiaux – *MSEAS: Multiscale two-way embedding schemes for free-surface primitive-equations*

17. **S. Harig**, D. Sidorenko, Q. Wang, R. Timmermann, C. Wekerle, N. Rakowsky, S. Danilov and J. Schroter - *Recent applications of FEOM and TsunAWI: regional and global experiments*

18. J. Hill, **M. Piggott**, D. Ham, E. Popova and M. Srokosz - *On the performance of a generic length scale turbulence model within an adaptive mesh finite element ocean model*

19. **M.E. Hope**, J.J. Westerink, A.B. Kennedy, J.C. Dietrich, C. Dawson, J. Proft, J. Atkinson, H. Roberts - *Application of the Coupled ARCIRC+SWAN Model to Hurricane Ike on the Texas Gulf Coast*

20. **S. M. Jachec** - *Numerical modeling the development of field-scale internal boluses via barotropic tidal forcings*

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22. **S.C. Kramer**, M.D. Piggott, R.B. Nelson, D.A. Ham,, C.J. Cotter, P.E. Farrell, G.J. Gorman and C.C. Pain - *Validation of the Imperial College Ocean Model with a wind-driven baroclinic gyre*

23. **Ethan J. Kubatko**, Clint Dawson, Colton Conroy and Ashley Maggi - *A sigma–coordinate, discontinuous Galerkin method for the three–dimensional shallow water equations*

24. **J. Lambrechts**, J.-F. Remacle and K. Hillewaert - *Efficient assembly of high order continuous and discontinuous finite element operators*

25. **Lyon W. J. Lanerolle**, Richard C. Patchen and Frank Aikman III - *The Design, Calibration, Validation and Application of a Model Nesting Methodology*

26. **Yoann Le Bars** and Florent Lyard - *Gradient, divergence and laplacian discrete approximations for numerical ocean modelling*

27. **V. Legat** - *SLIM: a three-dimensional baroclinic finite-element model; Time and spatial discretizations*

28. **R. Martyr**, J.C. Dietrich, J. Westerink, S. Tanaka, H. Westerink, L. Westerink, P. Kerr, H. Roberts, J. Atkinson - *Multi-scale Modeling of Riverine and Porous Coastal Environments In a Hydrodynamic Model*

29. Silvia Matt, **Mohamed Iskandarani**, Kevin Leaman - *Simulation of Mixing in 2D Gravity Currents Subject to Time-Dependent Forcing*

30. **P. McKay** and C.A. Blain - *Modeling of a Coastal River and Associated Floodplains*

31. **S.A. Melchior**, V. Legat, and P. Van Dooren - *Multigrid-based solvers for the shallow-water equations*

32. **Arthur J. Miller** and Hajoon Song - *State Estimate of the California Current System Using 4DVAR Ocean Data Assimilation*

33. P. Oddo and **N. Pinardi** - *The generalized Flather lateral open boundary condition*

34. **O. Svenstrup Petersen** and I. Sehested-Hansen - *A very large application of unstructured coastal models for infrastructure projects*

35. **J. Pietrzak**, O. Kleptsova, O. Cui and G. Stelling - *A comparison of Finite Volume and Finite Element Methods for simulating The Indian Ocean Tsunami*

36. **Shanon M. Reckinger** and Oleg V. Vasilyev - *Ocean Circulation Modeling Using Adaptive Wavelet Collocation Method*

37. **J. Sasaki**, Y. Komatsu, R. Matsumaru and R.U.A. Wiyono - *Application of FVCOM to 2004 Indian Ocean Tsunami Focusing on Inundation in Banda Aceh, Indonesia*

38. **B. Seny**, J. Lambrechts, J.F. Remacle and V. Legat - *Multirate Time Stepping for Accelerating Explicit High Order Discontinuous Galerkin Computations*

39. **Y. Peter Sheng**, Vladimir A. Paramygin, Tianyi Liu, Andrew Lapetina, and Justin R. Davis - *Recent Advances of An Integrated Modeling System for Coastal and Estuarine Environments*

40. **D. Shirokoff** and R. Rosales - An efficient method for the Incompressible Navier-Stokes Equations on Irregular Domains with no-slip boundary conditions, high order up to the boundary.

41. **S. Tanaka**, J.J. Westerink, C. Dawson, and R.A. Luettich, Jr. - *Scalability of Unstructured Grid Based Hurricane Storm Surge Model*

42. **H. S. Tang** and X. G. Wu - *Simulation of Thermal Discharge into Coastal Flow: An Example of CFD and GFD Hybrid Approach to Resolve Small-Scales*

43. **M. P. Ueckermann**, and P. F. J. Lermusiaux – *High Order Discontinuous Galerkin schemes for coupled physical-biogeochemical ocean modelling*

44. **B. Wang**, O.B. Fringer - *High-resolution simulation of stratified flow and separation over an abrupt sill in a estuary*

45. **Lei Wang**, Robert Krasny and John P. Boyd - *A Lagrangian vortex method for the barotropic vorticity equation on a rotating sphere*

46. **John C. Warner**, Brandy Armstrong, Ruoying He, Joseph Zambon - *Development and application of a Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System*

47. **C. Wekerle**, S. Harig, W. Pranowo, A. Androsov, A. Fuchs, N. Rakowsky, J. Schroter and J. Behrens - *Dependency of tsunami simulations on bathymetry, grid resolution and bottom friction*

48. **J.J. Westerink**, J.C. Dietrich, A.B. Kennedy, M. Zijlema, L.H. Holthuijsen, C. Dawson and R.A. Luettich, Jr. - *Coupled Waves and Storm Surge during Hurricane Gustav*

49. **Y.J. Zhang**, A.M. Baptista, A. Azevedo, A. de Oliveira, A.B. Fortunato, A. Roland - *SELFE Cross-Scale Modeling System: new developments and applications*

50. **Aijun Zhang**, Eugene Wei - *NOAA's Coastal Ocean Operational Forecast Systems*

51. **Di Zhao** - *HSS Preconditioner for Incompressible Navier-Stokes Equation on Multiscale Unstructured Mesh*

POSTER Presentations

1. Colton J. Conroy and Ethan J. Kubatko - *An Advanced Mesh Generator for Hydrodynamic Models*

2. J.-M. Campin, C. Hill, H. Jones, and J. Marshall - *Super-parameterization in Ocean Modelling using general multiscale techniques - a deep-convection case study*

3. H. El-Asrag, T. C. Iannetti, F. Ham, H. Pitsch - *Large Eddy Simulation of a Lean Direct Injection Combustor*

4. Ashley L. Maggi, Ethan J. Kubatko and Damrongsak Wiraset - *Discontinuous Galerkin Methods for the Shallow Water Equations Using Mixed Meshes*

5. Meng Xia - *The response of northern Gulf of Mexico estuary plume, water exchange to wind forcing: A model-guided mechanism study to Perdido Bay*

6. Zhaoqing Yang, Taiping Wang, and Tarang Khangaonkar - *Pushing the Limits of Coastal Ocean Modeling: from Estuarine and Coastal Waters to Upstream River Floodplains*

NECOFS: a FVCOM-based regional coastal and local inundation forecast tool

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NECOFS (Northeast Coastal Ocean Forecast System) is an integrated atmosphere-ocean model system which covers the northeast US coastal region from New York to the Scotian shelf. The system features three core models: the atmospheric mesoscale model WRF; FVCOM; and the unstructured-grid surface wave model FVCOM-SWAVE. The system became quasi-operational in 2009 and produces 3-day forecasts of the regional atmospheric surface forcing and ocean response. NECOFS is presently being extended to predict inundation at two pilot sites - Scituate (MA) and Saco (ME) – that experience significant local coastal flooding during strong "nor-easters". A high-resolution subdomain Scituate FVCOM inundation forecast model system has been developed and is in testing. This application required full dynamic coupling the wave and ocean models and ability to incorporate structures (e.g. coastal walls and dikes) into FVCOM. The Scituate FVCOM system is driven by one-way nesting with the regional NECOFS forecast.

The NOAA IOOS program recently funded SURA (Southeastern University Research Association) to conduct a "super-regional testbed" study of FVCOM and other unstructured-grid models for inundation and water quality prediction. The inundation component will focus on tropical storms in the northern Gulf of Mexico and extratropical storms in the northeast. With the NECOFS Scituate FVCOM inundation forecast system already in advanced development, Scituate has been picked as the site for the extratropical storm study. Inundation during two storms will be hindcast and compared with in situ water elevation measurements to assess model performance. The combined focus of NECOFS and SURA on Scituate should lead to a tested optimal inundation forecast system with quantified performance that can be readily applied to other northeast sites. An update of NECOFS and the Scituate inundation study will be presented.

Using Adaptive Mesh Refinement to Model Ocean Flows

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Many oceanic flows require the use of methods that can resolve many order of spatial and temporal scales but often these resolution requirements change in time and space. One way to take advantage of these dynamic processes is to employ adaptive mesh refinement which uses various aspects of the flow to determine the current required mesh refinement. This allows for a significant savings in computation and can lead to the ability to refine further in regions of interest.

We have developed a code named GeoClaw which uses adaptive mesh refinement to solve depth averaged equations over complex bathymetry. It is based on the Clawpack software (Conservation Laws Package, `www.clawpack.org`), designed for solving general nonlinear hyperbolic systems using high-resolution shock-capturing finite volume methods on logically rectangular grids. We will also include some sample demonstrations of the software as applied to tsunami propagation and storm surges.

IMUM-2010, MIT August 17-20, 2010

MODELING 3D DENSITY-DRIVEN FLOW IN A COMPLEX TWO-STRAIT, THREE-SEA SYSTEM

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The Turkish Strait System (TSS) is comprised of the Aegean, Marmara, and Black Seas interconnected by the Bosphorus and Dardanelles Straits. The extreme salinity and density differences between the fresh, light waters of the Black Sea and the saline, dense waters of the Aegean Sea drive two-layer flow through both straits and the intermediary, comparatively shallow Marmara Sea. Complexities in the geometry, topography and dynamics throughout the TSS present a formidable challenge in the application of numerical models.

The Advanced CIRCulation Model, ADCIRC, a finite element model based on unstructured grids, is applied to the TSS at resolutions of ~10m to simulate the two-layer, estuarine flow in the narrow straits. Initial conditions and open water forcing are supplied by a regional application (~1 km resolution) of the HYbrid Coordinate Ocean Model, HYCOM, which encompasses the entire Black Sea to the eastern Mediterranean Sea. Three deep depressions of over 1 km depth in the Marmara Sea occur in the midst of a broad, shallow shelf creating sharp changes in bathymetry over short horizontal distances. This geometry poses a challenge for ADCIRC's terrain-following, generalized, stretched coordinate system applied in the vertical. This study examines the importance of horizontal and vertical mesh resolution in overcoming numerically enhanced mixing, due to the steep bathymetry gradients in the Marmara Sea. Moreover, the distribution of sigma surfaces over the water column is considered in relation to its influence on the computed two-layer flow. Although HYCOM generally provides a considerably good solution for the dynamics in TSS, it cannot resolve flow in the narrow straits because of the coarse resolution of the model. In a system largely driven by internal density differences, the initialization of the density structure within the ADCIRC model is crucial for realistic simulations. Model representation of the two-layer flow within the straits is evaluated by comparing three sources for the initial condition. The first form of the initial condition is derived from available observations, a second created using climatological conditions, and the third is extracted from the regional HYCOM solution. Model performance for each numerical implementation considered above is assessed by comparison to observations obtained during the TSS08 and TSS09 Sea Trials in Sep. 2008 and Feb. 2009.

Adjoint-based error control and sensitivity analysis for shallow water models

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Abstract

We present an *a posteriori* error control framework, based on the solution of appropriate adjoint problems, valid for single and multiple-stack shallow water models. We focus on finite elements discretizations using various combinations of non-conforming and mixed elements for forward and adjoint solves. We extend the framework to handle adjoint-based sensitivity analysis, including the effect of numerical error in the sensitivity calculation. Finally, we discuss modifications to the error control framework to handle standard types of operator decomposition: *e.g.* iteration on multiple stacks in a stacked model, and/or multirate time integration.

IMUM-2010, MIT August 17-20, 2010

A Global-to-Wetland Scale FVCOM System: A New Unstructured-grid Model Tool to Resolve Multi-scale Ocean Processes

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A global-to-wetland nested FVCOM system has been developed to resolve and examine the multi-scale oceanic response to climate change. This system includes the Global-FVCOM, GoM-FVCOM, Mass Coastal-FVCOM, and PIS-MR-FVCOM. Global-FVCOM uses the spherical version of FVCOM to cover the entire global ocean with inclusion of all major rivers. Its grid features a horizontal resolution of 5 km (in the coastal region of the Gulf of Maine/Georges Bank and the East and South China Seas) to 50 km (in the interior). Arctic-FVCOM is the Arctic regional model nested with Global-FVCOM. This regional model features a horizontal resolution of 0.5 km (in narrow channels in the Canadian Archipelago) to 25 km in the interior. GoM-FVCOM is the northeast US coastal regional model nested with Global-FVCOM. The subdomain spans from the Scotian shelf to Cape Hatteras, thus covering the Gulf of Maine (GoM) with a horizontal resolution ranging from 0.5 km to 10 km. Mass Coastal FVCOM is a high-resolution subdomain model with horizontal resolution varying from 15 m to 5 km. This model is nested with GoM-FVCOM and constructed to resolve all water passages, islands, and harbors in Massachusetts and Cape Cod Bays. PI-MR-FVCOM is the estuarine/wetland model configured for the long-term NSF LTER ecosystem-monitoring site in the Plum Island and Merrimack River complex.

The FVCOM system is fully coupled with UG-CICE (an unstructured-grid version of CICE) and driven by a) astronomical tidal forcing with eight constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1 and Q_1), b) surface wind stress, c) net heat flux at the surface plus shortwave irradiance in the water column, d) surface air pressure gradients, e) precipitation (P) minus evaporation (E) and f) river discharge. The system has been validated by comparison with field measurement data. Examples will be given in our presentation.

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Assessing the effects of numerical diffusion in a three-dimensional unstructured-grid model of a periodically-stratified estuary

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Three-dimensional simulations of flow in San Francisco Bay are performed with the unstructured-grid SUNTANS model in order to assess the relative importance of using a high-resolution, second-order scalar transport scheme over the first-order upwind scheme. We devise a method to evaluate the effective numerical diffusion of each scheme which leads to a quantative measure of the spatial accuracy of the scheme as well as a means of understanding the relationship between the dynamics of scalar transport and the numerical diffusion. The results show that the effective numerical diffusion is lower for the high-resolution scheme only in regions where tidal straining is relatively low. In regions of high tidal straining, strong stirring of the scalar field leads to grid-scale variability that produces equivalent numerical diffusion for both the high-resolution and first-order schemes. In the presence of periodic stratification, the effect of the high-resolution scheme is compounded due to its indirect effect on the stratification dynamics. We show that, although vertical numerical diffusion is weak relative to vertical turbulent diffusion for both schemes, high horizontal numerical diffusion for the first-order scheme leads to a weaker horizontal salinity gradient which leads to weaker baroclinic circulation. The effect is a weaker vertical salinity gradient due to weaker tidal straining (due both to weaker currents and weaker horizontal salinity gradients) and due to increased vertical mixing which results from less supression of turbulence by stratification. The resulting indirect effect on the vertical stratification leads to substantially better results compared to the observations for the high-resolution scheme.

IMUM-2010, MIT August 17-20, 2010

SHYFEM, a numerical tool for investigating environmental processes in coastal seas and lagoons

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SHYFEM (http://www.ve.ismar.cnr.it/shyfem) is a software package consisting on a set of integrated numerical tools based on the finite element method developed to investigate, with a multi scale approach, the hydrodynamic and the main physical and biogeochemical processes occurring in both open ocean and coastal seas.

The core of the system is a fully coupled 3D current and wave numerical model based on unstructured meshes. The hydrodynamic module solves the Shallow Water equation with the hydrostatic and Boussinesq approximation. It uses a semi-implicit algorithm for the time integration and a finite element approach for the horizontal spatial integration (Umgiesser, 1997, Umgiesser et al., 2004). The model takes into account the main physical forcings characterizing the water circulation such as barotropic and baroclinic forcing, horizontal and vertical viscosity effects and non-linear inertial processes. Both z and sigma layers are adopted in order to solve the vertical dimension and a state of the art turbulence model, GOTM (Umlauf et al., 2007), is used to reproduce the vertical mixing. The 3D two way wave-currents interaction is computed by using the algorithm proposed by Xia et al. (2007), which takes into account the main physical processes that occur in very shallow areas such as shoaling, breaking and Stokes drift.

The current model is fully coupled via FIFO Pipes with a 3rd generation spectral wave model, called WWM (Wind Wave Model; Hsu et al., 2005a) which solves the WAE Wave Action Equation on unstructured spatial grids. The WWM adopts state of the science source term formulation for the generation, nonlinear interaction and decay of wave energy. The fractional step method (Yanenko, 1971) is used to split the wave action balance equation into spatial, frequency and directional space. These three parts are integrated successively, which makes it possible to apply efficient numerical algorithms to solve the WAE in the certain dimension. The source term integration is done in another separate fractional step where various methods can be used like, e.g., the dynamic source term integration method following (Tolman, 1997). The wave model has been verified in different environments (Hsu et al., 2005b, 2006; Roland et al., 2005, 2006).

The 3D coupled current and wave model is integrated with a set of numerical tools such as a sediment transport and morphological model (SEDTRANS05, Li and Amos, 2001; Neumeier et al., 2008), an

ecosystem model (BFM, Vichi et al., 2007) and an oil spill model which allows to deal with most of the main environmental processes interesting the coastal areas.

The integrated model has been applied with success to several sites around the Mediterranean Sea. We present a set of different applications of the SHYFEM package consisting in: reproduction of water circulation, wave propagation and sediment transport in coastal areas and tidal active lagoons, computation of water transport time scales in lagoons and semi-enclosed basins and implementation of operational systems for predicting waves, currents, water levels and trajectories followed by pollutants released in shallow water areas.

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A non-hydrostatic two-dimensional unstructured finite volume model for tsunami waves

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As the recent Indian Ocean tsunami demonstrated it is important to develop accurate tsunami models, that can be incorporated into early warning systems. Many tsunami models employ the hydrostatic assumption. This is because the tsunami wave is generally much longer than the ocean depth. However, there is the potential to introduce inaccuracies into the numerical solution in regions where non-hydrostatic effects may be important. For example, in areas with complex sea topography, dispersion needs to be taken into account in order to accurately model the propagation and shoaling of the tsunami waves.

Recently, a two-dimensional unstructured finite-volume model has been developed by Cui et al. (2010). This model has been shown to be mass and momentum conservative. The model produces accurate solutions in the simulation of flooding and drying. Based on this model, we use a non-hydrostatic correction method to incorporate the dispersive effects. The non-hydrostatic algorithm utilizes a non-hydrostatic pressure term to describe weakly dispersive waves. A fractional step numerical procedure proposed by Stelling and Zijlema (2003) is employed. In the first step, the model uses the conventional shallow water equations to compute the velocities and water levels. Then in the second step, the non-hydrostatic pressures are calculated implicitly by using the Poisson equation, which guarantees the new velocity field is divergence free. The velocities and water levels are then updated using the resulting non-hydrostatic pressure field.

The original implementation of the non-hydrostatic algorithm results in a sparse matrix with a large bandwidth, because the non-hydrostatic pressure gradient is approximated by the four node values within the two neighboring triangles of each edge. The solution of this matrix requires significant computational effort. To improve the efficiency of the model, the non-hydrostatic pressure gradient is only approximated by the three node values within one triangle when substituting the new velocities into the Poisson equations. In so doing, the bandwidth of the matrix is reduced by half. The new model is validated against several classic tsunami test cases, such as a standing wave, the propagation of solitary wave, and wave run-up onto a conical island.

Keywords: non-hydrostatic, finite-volume, unstructured mesh

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A Coupled HYCOM/ADCIRC System for the Northern Gulf of Mexico

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In order to accurately resolve the complex fluid dynamics that occurs within topographically complex shallow straits and coastal zones, a significant level of resolution is needed that is not feasible with structured grid regional/global ocean models, such as HYCOM. However, an unstructured coastal model can provide the level of resolution needed within these shallow straits and coastal zones. Thus, recent development efforts have looked to enhance the 3D baroclinic unstructured coastal model, ADCIRC, and couple it to the HYCOM model. Many of the barotropic applications utilize a model domain that encompasses large portion of oceans, which allows for simplification of the ocean boundary conditions. However, due to the computational demands of the 3D baroclinic simulations, we restrict the domain to the region of interest. One consequence of restricting the domain to the shallow water regions is the difficulty in specifying the ocean boundary information for the baroclinic fields. Thus, protocols have been developed to extract information from the structured regional/global ocean model, HYCOM, to ADCIRC in order to obtain initial and boundary conditions. Specifically, this presentation will summarize the procedures as applied to the coupled HYCOM/ADCIRC system in the Northern Gulf of Mexico.

Active particle-based modeling of blooms of a mixotrophic ciliate in the lower Columbia River Estuary

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Lagrangian particle tracking is performed based on output from a very high resolution realistic SELFE three-dimensional finite element model simulation of the Columbia River Estuary circulation for April through August 2009. Massive red blooms develop in summer each year in the main channels of the Columbia River estuary. These blooms are identified with very high concentrations of Myrionecta rubra, a mixotrophic planktonic ciliate that at times acts as an autotroph in the estuary by utilizing cryptophyte-derived chloroplasts. Observational studies have suggested that while the red blooms occur in the strongly tidally driven and rapidly flushed main channels of the estuary, the source region for the chloroplasts is a shallow semi-enclosed region along the northern edge of the estuary called Ilwaco Harbor (in Baker Bay). The duration of Myrionecta rubra blooms (over 30 days) well exceeds the flushing time in the estuary (0.5-5 days). So particle based modeling of the growth, transport, mixing, motility and mortality of Myrionecta rubra is performed to determine possible mechanisms by which the ciliates could both attain their food source from the shallow peripheral regions and form and sustain the intense blooms in the rapidly flushed main channels. Technical complexities such as particle behavior in the rapidly wetting and drying embayments, and active particle 'patch' formation within the unstructured grid framework are directly addressed.

Circulation Models for the Discovery Islands, British Columbia

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In order to better understand viral transmission between salmon farms, high and low resolution grids have been constructed for the Discovery Islands region of British Columbia and the models FVCOM and RiCOM are being used to simulate the regional circulation. Numerous narrow passages, deep fiords, seasonal river discharges, and some of the strongest tidal currents in the world make this a very challenging area to model and an ideal application for unstructured grids. The presentation will briefly describe the creation of initial and forcing fields and then assess model accuracy through comparisons with tide gauge and current meter observations.

A new wetting and drying algorithm using a combined pressure/free-surface finite element method

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A new wetting and drying method for numerical modelling of free-surface flows based on the Navier-Stokes equations is proposed. The method can be used in implicit schemes to allow large timesteps where several mesh elements are dried or wetted in a single timestep. A non-uniform unstructured mesh in the horizontal is employed. The mesh structure is fixed in time with layers moving in the vertical, although the long-term aim is to allow the use of fully unstructrered meshes in 3D and dynamic mesh adaptivity. The positivity of the water level is ensured by fixing the depth in dry regions such that a thin layer is maintained.

The key idea of the proposed method is the usage of a combined free-surface/pressure method in the wet areas and to apply a no-normal flow boundary condition on dry regions. The result is an accurate, stable and easy to implement scheme. These features are illustrated on idealised test-cases and on a more realistic wetting and drying process in a tidal estuary.

IMUM-2010, MIT August 17-20, 2010

Development of a Coastal Inundation Model using a Triangular Discontinuous Galerkin Method

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The use of unstructured triangular meshes provides an opportunity to accurately model coastlines which will aid in the study of tsunamis and storm surges. Discontinuous Galerkin methods employing triangular elements applied to shallow water equations have been developed by Giraldo and co-workers [1,2]. The attractive features of the discontinuous Galerkin method over the finite element and finite volume methods are the higher order accuracies and the local conservation properties. The local nature of the discontinuous Galerkin method inherently lends itself to efficient parallelization on massively parallel processing computers. A coastal inundation model applied in the triangular discontinuous Galerkin framework will be discussed in this presentation.

Adaptive mesh techniques will enable the optimal use of computational resources while providing higher resolutions in regions of interest. A combination of proposed R-refinement and H-refinement schemes for triangular grids applied to the DG method will also be presented in the talk.

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A fine sediment module for the two-dimensional component of SLIM

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Suspended particulate matter has a great influence on most of the biological and chemical organisms in aquatic environments. A good representation of the sediment dynamics is therefore essential for ecological modeling. To this purpose, a fine sediment module is developed and coupled to the two-dimensional component of the finite-element model SLIM.

In this module, two tracers are calculated: the concentration of suspended sediments and the concentration of sediments on the bottom. The first one is transported according to the hydrodynamics and diffused, while the second one does not move. Classical parameterizations of erosion and deposition allow exchange between tracers. The talk focusses on two studies using SLIM and implying sediments.

The first case studied is the Scheldt Estuary (Belgium, the Netherlands). The model, covering the whole continental shelf, the estuary, the tidal river and the main tributaries of the Scheldt, is thoroughly multi-scale (de Brye *et al*, 2010). In this application, the sediment module is only a step forward in order to obtain a more complex ecological model (fecal bacteria and heavy metals modules interacting with the present sediment module will follow). The Scheldt is a relatively turbid estuary, with a maximum of turbidity zone that is quite well represented by the model. The model is validated against data measured at three different stations along the estuary. While the seasonal variability seems to be correctly predicted by the model, the tidal variability is not. Taking into account wave-

driven resuspension at the mouth or even biology may improve the results. This is still an ongoing study.

In the second study, the sediment module is used to investigate the degradation of coral reefs in Cleveland Bay (Australia). For present land-use conditions, the model shows that the amount of riverine sediments settling on the bay may exceed by 50-75 % the amount of sediment exported from the bay. Sediment is thus accumulating in the bay on an annual basis, which may be responsible of the observed degradation of fringing coral reefs (Lambrechts *et al.*, accepted for publication).

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TUGOm – progress, application and testing

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T-UGOm (Toulouse Unstructured Grid Ocean Model) is designed to be a flexible triangular grid model for research and application to ocean scales from nearshore to global. It is written in C++, with many options, such as fe/fv geometry, solution modules and major parameterization runtime selectable. This setup allows us to explore the suitability and efficiency of different model configurations. The presentation will give a report on the model development, describe some of the applications for which it has been used and outline a suite of tests performed on each version of the model. These test results are compared to to results from other FE, FV and FD models.

MSEAS: Multiscale two-way embedding schemes for free-surface primitive-equations

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Our goal is to resolve tidal-to-mesoscale processes and interactions over large multi-resolution telescoping domains with complex geometries including shallow seas with strong tides, steep shelfbreaks and deep ocean interactions. In this presentation, we summarize our novel time-dependent structured discretizations and two-way embedded (nested) schemes for multiscale coastal dynamics governed by primitive-equations (PEs) with an implicit time-stepping algorithm for the fully nonlinear free surface. We compare 2-way nesting implicit in space and time, which exchanges all of the updated fields values across grids as soon as they become available, to more traditional explicit schemes. We present the initialization procedures and open boundary conditions needed for both the nonlinear free surface PE and for nesting, including the corresponding procedures for utilizing barotropic tidal forcing. We complete a theoretical truncation error analysis which explains how increasing the implicit couplings among grids improves the accuracy. We present results of our novel discretizations and 2-way nesting in realistic multiscale simulations with data assimilation. In the Philippine Straits Dynamic Experiment (PhilEx), we employed our system to simulate the coupled physical/biological processes and features arising in and around straits and to predict the spatial and temporal variability. In the Quantifying, Predicting and Exploiting Uncertainty (QPE) experiment in the Taiwan-Kuroshio region, we integrated coupled ocean-acoustic modeling, multidisciplinary data assimilation and two-way nesting to improve prediction and reduce uncertainties. In the Shallow Water 2006/Autonomous Wide Aperture Cluster for Surveillance (SW06/AWACS) in the New Jersey Shelf/Hudson Canyon region off the east coast of the USA, we resolved the multiscale shelfbreak front interactions with the larger scale oceanographic conditions, tidal and atmospheric forcings and explored the generation/propagation of internal tides.

IMUM-2010, MIT August 17-20, 2010

Recent applications of FEOM and TsunAWI: regional and global experiments

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We present the recent status and applications of the unstructured mesh ocean models TsunAWI and FEOM (Finite Element Ocean Model) currently under development at AWI.

TsunAWI is a wave propagation model based on the nonlinear shallow water equations and employing the $P_1^{NC}-P_1$ element pair in triangular meshes of regional and global extent. The model is optimized and validated in academic test cases and realistic events with measured data as well. Recently TsunAWI was used to simulate the tsunami caused by the M_w 8.8 earthquake on 27 Feb 2010 offshore the coast of Chile. We present model results in a global mesh with high resolution in the source area and at tide gauge locations. The results compare well with buoy and tide gauge data as well as satellite altimetry data.

The 3D ocean general circulation model FEOM was recently applied in the setting of the Coordinated Ocean-Ice Reference Experiments (CORE I). The global mesh has horizontal resolution varying from 1/5 ° near the coast to 1 ° in the deep ocean, and 43 unevenly spaced z-levels in the vertical. The heat, fresh water and momentum forcing is computed using the atmospheric fields and bulk formulae provided by Large and Yeager (2004). The model was run for 500 perpetual years. It is shown that FEOM performs very well compared with the previous CORE I results.

Examples of regionally focused studies will be presented to show FEOM's advance in oceanographic applications.

On the performance of a generic length scale turbulence model within an adaptive mesh finite element ocean model

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A two-equation turbulence model, the Generic Length Scale (GLS) model as proposed by Umlauf and Burchard, 2003 [J. Marine Research 61 (2003) 235] is implemented in a finite-element, unstructured mesh, non-hydrostatic, 3D ocean model (ICOM). These two equations, along with several stability functions, can represent many popular mixed layer turbulence closures, including the k-kl (cf. Mellor-Yamada Level 2.5), k-ϵ, and k-ω schemes. The implementation adds flexibility to the model by providing a range of turbulence closure selections in a single oceanographic model and allows comparison and evaluation of turbulence models in an otherwise identical numerical environment.

This talk describes the GLS model as implemented in ICOM and shows how it compares to the leading 1D turbulence model, GOTM. We show that the seasonal mixed layer depth cycle can be accurately modelled at Ocean Weather Station PAPA on both fixed and adaptive meshes, where adaptive meshes reduce the computational time whilst maintaining or improving the best fixed mesh result.

Application of the Coupled ARCIRC+SWAN Model to Hurricane Ike on the Texas Gulf Coast

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The geometrically complex system of narrow inlets, back bays, rivers, coastal ridges, and intricate topology that comprises the Texas Gulf Coast requires a high resolution, unstructured mesh in order to accurately depict the propagation of tropical storm driven surge and waves. The adjacent shelf, with a width of over 200 km at some points, makes the area particularly susceptible to highly localized water level and current gradients that are associated with tropical storm induced flooding. With many population centers lying on bays that are hydraulically connected to the Gulf, the need for a highly accurate surge and waves model is apparent.

In this study, the tightly coupled ADCIRC+SWAN hydrodynamic and wave models are applied to Hurricane Ike. Hurricane Ike was a strong category 2 hurricane that made landfall on the Texas Gulf coast on September 13, 2008 creating significant storm surge and inland flooding. The study applies the tx2008 computational grid consisting of over 3.3 million computational nodes resolving coastal features as small as 50 meters. The grid domain stretches from the Texas coastal flood plain to the Atlantic Ocean incorporating the entire Gulf of Mexico and Caribbean Sea.

The coupled ADCIRC+SWAN model results will be validated using extensive surge and wave data collected by NOAA, USGS, US Army Corps of Engineers, and other federal and local authorities.

This study also investigates the origin of the previously undocumented forerunner surge which inundated the Texas Coast with up to 2.5 meters of water 15

hours prior to landfall, while the center of the storm was off the continental shelf. The slowly developing forerunner efficiently pushed water into estuarine systems, including the heart of Houston more than 80 km inland, and propagated as a large shelf wave past Corpus Cristi more than 300 km away from the track of the storm.

Numerical modeling the development of field-scale internal boluses via barotropic tidal forcings

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Two-dimensional, nonlinear, nonhydrostatic numerical SUNTANS simulations are carried out to investigate the evolution of field-scale internal boluses and bottom surges across a shelf break. The goal is to better understand the generation, propagation, and dissipation of these field-scale boluses. The model experiments are motivated by results from April, 2005 in the South China Sea which show the formation of detached bottom-trapped boluses which propagate shoreward over the continental shelf. Associated with the boluses are a highly nonlinear internal tide as well as strong near-bottom stratification. The characteristics of these boluses / surges will depend on several factors, including the incoming tide which may have barotropic and baroclinic components. This study explores the effect of semidiurnal (M2) and diurnal (K1) barotropic tidal boundary conditions on the resulting boluses/surges structure and propagation. High-resolution (50 m horizontal, 1 m vertical) numerical simulations are executed using realistic stratifcation collected from data in the South China Sea. Preliminary results show a nonlinear steepening face of the isopycnals landward of the shelfbreak. As the propagation continues, instabilities appear on the back side of the wave lead to wave breaking. Quantitative comparison of the model runs with observations from the South China Sea are underway. Algebraic multigrid solver is presently being incorporated into SUNTANS to expedite the nonhydrostatic pressure Poission equation solution.

Tidally Averaged Circulation in Fjordal Sub-basins of Puget Sound: Model Validation Using Historic Records

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Through extensive field data collection and analysis efforts since the 1950s, researchers have developed a good understanding of the characteristic features of circulation in Puget Sound, Washington, consisting of a two-layered circulation system hydraulically bounded by two sills with net outflow through the mixed surface layer. An attempt at reproducing this behavior by fitting an analytical formulation to past data sets was successful but quickly re-confirmed that the hydrodynamic response is complex, and ranges from the classic fjordal behavior in some basins, with shallow brackish outflow and compensating inflow immediately below, to the typical two-layer flow observed in many partially mixed estuaries, with saline inflows at much lower depths. A three-dimensional circulation and transport model of Puget Sound (PS-CTM) was therefore developed incorporating multiple connected basins, presence of numerous islands, and site specific strong advective vertical mixing created by shallow sills and includes the effects of inflows, point and non point sources, meteorological forcing. The model developed using unstructured grid finite volume method was calibrated using available recent short term oceanographic time series data sets from different parts of the Puget Sound basin. This paper presents its application over year-long simulations to validate its capability of reproducing long term average circulation in Puget Sound. The results are compared against (i) a recent 1-year record of velocity and current profiles collected in Puget Sound from 2006 and (ii) a well established set of previously analyzed historical records, mostly from the 1970s. The model successfully reproduced velocity and salinity profile characteristics and their variation among Puget Sound sub-basins. Sensitivity of the residual circulation to seasonal variations, and influence of point sources and ungaged flows are also investigated.

Validation of the Imperial College Ocean Model with a wind-driven baroclinic gyre

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The Imperial College Ocean Model [Piggott *et al.* , 2008] is a fully unstructured, mesh-adaptive, non-hydrostatic ocean model. A key advantage of mesh adaptivity is that the flexibility provided by unstructured meshes to focus resolution where needed, is enhanced by enabling this focus to follow the dynamic features of the flow. The mesh adaptive technology of ICOM has already been applied successfully to many smaller scale process studies in geophysical fluid dynamics, as well as larger scale barotropic problems. Several challenges encountered in the use of ICOM in a wider range of oceanographic applications, have been met with the development of new numerical techniques, such as the ability to conservatively interpolate between the subsequently adapted meshes [Farrell *et al.* , 2009], without violating boundedness and introducing too much diffusion, and a novel algebraic multigrid method [Kramer *et al.* , 2010] to deal with the ill-conditioning of large aspect ratio problems.

In this contribution the application of ICOM to an important large scale oceanographic problem, in the form of a wind-driven, baroclinic double gyre is studied. The results are compared with that of two other, more traditional ocean models, the widely used MITgcm and NEMO. This study will provide validation of ICOM and is a major step towards application of ICOM in larger scale ocean applications with full baroclinic dynamics. A comparison will be made based on the main statistics of the flow fields, velocity, pressure, free surface and temperature, the turbulent bifurcation behaviour, and water mass mixing statistics to investigate

the models' ability to maintain stratification. Although the simplified geometry does not necessarily bring out the main advantages of unstructured and adaptive mesh technology, a comparison is also made in computational efficiency and in particular parallel scaling.

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A sigma–coordinate, discontinuous Galerkin method for the three–dimensional shallow water equations

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In this presentation, we describe the development, implementation, and application of a novel discontinuous Galerkin (DG) method for the three–dimensional shallow water equations. A key feature of the developed DG method is the discretization of all the primary variables using discontinuous polynomial spaces of arbitrary order, including the free surface elevation. In a standard Cartesian–coordinate system, this results in elements in the surface layer having mismatched lateral faces (a staircase boundary). This difficulty is avoided in the current method by employing a sigma–coordinate system in the vertical, which transforms both the free surface and bottom boundaries into coordinate surfaces. The top sigma–coordinate surface, which corresponds to the free surface, is discretized using a combination of triangular and quadrilateral elements that are extended in the vertical direction to produce a three–dimensional mesh of one or more layers of triangular prism and hexahedral elements. The polynomial spaces over these elements are constructed using an orthogonal basis, which results in a matrix–free implementation of the method. New symmetric quadrature rules for the integration of complete polynomials over triangular prisms are also developed, which require fewer integration points than other available methods of numerical integration over triangular prisms. The h (mesh) and p (polynomial order) convergence properties of the method are demonstrated on a set of analytic test cases for the three-dimensional shallow water equations.

IMUM-2010, MIT August 17-20, 2010

Efficient assembly of high order continuous and discontinuous finite element operators

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There is a growing consensus that state of the art Finite Element/Finite Volume technology is and will remain too computationally expensive to achieve the necessary resolution, even at the rate that computational power increases. The requirement for high fidelity computations naturally leads us to consider methods which have a higher order of grid convergence than the classical (formal) second order provided by most industrial grade codes. This indicates that higher-order discretization methods will at some point replace the solvers of today, at least for part of their applications.

Although the potential of high order methods has been clearly demonstrated in literature, their inefficiency has been stressed by many authors. Only few publications are really dedicated to the matter; most of these focus on efficient, if not simplified, quadrature (Atkins and Shu, 1998). It is our opinion that this is not a desirable solution for non-linear problems as the potential savings are not tremendous. And these methods usually degrade or limit accuracy which may lead to decoupling for non-linear weakly hyperbolic equations. Moreover, it is shown in many contributions that the accuracy of a high order method strongly depends on the accuracy of the geometrical discretization (Bassi and Rebay, 1997 ; Bernard *et al.*, 2008). In other words, high order methods require high order meshes and full precision quadrature.

The finite element analysis process is classically decomposed into two parts: (i) the assembly process and (ii) the resolution process. At high orders, it is easy

to show that the number of operations for the evaluation of the element matrices grows quickly with p, the polynomial order used for the approximation ($\mathcal{O}(p^9)$ in 3D). There is indeed a point, i.e. at some high order of approximation, where the assembly process inevitably becomes more expensive than the resolution process.

In this work, we will show that it is possible to dramatically enhance the computational efficiency of the evaluation of finite element matrices by re-casting most of the floating point operations as large matrix-matrix multiplications. In this assembly process, no approximations are made on the quadrature or on the shape of the elements.

The method can be applied both to continuous and discontinuous Galerkin formulations of systems of nonlinear PDEs.

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The design, calibration, validation and application of a model nesting methodology

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Motivated by a need for forecasting the initiation and fate of Harmful Algal Blooms (HABs) on the West Florida Shelf (WFS), a shelf-scale numerical ocean model was nested within a basin-scale model which covered the whole of the Gulf of Mexico. The basin-scale model was based on the Princeton Ocean Model (POM) and the higher resolution, nested model employed Rutgers University's Regional Ocean Modeling System (ROMS). The nested model was forced along the open ocean boundaries with water elevations, baroclinic and barotropic (re-calculated for the nested domain) currents, and temperature/salinity from the basin-scale model. At the ocean surface, both models were forced with COAMPS-based wind stresses and climatological heat fluxes and sea surface temperatures. The nesting calibration was achieved with a series of short 15-day runs and the comparison of water elevation, currents, temperature and salinity fields between the two models for similarity and consistency for a range of open boundary conditions. This exercise showed that for the nesting to be effective, (i) the model bathymetries needed to match along the open ocean boundaries so that the volume transport between the two model domains was consistent, (ii) a special open boundary condition for the normal component of the current needed to be employed without which barotropic waves remained trapped within the nested model domain and caused significant wave reflections, and (iii) the application of a volume conservation criterion to the nested domain was excessively restrictive especially during extreme phenomena such as hurricanes. The nesting validation for the WFS region involved running the coupled set-up for a 6-month period in 2005, which included 5 hurricanes. This ensured that (a) the nested model faithfully reproduced the water elevation, currents, temperature and salinity fields of the basin-scale model and was free of barotropic wave effects and (b) these physical fields were also in good agreement with observed data for 2005.

This model nesting strategy was thereafter employed in two other applications. The first was to model the circulation around Poplar Island, MD which is being restored by the US Army Corps of Engineers; the modeling challenge associated with this application arises from the need to have all the nested model boundaries as open ocean boundaries and the stronger presence of tides relative to the WFS region. In this application, the Poplar Island model was nested within a larger model covering the whole of the Chesapeake Bay and a segment of the coastal shelf, and both models were based on ROMS with the latter system being known as National Ocean Service's Chesapeake Bay Operational Forecast System upgrade (CBOFS2). The second application involved the placing of two ROMS-based nested models within a ROMS circulation model for the Cook Inlet, AK region.. One nest covered the upper region of this model domain (Knik Arm, Chickaloon Bay and Tumagain Arm), and the second nest covered Kachemak Bay both of which are of importance to the navigational marine community. The numerical modeling challenges pertaining to this application arise from the large tidal ranges in the upper Cook Inlet and the extensive expanse of tidal flats and extremely strong tidal currents throughout the region.

Gradient, divergence and laplacian discrete approximations for numerical ocean modelling

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Ocean modelling imply to handle the integration of the gradient and divergence, occasionally laplacian when it comes to explicitly diffusive problems, of possibly discontinuous functions, hence with their derivative not defined along discontinuity limits. It is generally done using some sort of finite differences analogy, but these approximations are mostly empirical and can lead to inconsistencies.

For first derivative operators (under integral sign), we propose new approximations (expressed as a correction term to the Rieman's integral) that master these inconsistencies and are compatible with standard integrations propriety, especially Liebniz's and Stokes' formulas. Using these approximations permits some unification of the finite differences, finite elements and finite volumes methods. However, the authors would like to open two fundamental questions:

1. The laplacian operator of a discontinuous function is not integrable, and an arbitrary re-formulation must be used in place of this operator (such as second order finite difference or an intermediary change of discretisation). Inappropriate re-formulation can lead to some difficulties in advection-diffusion applications as the efficiency of the re-formulated diffusion operator is not guaranteed to minor the velocity field variance in space. Our first question is: what would be then an optimal re-formulation?

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2. The issue of discontinuities is somehow even more worrying in 3D modelling. In the finite volumes approach, the use of discontinuous elevation (hence discontinuous σ-layer discretisation), would, in theory, need extremely heavy derivation to rigorously take discontinuities into account, with a very significant additional numerical costs. In most of finite volumes models (structured or not structured), those discontinuities are simply ignored to maintain a low numerical costs (elevation/layer displacement is discontinuous in the mass conservation equation, but taken as continuous when deriving the pressure terms, and sigma layers are seen as continuous tilted surfaces to justify the horizontal transport from one column to another). The so-called "hydrostatic inconsistency" directly derive from this simplification (through the violation of Liebniz's rule). Our Second question is: shall we keep going with non-rigorous models (in case of finite volumes, cost-efficient and with well-known errors and limits) or shall we investigate and invest community efforts in more rigorous approaches, with a predictable significant impact on computational costs?

SLIM : a three-dimensional baroclinic finite-element model Time and spatial discretizations

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This presentation describes both spatial and time discretizations of the three-dimensional baroclinic finite element SLIM model, based upon a Discontinuous Galerkin [Blaise *et al.*, 2010; Comblen *et al.*, 2010] . We solve the hydrostatic Boussinesq equations governing marine flows on a mesh made up of triangles extruded toward sea-bottom to obtain prismatic three-dimensional elements. Diffusion is implemented using the symmetric interior penalty method, with modified penalty coefficients to handle the anisotropy. The tracer equation is consistent with the continuity equation. A Lax-Friedrichs flux is used to take into account internal wave propagation. As a relevant illustration, a flow exhibiting internal waves in the lee of an isolated seamount on the sphere is simulated. This enables us to show the advantages of using an unstructured mesh, where the resolution is put in areas where the flow varies rapidly in space, the mesh being coarser far from the region of interest. The solution exhibits the expected wave structure. Linear and quadratic shape functions are used and the extension of to higher order discretization is straightforward.

The time stepper is based on an efficient mode splitting. To ensure compatibility between the barotropic and baroclinic modes in the splitting algorithm, we introduce Lagrange multipliers in the discrete formulation. The use of implicit-explicit Runge-Kutta methods enables us to treat stiff linear operators implicitly, while the rest of the nonlinear dynamics are treated explicitly. For such an implicit/explicit approach to be interesting, the discrete operators for the dynamics handled implicitly must be significantly stiffer than those for the explicit dynamics. Indeed, the time step allowed by the IMEX scheme must be significantly larger than the time step of a purely explicit discretization. Gowever, those time steps are much more expensive, as local linear systems are solved. To faster computations, the way is

twofold. On the one hand, the computation of the discrete terms can still be improved, by recasting most of the operations into efficient matrix matrix products computed with highly optimized linear algebra subroutines. On the other hand, the time stepping strategy can itself be improved. IMultigrid methods have the potential to provide scalable solutions to large-scale discrete problems. Further such multigrid methods do not need the matrix of the linear system to be assembled, dramatically reducing the memory footprint of the algorithm. However, the design of an efficient multigrid algorithm is itself a whole domain of research.

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Multi-scale Modeling of Riverine and Porous Coastal Environments In a Hydrodynamic Model

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The Lower Mississippi River and its delta are forced by a range of processes and scales including riverine flows, tides, winds, atmospheric pressure fields and wave fields. This region has been modeled using the Southern Louisiana SL16 unstructured mesh, which utilizes a large domain encompassing the U.S. Gulf Coast, the Gulf of Mexico, the western North Atlantic Ocean and the Caribbean Sea. This large domain allows simple and well established boundary conditions to be applied. A wide range of resolution (from 30m to 25 km) has been applied within the domain, particularly in Louisiana, where there are significant wave-breaking zones; large bathymetric gradients due to the continental shelf; and large swaths of coastal wetlands that cause large localized gradients in surface elevation, current and wave fields. Significant resolution is placed within the Mississippi River and its delta for improved riverine and tidal flow, as well as hurricane surge propagation.

The SL16 unstructured mesh will be used with the ADCIRC Coastal Circulation and Storm Surge Model in the validation of riverine flows and hurricane surges in the Lower Mississippi River. A study of riverine stage-discharge relationships will be shown, with comparisons to the previous SL15 unstructured mesh and to measured riverine stages at various stations along the River. In addition, discharges at various distributaries in the River delta will be compared to measured discharge information at the same locations, and previous simulations with the SL15 computational mesh. The coupled SWAN+ADCIRC model will be used to highlight surge propagation along the River during various hurricane events.

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Simulation of Mixing in 2D Gravity Currents Subject to Time-Dependent Forcing

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The mixing in 2D gravity currents subject to time-dependent forcing is simulated using a non-hydrostatic spectral element code. Two different forcing mechanisms were investigated, one due to periodic internal waves, and the other due to periodic changes in barotropic transport; and two different Reynolds were studied: 15,000 and 50,000. For the transitional Reynolds number, the incident internal waves lead to a dramatic increase in the mixing and the formation of individual heads, while changes in background transport lead primarily to an increase in interfacial layer thickness. For the high Reynolds number case, the time-dependent forcing had a lesser impact; however, the time-dependent forcing seem to influence the transport in density classes and the channel exit.

Modeling of a Coastal River and Associated Floodplains

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Efforts to model coastal rivers are often complicated by a lack of the high quality information needed to produce a good mesh. The physical difficulty of surveying river banks, and the stage dependent nature of those banks, as well as the changing nature of the river bed, which is reworked by annual floods and major storm events, and the expense of bathymetric surveys in such systems, often renders it prohibitive to directly gather this information.

In an effort to overcome this limitation, a procedure has been developed to extract river bank locations based on aerial imagery at bank full conditions. A simple synthetic bathymetry has been developed as well, based on an idealized profile fit to the channel edges, which allows river depth to be estimated in areas where surveys are not available. Combining this river edge location information with the synthetic bathymetry and available topography, a high quality unstructured mesh can be generated covering the river channel and floodplains, allowing the modeling of in channel flow, flood events and intertidal processes.

These techniques are applied to generate a grid for the Pearl River in Mississippi and Louisiana from aerial imagery and a LIDAR derived DEM. The river is then modeled using ADCIRC and the resulting solution is compared to available data.

Multigrid-based solvers for the shallow-water equations

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Fast iterative multigrid solvers in fluid mechanics have been the subject of a large amount of research since the 1980's [Barros *et al.*, 1990; Benzi *et al.*, 2005; Elman *et al.*, 2005]. In ocean modeling, the development of numerical techniques is important to improve the implicit treatment of the stiff dynamics. For example, an efficient iterative solver for the computation of the sea surface elevation could allow for getting rid of time step constraints imposed by gravity waves. The computational cost would be highly reduced, using a multi-scale numerical approach. Then, the ocean global circulation could be simulated by finite element models such as the *Second-generation Louvain-la-Neuve Ice-ocean Model* (SLIM) [White *et al.*, 2008].

The three-dimensional baroclinic free-surface marine SLIM model relies on a hydrostatic Boussinesq equation discretized with a Discontinuous Galerkin method on a mesh of prisms extruded in several layers from an unstructured two-dimensional mesh of triangles [Blaise *et al.*, 2010; Comblen *et al.*, 2010]. As the prisms are vertically aligned, the calculation of the vertical velocity and the baroclinic pressure gradient can be implemented in an efficient and accurate way. All discrete fields are defined in discontinuous finite element spaces, in order to take advantage of the well-known good properties of the Discontinuous Galerkin methods for advection dominated problems and for wave problems. The discretization of the three-dimensional horizontal momentum and the continuity equations are defined in such a way that their discrete integration along the vertical axis would degenerate in a stable discrete formulation of the shallow-water equations.

As a first step in the development of an efficient preconditioned Krylov solver of the three-dimensional baroclinic ocean model, we propose to design an efficient multigrid-based solver for the two-dimensional shallow-water equations where we

assume a constant bathymetry and remove all nonlinear inertia and free surface terms. Hence, the steady-state equations degenerate into a usual saddle-point problem [Benzi *et al.*, 2005] exhibiting a similar mathematical structure as the Stokes equations . The finite element discretization of this simplified model yields

$$\begin{bmatrix} F & B^T \\ B & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ g\boldsymbol{\eta} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{0} \end{bmatrix}$$

where F contains the discrete diffusion and Coriolis operator; B and B^T are the discrete negative divergence and gradient operators, respectively. The sea surface elevation $\boldsymbol{\eta}$ plays here the role of the pressure.

To solve such a discrete saddle-point problem with a rate of convergence independent of the mesh size, we use a block approach. An approximation of an ideal block preconditioner based on the Schur complement is obtained from a geometric multigrid approach [Elman *et al.*, 2005; Hackbush, 1985]. We consider approximate L_2 projections between non-nested meshes and multi-directional smoothers using block Gauss–Seidel splittings. Special care for the design of the preconditioner is required to take the impact of both the Coriolis force and the discontinuous discretization into account. Nevertheless, our approach is general and can then be applied on both standard and non-conforming Galerkin finite element methods.

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State Estimate of the California Current System Using 4DVAR Ocean Data Assimilation

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4DVAR data assimilation (DA) over the California Current System is performed using all available observations during key time intervals in April 2002 and 2003. The resultant model fits can help to interpret biological observations that exhibited extreme conditions during these periods. They also provide initial conditions that improve model forecast skill of the physical state.

Passive tracers are used with the ROMS adjoint model to identify how source waters of upwelling are depending on the structure of the wind stress and wind stress curl forcing.

The generalized Flather lateral open boundary condition

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The barotropic lateral open boundary conditions are reviewed and a formal derivation of the generalized Flather boundary condition is shown which allows to apply scale dependent approximations in a consistent way. One of the main conceptual problems in the Flather (1976) lateral boundary condition is the simplification made in its derivation. However, the generalized Flather lateral boundary condition derived in this presentation relaxes all simplifications and use a more complete formulation of the lateral boundary conditions for barotropic normal velocities. After decomposing the nested model fields in 'global' and 'regional' components, we derive two new general lateral boundary conditions, for the barotropic velocity components.

Idealized and realistic numerical experiments are carried out in order to study the impact of the scale selective lateral boundary conditions. The idealized experiments results show significant improvements in the model solution related to the application of the scale selective approach to the lateral boundary conditions. A system composed by a coarse model with rigid lid, covering the entire Mediterranean Sea, and a fine resolution free surface model, reproducing the Adriatic Sea, has been used to evaluate the performance of different boundary conditions in a realistic framework. Three test cases in the realistic framework will be presented and the results discussed.

A very large application of unstructured coastal models for infrastructure projects

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The use of unstructured models in marine planning has in recent year been increasing and is today part of many large infrastructure projects. The presentation will describe, what may be one of the most comprehensive coastal modeling applications today, of the MIKE 3/21 modeling framework in one a very large bridge projects, the Fehmern Belt, linking Denmark and Germany across the 20 km wide entrance to the Baltic Sea. The focus of the modeling is to ensure a proper description of both the long term impact of the bridge on the Baltic sea environment, and to provide detailed impacts and design conditions for the construction. The modeling comprise 2D and 3D long term modeling of the impacts of the bridge pylons on the Baltic sea ecology, assessment of impacts on the sand transport affecting the seabed and waves and currents for design. The presentation will briefly describe the MIKE 3/21 models involved and the concept for how the modeling is integrated into the planning decisions. Emphasis will be on how the unstructured models are used to link the detailed design of bridge pylons to the long term (30 years or more) development of the Baltic ecosystem.

A comparison of Finite Volume and Finite Element Methods for simulating The Indian Ocean Tsunami

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Tsunamis pose an enormous threat worldwide. Tsunami warning systems require accurate models that not only simulate the arrival times of tsunami waves but also accurately simulate extreme run up heights and the extent and risk associated with potential inundations. Here we compare three different low order and efficient finite element and finite volume methods; namely TsunAWI, H2Ocean and Delfin. These models are based on the $P1_{NC}$ -P1 finite element, its' finite volume equivalent and an orthogonal FV method, these models are described in Harig et al. (2008), Cui et al. (2010) and Kleptsova et al. (2010). We describe the flooding and drying algorithms and how they can be implemented in unstructured models. The first model uses an extrapolation technique, whereas the latter two models employ the flooding and drying routines described in Kramer and Stelling (2008). A number of examples are presented, and in particular we pay attention to simulations of the Indian Ocean Tsunami. Part of this work has been carried out in collaboration with the Alfred Wegener Institute in the framework of the GITEWS tsunami warning system.

The Indian Ocean Tsunami was caused by the massive Sumatra-Andaman earthquake that occurred on December 26, 2004. It was recorded by tide gauges in the Indian, Pacific and Atlantic Oceans. It was also the first tsunami to be clearly recorded by a number of satellite altimeters. Many models have been validated against the arrival of the leading tsunami waves when compared with the Jason-1 satellite data, for example, see Pietrzak et al. (2007). However, we show here that the satellite information is not enough to discriminate between tsunami source models. We first show that the three models accurately simulate the inundation of Bande Aceh. Then we use this result to show how accurate inundation models also allow us to determine the source region and discriminate between source models.

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Ocean Circulation Modeling Using Adaptive Wavelet Collocation Method

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The adaptive wavelet collocation method is applied to basin-scale, wind-driven ocean circulation models. This method solves the governing equations on temporally and spatially varying meshes, which allows higher effective resolution to be obtained with less computational cost. The grid adaptation is achieved by using the ability of wavelet multiresolution analysis to identify and isolate localized dynamically dominant flow structures, e.g., vortices, and to track these structures on adaptive computational meshes.

In addition to studying how various ocean models behave on non-uniform, time varying grids, this work also sets out to improve the representation of continental topology and bottom bathymetry through an extension of the Brinkman penalization method. Due to the complicated geometry inherent in ocean boundaries, the stair-step representation used in the majority of current global ocean circulation models causes accuracy and stability problems. Brinkman penalization is a numerical technique used to enforce no slip boundary conditions through the addition of a term to the governing equations. When coupled with the adaptive wavelet collocation method, the flow near the boundary can be well defined. This is especially useful for simulation of boundary currents. Therefore, the Gulf stream and western boundary currents have been the focus of the work presented here.

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Application of FVCOM to 2004 Indian Ocean Tsunami Focusing on Inundation in Banda Aceh, Indonesia

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Most of the tsunami computations have been based on a nesting approach on a structured grid system (Koshimura *et al.*, 2009). Recently, free and open source unstructured grid ocean circulation models have been proposed and started to be applied to tsunami simulation (Zhang and BaptistaC2008). FVCOM, developed by Chen *et al.* (2003), is one of the free and open source unstructured models, becoming popular among scientists and engineers because of its high performance and provision of useful manuals. Some features of the model are the adoption of finite volume method, capability of wet and dry cell treatment and efficient parallel computing based on MPI. These advantages will also be effective for application to tsunami propagation and inundation problems to which FVCOM has not been applied. Thus, the objectives of the present study are to consider the applicability of FVCOM to tsunami problems.

We selected the 2004 Indian Ocean tsunami as an application target, focusing on inundation in Banda Aceh, Indonesia. First, we slightly changed the source code to give arbitrary initial variation in surface elevation that is determined using a tsunami fault model of Mansinha and Smylie (1971) with parameters proposed by Oie *et al.* (2006). We constructed unstructured grids using SMS with the bathymetric data for propagation region provided by GEBCO and the nearshore bathymetric and land elevation data of ARRIS (JICA, 2005) and ASTER GDEM. The ARRIS data includes the height of major buildings and structures in Banda Aceh. The Grid size for the propagation region ranges from 50 m in the coast to 50 km in the ocean basin while it ranges from 5 m to 50 m in the inundation region. Roads and structures are resolved in some local area in the inundation region.

We simulated for two-hour wall clock time and verified the computed results comparing with the measured tidal gauge data at Krabi, Kuraburi and Sibolga. Although there was retardation in phase at Shibolga, the model results are mostly consistent with the measured ones in Krabi and Kuraburi, as well as with some other numerical works. Computed time series of tsunami surface elevation at the Ulee Lheue coast was also consistent with verbal evidence given by local people.

Maximal tsunami inundation heights and horizontal runup distances were compared between computed and measured values after Tsuji *et al.* (2006). The model results are consistent with measured ones in the area where roads and structures were resolved with fine grids while in most of the remaining areas the simulated results underestimate the measured ones. One of the causes of this discrepancy may attribute to the inclusion o f the height of structures in unresolved region into the elevation of grids. Thus, the model works well when the fine structure of the city is resolved, while a careful treatment is required for the region of coarse resolved areas, including an application of the resistance law with the composite equivalent roughness coefficient according to land use and building conditions rather than considering building heights directly (Koshimura *et al.*, 2009).

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Multirate Time Stepping for Accelerating Explicit High Order Discontinuous Galerkin Computations

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The development of suitable and fast time integration methods for ocean modeling constitutes an important challenge. No single time-discretisation works well for all physical processes in a complex marine model, as different subsystems have widely different characteristics in terms of time scales, dynamic behaviour, and accuracy requirements. The primitive equations for ocean flows allow for the existence of phenomena exhibiting a wide spectrum of propagation speeds. Typically, external gravity waves propagate at $10^1 - 10^2\ ms^{-1}$ and internal waves at a few meters per second, whereas advection is characterized by speeds ranging from 10^{-3} to $1\ ms^{-1}$.

We believe that building appropriate time stepping strategies for multi-scale computations will enable us to gain an order of magnitude. For instance, consider the case of a typical mesh of the Great Barrier Reef (GBR) made up of about 1 million triangles. Element sizes were determined in order to capture the relevant bathymetric and topographic features, and the associated hydrodynamic processes, such as eddies and tidal jets (Lambrechts *et al.*, 2008). Unstructured-mesh generation processes are complex and, even though it is possible to control average element sizes in specific regions of the domain, it is not the case for each element size. The smallest element is usually much more smaller than the criterion that was prescribed a priori. Typically, it is often possible that more than 99% of the elements have a size that is much more larger than the smallest element. So, if we apply a local Courant–Friedrichs–Lewy (CFL) condition, the global time step would be critically smaller than the one required for 99% of the elements.

We propose a class of methods that use various time steps on different grid

cells. It elegantly addresses varying cell sizes between adapted elements. For multirate schemes, the strategy consists in splitting the domain in a smart way. Grid cells are gathered in different multirate groups that satisfy the local CFL stability conditions for a certain range of time steps. Standard Explicit Runge-Kutta (ERK) methods are applied, on independent partitions, with a local time step in such a way that the total computational efforts are drastically reduced. Finally, we ensure that these different time steps are globally synchronized in order to be consistent.

Whereas the multirate approach considerably attempts to reduce the computational costs of explicit time integration by adapting the characteristic time steps locally, the development of such methods is still challenging. Both, stability requirements and conservation properties should be satisfied. The major difficulty is intrinsically linked with the interface treatment between the different multirate partitions. In this context, we explore two approaches that should accommodate these transitions with adapted methods. The first one, introduced by Constantinescu *et al.*, 2007, preserves the system invariants but is at most second order accurate. On the contrary, Schlegel *et al.*, 2009, proposed a method that is based on a right-hand side splitting and borrows some ideas of the implicit-explicit splitting scheme. Unfortunately this method turns out to be non-conservative. It is proved that a third order multirate scheme can be achieved with an appropriate base ERK method.

Applications like the GBR require the use of parallel computers. Some kind of load balancing strategy has to be supplied to accomodate multirate time stepping schemes: indeed, small elements have a higher coast than large elements in such a strategy. Moreover, small elements at inter-processor interfaces will require more frequent updates. The key idea consists in creating an optimized mesh partition in a way that the amount of grid cells of the different multirate groups is ideally the same on each computer core. In other words we require that each processor treats a partition where the grid cell's spectrum is equivalent. This problem can be posed as a graph partitioning problem with multiple objectives.

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Recent Advances of An Integrated Modeling System for Coastal and Estuarine Environments

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This presentation describes the recent advances of an integrated modeling system for coastal and estuarine environments, CH3D-SSMS (Sheng et al. 2010), which is based on the boundary-fitted curvilinear grid hydrodynamic model CH3D (Sheng 1987, 1990) coupled to the SWAN model in the coastal region and basin-scale hydrodynamic model (HYCOM, NCOM, and ADCIRC, etc.) and wave model (WW3).

Recent advances of the modeling system include (1) combination of 3D baroclinic feature with flooding-drying capability; (2) enhancement of current-wave interaction with depth-dependent radiation stress; (3) incorporation of a vegetation canopy model; and (4) coupling of an oyster population model.

Results of the integrated modeling system obtained with the new model features will be highlighted during the presentation.

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An efficient method for the Incompressible Navier-Stokes Equations on Irregular Domains with no-slip boundary conditions, high order up to the boundary.

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Common efficient schemes for the incompressible Navier-Stokes equations, such as projection or fractional step methods, have limited temporal accuracy as a result of matrix splitting errors, or introduce errors near the domain boundaries, resulting in weakly convergent solutions. We recast the Navier-Stokes incompressibility constraint as a pressure Poisson equation with velocity dependent boundary conditions. Applying the remaining velocity boundary conditions to the momentum equation, we obtain a pair of equations, for the primary variables velocity and pressure, equivalent to the incompressible Navier-Stokes. Since in this recast system the pressure can be efficiently recovered from the velocity, this reformulation is ideal for numerical marching methods. The equations can be discretized using a variety of methods, in principle to any desired order of accuracy. In this work we illustrate the approach with a 2-D second order finite difference scheme on a Cartesian grid, and devise an algorithm to solve the equations on domains with curved (non-conforming) boundaries, including a case with a non-trivial topology (a circular obstruction inside the domain). This algorithm achieves second order accuracy in the L^∞ norm for both the velocity and the pressure. The scheme has a natural extension to 3-D.

IMUM-2010, MIT August 17-20, 2010

Scalability of Unstructured Grid Based Hurricane Storm Surge Model

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The simulation of hurricane storm surge is a powerful tool used to evaluate inundation risk, design of hurricane protection systems, analyze the physics of storms, and plan evacuations. However, realistic solutions require the use of high resolution computational grids that express complicated domain shapes, detailed topography, geographical features, bathymetry and flow structures. High resolution grids require significant memory and computational time. The rapid development of multi-CPU/core parallel architectures with fast networks has dramatically improved the potential for large scale simulations. In order to take advantage of these parallel computational platforms, it is critical that the computations be scalable. As we increase the number of cores, we must consider both the time of the computation and the time required for managing and processing the necessary output files.

We present the scalability of unstructured grid based ADCIRC when computing tides and storm surge using large high resolution grids. We measure parallel scalability on different resolution grids, and evaluate the costs of outputting the very large requisite result files. It was necessary to designate specialized writer cores which are dedicated to writing output. In order to handle the latency of the disk storage system, we implemented these writer cores in sequential batches which can simultaneously write different types of output files at various solution times.

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Simulation of Thermal Discharge into Coastal Flow: An Example of CFD and GFD Hybrid Approach to Resolve Small-Scales

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In the few past decades, a number of geophysical fluid dynamics (GFD) models have been developed for coastal ocean flows, such as POM, ROMS, FVCOM, and ADCIRC. These models are basically designed for large-scale layer flows such as estuary circulations, and they have been greatly successful in many practical problems. In general, however, coastal ocean flows are multi-physics processes spanning a vast range of spatial and temporal scales and, in correspondence to many emerging issues such as the catastrophic Mexico Gulf oil leakage and harmful algae blooming in many waters, there is an urgent need to develop capability to simulate small-scale and really 3D phenomena. We propose a computational fluid dynamics (CFD) and GFD hybrid approach to predict small-scale problems in coastal flow settings (Wu and Tang, 2010). The former is used to capture local flow motions, and the latter is employed to compute the large-scale background currents. The hybrid approach is realized by two-way coupling of CFD and GFD models and domain decomposition method (zonal method) with Chimera overset grids (Tang *et al.*, 2003; Tang *et al.*, 2008). In this presentation, this approach couples FVCOM (Chen et al., 2003) and a CFD model and is applied to a seabed multiport thermal discharge, with full resolution of real configuration of the ports with 10 cm in diameters and the effluent plumes, into estuary with sizes in hundreds of kilometers. The results clearly illustrate the feasibility and potential of the proposed approach in prediction of multi-scale coastal ocean flows. Difficulty and unresolved issues will be discussed also (Tang and Zhou, 1999; Tang, 2006).

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High Order Discontinuous Galerkin schemes for coupled physical-biogeochemical ocean modelling

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Accurate modeling of biogeochemical ocean dynamics is essential for numerous applications, including coastal ecosystem science, environmental management and energy, and climate dynamics. Providing computational requirements for such often highly nonlinear and multiscale dynamics is critical. We complete comprehensive numerical analyses, comparing low to high order discretization schemes both in time and space, employing standard and Hybrid discontinuous Galerkin Finite element methods. We examine the effects of: using straight versus new curved elements; quadrature-based or quadrature-free source term discretization; and mesh resolution. We quantify the smoothness of the solution by the decay rate of coefficients of a modal orthogonal polynomial basis, and show that the high-order scheme performs best in smooth solution regions. We also investigate slope limiting and filtering approaches to improve the performance of the high-order schemes in non-smooth regions. Finally, we outline our current efforts towards a high-order three-dimensional, free-surface, non-hydrostatic coastal ocean simulation code.

High-resolution simulations of stratified flow and separation over an abrupt sill in a shallow estuary

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Simulating the local flow field produced by an abrupt bathymetric feature or obstacle in an estuary is crucial to understanding the potential for erosion and deposition of sediments. While simulations are relatively straightforward to perform for small domains with idealized geometry and uniform ambient flows, they are much more difficult in realistic estuarine settings with complex bathymetry and strong tidal forcing. In this work, a high-resolution numerical model is developed to study the flow field around an abrupt sill in the Snohomish River estuary, WA, where energetic eddies are observed on the free surface in the wake of the sill. Because the flow and salinity fields are highly variable in time and space and wetting and drying occurs on nearby intertidal mudflats, it is impossible to provide the boundary conditions needed to simulate the sill as a small isolated system. Therefore, in our model, we employ an unstructured grid with resolution varying from 300 m offshore to 1 m around the sill, and aim to incorporate both the estuarine dynamics at the scale of tens of kilometers and the flow features in the vicinity of the sill at the scale of several meters. The predicted tidal flow and salinity dynamics and the eddies around the sill are consistent with field observations. Based on the model predictions, we discuss how the sill interacts with the tidal flow and salinity field at different stages of a tidal cycle.

A Lagrangian vortex method for the barotropic vorticity equation on a rotating sphere

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We present a Lagrangian vortex method for the barotropic vorticity equation (BVE) on a rotating sphere. The solution of BVE involves solving a conservative transport equation for the vorticity fields and a Poisson equation for the stream function. The vortex method tracks the flow map and absolute vorticity using Lagrangian particles and panels. The velocity is computed from the Biot-Savart integral on the sphere. An adaptive refinement strategy is implemented to resolve small-scale features and a treecode is used for efficient computation. A fourth-order Runge-Kutta scheme is used for time integration.

We start our investigation with point vortex method and the first test case is the Rossby-Haurwitz wave, which is the exact solution for BVE. Convergence study shows that the method is fourth order in time and first order in space for a uniform panel discretization of the sphere. Then we switch to vortex blob method for stability consideration. We also tested the evolution of vortex patch(s), which means the vorticity field is highly nonuniform on the surface of the sphere. Adaptive refinement strategy improves the computational efficiency.

IMUM-2010, MIT August 17-20, 2010

Development and application of a Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System

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Understanding the processes responsible for coastal change is important for managing both our natural and economic coastal resources. The current scientific understanding of coastal processes suggests that examining coastal systems at sub-regional to regional scales can lead to significant insight into how the coastal zone evolves. In the coastal zone, storms are one of the primary driving forces resulting in coastal change. Here we utilize a numerical modeling approach to investigate the dynamics of coastal storm impacts.

We use a newly developed Coupled Ocean – Atmosphere – Wave – Sediment Transport (COAWST) Modeling System that is based on the Model Coupling Toolkit to exchange prognostic variables between the ocean model ROMS, atmosphere model WRF, wave model SWAN, and the Community Sediment Transport Modeling System (CSTMS) sediment routines. The models exchange fields of sea surface temperature, ocean currents, water levels, bathymetry, wave heights, lengths, periods, bottom orbital velocities, and atmosphere radiation fluxes, winds, atmospheric pressure, relative humidity, precipitation, and evaporation. Data fields are exchanged using regridded flux conservative sparse matrix interpolation with weights from SCRIP.

We describe the modeling components and the model field exchange methods. As part of the system, the wave and ocean models are run with cascading, refined, spatial grids to provide increased resolution at selected regions within a larger, coarser-scale coastal modeling system. The modeling system is applied to the U.S. East coast to simulate impact from Hurricane Isabel. Results identify that hurricane intensity is extremely sensitive to sea surface temperature. Intensity is reduced when coupled to the ocean model although the coupling provides a more realistic simulation of the sea surface

temperature. Coupling of the ocean to the atmosphere also results in decreased boundary layer stress and coupling of the waves to the atmosphere results in increased bottom stress. Wave results are sensitive to both ocean and atmospheric coupling due to wave-current interactions with the ocean and wave-growth from the atmosphere wind stress. Sediment resuspension at regional scale during the hurricane is controlled by shelf width and wave propagation during hurricane approach. Also presented will be some of the challenges faced to develop the modeling system.

Dependency of tsunami simulations on bathymetry, grid resolution and bottom friction

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After the devastating 2004 Sumatra-Andaman Tsunami the ocean modeling group at Alfred Wegener Institute started to build up a database of tsunami scenarios in the context of the GITEWS project (German Indonesian Tsunami Early Warning System). These scenarios cover the Sunda trench where most tsunamigenic earthquakes threatening Indonesia and surrounding countries occur. Scenarios serve as a forecast for tsunami early warning by estimating arrival times of the wave and maximum wave heights.

For modeling wave propagation and inundation, the unstructured mesh shallow water code TsunAWI was developed. TsunAWI is based on a finite element discretization. Unstructured meshes have the advantage that complex geometries such as the coastline can be accurately represented and a local refinement of the mesh in regions of interest can be easily carried out. The code comprises coastal inundation.

In this presentation we analyse the sensitivity of tsunami simulations with regard to bathymetric and topographic data, mesh resolution and bottom friction parameters. As a test case we investigate the 1993 Okushiri tsunami generated by a $M_w 7.8$ earthquake off the southwest coast of Hokkaido, Japan. This field benchmark serves for validating tsunami models (Synolakis et al., 2007). NOAA supplies detailed measurements of bathymetry and topography, tide gauges and run-up.

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Coupled Waves and Storm Surge during Hurricane Gustav

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Recent modeling of hurricane storm surge has coupled circulation and wave models so that they run on the same unstructured meshes and by the same computational processors. This method improves both the efficiency and accuracy of the computed solution. The coupled SWAN+ADCIRC model is well-positioned to generate waves and surge in deep water, propagate them onto the continental shelf, and dissipate them in complex nearshore systems and can do so operationally using very high resolution unstructured grids.

Gustav impacted southern Louisiana in 2008, during the same intense hurricane season as Ike. Gustav made landfall in south-central Louisiana, but its winds forced waves and surge against the levees and infrastructure near New Orleans. It is an excellent validation hurricane because of the wealth of measured time series for waves and surge, which show how the hurricane response evolved as it moved through the system. In particular, 15 nearshore and 7 inland wetland gauges captured the detailed dynamics in very complex regions. Validation results show that SWAN+ADCIRC simulates accurately the waves and storm surge during this hurricane event.

IMUM2010, MIT August 17-20, 2010

SELFE Cross-Scale Modeling System: new developments and applications

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SELFE is an open-source community-supported modeling system, based on unstructured grids, designed for the effective simulation of 3D baroclinic flows across river-to-ocean scales. It uses a semi-implicit finite-element Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations (in either hydrostatic or non-hydrostatic form), written in MPI FORTRAN90 to realistically address a wide range of physical processes and of atmospheric, ocean and river forcings. The combination of unstructured triangular grids, implicit time stepping and an Eulerian-Lagrangian Method in SELFE leads to flexibility, accuracy, efficiency and robustness.

Here we present new developments of the SELFE modeling system in the areas of tsunamis, internal waves, global circulation, wave-current interaction, and oil spill. Many of these new modules that are fully coupled into SELFE are developed by the user community. Some application cases will be presented to showcase the impressive quantitative skills and cross-scale nature of the SELFE modeling system, from minutes to decade, and from meters to hundreds of kilometers.

NOAA's Coastal Ocean Operational Forecast Systems

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The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) has selected two core ocean models for development of NOS Operational Forecast Systems (OFS). One is the ROMS developed by Rutgers University for curvilinear structured model grid choice, and the other is the Finite Volume Coastal Ocean Model (FVCOM) developed at the University of Massachusetts, Dartmouth (UMASSD) for unstructured model grid choice. All NOS OFSs are implemented and operated within an NOS standardized functional framework called the Coastal Ocean Modeling Framework (COMF), and will be run on NOAA's operational High Performance Computing (HPC) System. COMF is a set of standards and tools for developing and maintaining NOS's hydrodynamic model–based operational forecast systems. The goal of COMF is to provide a standard and comprehensive software infrastructure to enhance ease of use, performance, portability, and interoperability of NOS's OFS. COMF will increase time-and-cost efficiency for OFS development, transition, operations and maintenance, while enabling the community-sharing of validated improvements and minimizing redundant parallel efforts.

Three new ROMS based NOS OFSs are being developed for the Chesapeake Bay (CBOFS), Delaware Bay (DBOFS), and Tampa Bay (TBOFS), and FVCOM based OFS is being developed for the Northern Shelf of Golf of Mexico (nGOM). These OFS have been developed to provide maritime community users with real-time operational products which include nowcasts and short-term forecast guidance of water levels, currents, water temperature, and salinity for the next 1 to 2 days. These parameters are fundamental physical variables for other applications such as emergency response (e.g. oil spills; search and rescue) and ecological forecasting.

HSS Preconditioner for Incompressible Navier-Stokes Equation on Multiscale Unstructured Mesh

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August 2010

Abstract

In this paper, we firstly generate the multiscale unstructured mesh by the mesh generator, then we discretize incompressible Navier-Stokes equation (NSE) by finite element method and linearize it by Newton/Picard iteration, and we obtain the linear system from incompressible NSE with the saddle point structure. Since the linear system is a large sparse matrix with full rank, we solve the system by GMRES. To further accelerate the solution speed, we apply Hermitian/Skew-Hermitian Separation (HSS), a newly developed preconditioner, to the solver GMRES, and finally we provide two-dimensional numerical examples. Computational results show that, the mesh generator will produce multiscale mesh for complex geometries, and HSS can significantly increase the solution speed of incompressible NSE.

Key words: Incompressible Navier-Stokes equation, multiscale mesh, GMRES, preconditioner, HSS

Super-parameterization in Ocean Modelling using general multiscale techniques - a deep-convection case study.

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Multiscale approaches allow explicit modeling of the many different phenomena that are present in real ocean dynamics. We present results from a novel, multiscale, approach to the parameterization of non-hydrostatic deep-convection in coarse, hydrostatic, ocean simulations. In our approach, a two-dimensional (vertical slice), nonhydrostatic, prognostic, process model is embedded in each grid cell of a large-scale, three-dimensional, hydrostatic model. Consistency of the time evolving property budgets in the embedded and large-scale models is achieved by ensuring that domain extents of the embedded model are coincident with cell boundaries in the large-scale model mesh. Double accounting of forcing and internal dynamics for the overset models is avoided by detailed analysis of the terms solved in each part of the system.

We measure the impact of this approach, in terms of both improved numerical accuracy and computational cost, by comparing quantitative metrics with respect to, on the one hand, a fully resolved, three-dimensional, non-hydrostatic ground-truth simulation and on the other hand a purely hydrostatic, coarse-resolution numerical experiment. The time evolving state and statistics of the multiscale system are found to be significantly closer to the ground-truth model solution. For example, in the embedded simulation, the slanting of convective plumes due to large scale flow vertical shear is reproduced and higher order statistics, such as the variance and skewness of the model fields, are all much closer to the ground-truth model solution.

The improved accuracy of the multi-scale model is achieved for a computational cost far less than that of a fully resolved non-hydrostatic model. By exploiting parallelism amongst the embedded models, we can achieve a wall-clock time to solution that is a small multiple of a pure hydrostatic simulation.

The approach we have taken is by no means limited to deep-convection parameterization and can be generalized fairly broadly. For example mixed-layer processes, biogeochemical processes, eddy flux coefficients could all be estimated

by appropriate local, prognostic sub-models that are then coupled to a larger scale model, provided the factors and analysis we described are appropriately considered.

An Advanced Mesh Generator for Hydrodynamic Models

(poster presentation)

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The purpose of this research is the development and implementation of an advanced automatic mesh generator for hydrodynamic models. Starting with only a target element size and points defining the boundary and bathymetry/topography of the domain, the goal of the mesh generator is to automatically produce a high-quality mesh from this minimal set of input. From the geometry provided, properties such as local features, curvature of the boundary, bathymetric/topographic gradients, and approximate flow characteristics can be extracted, which are used to determine local element sizes. The result is a high quality mesh, with the correct amount of refinement where it is needed to resolve all of the geometry and flow characteristics of the domain. Techniques incorporated include the use of the so-called signed distance function, which is used to determine critical geometric properties, the approximation of piecewise linear coastline data by smooth periodic cubic splines, a so-called mesh function used to determine element sizes and control the size ratio of neighboring elements, and a force-displacement method which iterates to improve the element quality of the mesh. Meshes of coastal domains created by the new mesh generator will be compared to meshes of the same domain developed using existing mesh generation techniques. Figures of the meshes, along with element quality measures for the different mesh generation methods, will also be presented.

LARGE EDDY SIMULATION of a LEAN DIRECT INJECTION COMBUSTOR

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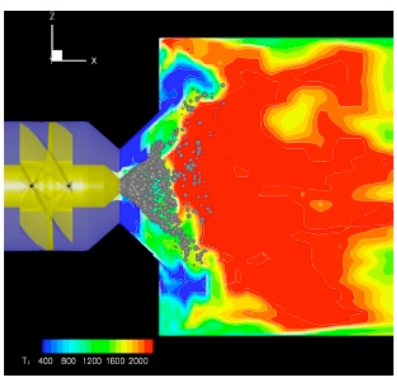
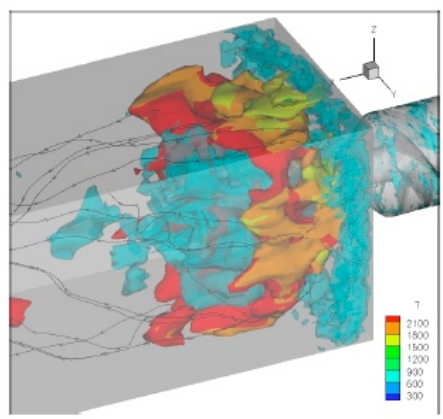
Designing commercially viable propulsion systems for supersonic aircraft is a major challenge. All modern combustors must balance the need for stability and performance with the goals of efficiency and cleanliness. These competing demands, however, are exacerbated in supersonic situations where the operating conditions are much more severe. Supersonic transport aircraft usually fly in the stratosphere, at cruising altitudes around 60,000 - 65,000 ft. Engine emissions produced at such high altitude contribute to depleting the ozone layer. Therefore, special combustor design considerations are needed to account for more stringent environmental and safety demands. The Lean Direct Injection (LDI) configuration is a good candidate for supersonic civil transport aircraft, where a combined geometry of a swirler and a venturi supposedly results in ultra low NOx and soot emissions. The combination of the swirl and the venturi has proven to maximize the liquid fuel atomization performance, and minimize pressure drop across the injector. In addition, it provides sufficient residence time for mixing of the fuel droplets with the swirling air to form a lean mixture. The swirler produces a central recirculation zone, which provides the required flame stability.

The current work studies the LDI configuration. Numerical simulations are done using the unstructured mesh, node-based CDP code with the flamelet/progress variable model for combustion closure. The main LDI flow features are shown and compared with experiments for the reactive and the nonreactive flow simulations. The effect of air preheating on the secondary droplet breakup is studied by investigating the spray histogram, the Sauter mean diameter, and the spray pattern. By comparison of the non-reactive and reactive test cases, the recirculation zone structure is found to change significantly by the effect of heat release. The effect of preheating is to change the thermal profile distribution, the rate of breakup, and finally the spray evaporation rate. All these factors control the flame structure and consequently the performance of the LDI combustor.





Discontinuous Galerkin Methods for the Shallow Water Equations Using Mixed Meshes

(poster presentation)

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Discontinuous Galerkin (DG) methods for the shallow water equations using mixed meshes that consist of triangular and quadrilateral elements in two-dimensions and triangular prisms and hexahedra in three-dimensions are developed, implemented, and tested. The main motivation behind this work is to gain more insight on whether the use of quadrilateral/hexahedral elements improves the efficiency of DG methods in a setting in which two (adjacent) triangular/triangular prism elements are merged to form a single quadrilateral/hexahedral element. The elements that are used in this study are constructed from a set of orthogonal, modal basis functions formed from products of Legendre and Jacobi polynomials. Given the fact that DG methods do not require continuity of the approximate solution between elements, quadrilateral and hexahedral element basis functions may be developed that exclude the usual cross-terms that are present in standard C^0 elements, e.g., a linear quadrilateral element may be used instead of a bilinear quadrilateral element. The performance of the developed DG methods on triangular/triangular prism meshes, quadrilateral/hexahedral meshes, and mixed element meshes of arbitrary polynomial order p is evaluated in terms of accuracy and computational time on a set of analytic test cases for the linear shallow water equations. The numerical results provide evidence that there may be a substantial benefit in using quadrilateral/hexahedral elements, especially for cases where p is low to moderate (up to $p = 5$ to 6).

IMUM-2010, MIT August 17-20, 2010

The response of northern Gulf of Mexico estuary plume, water exchange to wind forcing: A model-guided mechanism study to Perdido Bay

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Abstract

In this study, the Environmental Fluid Dynamic Code (EFDC) is used to simulate the salinity plume distribution at the mouth of the Perdido Bay Estuary (PBE), a typical shallow bay in the northern Gulf of Mexico. To better understand the plume structure in the PBE, and in other similar bay systems in the future, ideal sensitivity experiments were conducted to examine the sensitivity of the plume structure to various horizontal and vertical grid resolutions, and an advection scheme was developed to compare the differences in the surface plume structure. An existing calibrated EFDC Perdido Bay model has been demonstrated and calibrated in detail elsewhere [Xia, 2010], which includes variable wind, river flow, and realistic boundary conditions from five major tidal constituents. With the help of model sensitivity experiments, the effect of wind stress on the plume simulation was tested to investigate the 3-D plume PBE structure. The results were then applied to realistic simulations. The ramifications to previous studies of idealized plume models is also discussed. Wind direction dominates plume orientation, while wind speed significantly influences the plume size and vertical depth. Salt flux is a key for the 3-D plume structure. Under the wind forcing condition, water exchange and salt flux were analyzed to see how the wind forcing interacted with the bay-ocean. It was obvious that an unforced northerly wind favored the salt flux into the bay, while a south wind with a high wind speed resulted in less salt in the bay. Thus, a significant surface plume consists with salt flux into the bay system; since the surface favors the water outflow to the bay while the bottom estuarine circulation should increase the salt flow into the bay. Additional particle transport analysis was conducted with a variable wind forcing to determine the influence of the plume on particle distribution. Results showed a consistency between the surface plume and particle transport.

International workshop on Multiscale (Un)-structured mesh numerical ocean Modeling
Cambridge, MA, 17-20 August 2010

Pushing the Limits of Coastal Ocean Modeling: from Estuarine and Coastal Waters to Upstream River Floodplains

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Economic development, agriculture land use, and human activities in the coastal zone have altered the infrastructures and ecosystems in the coastal region and upstream river floodplain. Many restoration actions are currently being proposed or undertaken to improve habitats in the estuarine and river floodplain as well as the connectivity between the two regions. Traditionally, hydraulic analysis in floodplains is conducted with the assumption that the effect of tidal influences from the downstream boundary is small, using one-dimensional models. While this approach may be sufficient for engineering design for peak flood protection, it is inadequate when flood waters flow across the floodplain in a complex manner. Another limitation of 1-D model is the lack of details information on horizontal distributions of inundated water depths and current magnitudes in the floodplain, which are important to juvenile salmon downstream migration. Similarly, typical estuarine hydrodynamic modeling studies do not consider the effect of floodplains at the upstream end of the river due to the technical challenge of wetting and drying process in the large floodplains. High river slope also presents a stability challege. While various multi-scale model frameworks have been proposed for modeling the coastal oceans, estuaries, and rivers with a combination of 1-D, 2-D and 3-D models, this paper presents an approach for simulating the hydrodynamics in the estuary and river floodplain with smooth transition between the two regimes using a single unstructured-grid coastal ocean model. This approached was applied to the Skagit River estuary and floodplain of Puget Sound in the northwest coast of North America. The model was validated with observed data for water level and velocities under normal and flood conditions. This study successfully demonstrated that an estuarine and coastal ocean model could be extended much further upstream to simulate the inundation processes in the river floodplain and the dynamic interaction between the estuary and floodplain regimes.

Key words: modeling, unstructured-grid, floodplain, estuarine circulation

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