Adaptive Unstructured Grid Generation for Modeling of Coastal Margins

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LONG-TERM GOALS

This project is part of our effort to make unstructured-grid models, whether based on finite element or finite volume methods, a viable alternative to structured-grid models for scientific and operational simulation and prediction in coastal regions.

OBJECTIVES

Our goal is to advance the quality and efficiency of coastal modeling by minimizing conceptual and practical limitations associated with the generation and evaluation of 2D and (2+1)D unstructured grids. We seek fast and user-independent procedures to produce optimal grids, defined as grids that, within prescribed tolerance, lead to robust solutions, minimize global errors, equidistribute local errors, and minimize computational costs. Specific objectives include:

Objective 1: To develop adaptive grid optimization strategies for large 2D coastal simulations. An optimal grid is defined as one that, for a given problem and accuracy constraint, and within prescribed tolerances, equally distributes errors in space and results uniquely from the adaptive process regardless of the initial grid. We seek understanding, as often as possible in the form of quantitative criteria, of conceptual and practical issues that are critical to the generation of "optimal grids".

Objective 2: To develop local vertical refinement strategies for 2+1D grids. Regardless of what they do in the horizontal, the vast majority of coastal models look at the vertical dimension in the perspective of structured grids: either z- or sigma-layers inconveniently extend across the entire domain, causing significant computational inefficiencies. Extension to the vertical dimension of unstructured grid concepts is potentially a major cost saving in cross-scale coastal modeling applications. We seek to investigate novel formalisms to enable and guide distinct vertical refinement (in number and distribution of vertical nodes) at each horizontal node of coastal grids.

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Objective 3: *To foster, through pilot products and demonstrations, a new cycle of development of software for evaluation and adaptive generation of coastal grids.* We seek specifically to incorporate in coastal grid generation software the expectation of uniqueness and of equidistribution of errors that are becoming common in other areas of computational fluid dynamics. Two types of products will be developed and demonstrated: one, model-independent, enabling off-line grid generation and evaluation with visual user control; and the other embedding the grid generation and evaluation procedures in a specific circulation model.

APPROACH

We envision the process of unstructured grid generation as an iterative loop, which relies within each iteration on global or local maps of error estimators to define/adjust the density of build points in space. Once the location of the build points is defined, commonly available triangulation techniques that account for boundary information are applied to define nodal connectivity. Our primary challenge here will be to develop process-based strategies to optimally place build points, based on appropriate error norms. Efficient triangulation techniques are available.

In the 0^{th} iteration, either surrogate "error" maps are derived from dimensionless numbers known to control the accuracy of the solution, or an arbitrary grid is adopted to start the process. Choices at this level should not impact the final grid, but may impact how fast you get to that grid. Beyond the 0^{th} iteration, maps of error estimators will be obtained from instantaneous or (more likely) time-aggregated model results. To estimate the errors, models may be run for smaller periods than the target period of simulation with the final grid. For instance, one tidal cycle simulations may produce error estimators to guide the generation of a grid for a full spring-neap tidal cycle or longer.

Whether the user wants to retain visual control of the final grid (and/or intermediate steps) should be a matter of choice, and may depend on factors that include familiarity with the simulation model, the grid generation software, and the application. Enabling the user to make such a choice is important and will require the development of two related software packages. One is an interactive grid generator with a graphical interface, and the other is a non-interactive module to be integrated into specific target models. In both cases, the interactions between model and grid generator will be minimized, perhaps to the point where only grids and primary variables (e.g., levels, velocities, and concentrations) are exchanged. A key requirement for our software development is to maximize the ability to support or integrate multiple models and to port well to diverse testbed applications.

Most of the attention in coastal grid generation is, justifiably, placed on the horizontal component of the grids. The vast majority of coastal models uses 2+1D domain splits, consistent with the shallow water approximations. The models then look at the vertical discretization in the perspective of structured 1D grids: either z- or sigma-layers inconveniently extend across the entire domain, causing significant computational inefficiencies. Extension to the vertical dimension of unstructured grid concepts has been recently explored theoretically (Fortunato and Baptista 1996) and applied to the 2+1D simulations of the barotropic circulation in the Tagus estuary (Fortunato et al. 1997).

The approach, denoted localized sigma coordinates, allows the number of nodes per vertical to vary horizontally. It further provides criteria to decide on the relative density of nodes among verticals and to place the assigned nodes within each vertical. Criteria are derived empirically, with guidance from process-based dimensionless analysis. Application to the Tagus does not appear to have produced new pathologies relative to a conventional sigma-coordinate discretization, and reduced maximum errors by a factor of two within similar computational effort. We propose to extend this approach for baroclinic circulation, and analyze its benefits in the context of diverse testbed applications.

WORK COMPLETED

A web site was developed for the interactive grid generation software ACE/gredit. The site enables the download of the software (source and binaries for selected operating systems, currently IRIX 6.2 and 6.4, SUN Solaris 2.5.1, and DEC Alpha OSF/4.0), provides documentation, and supports a mail list.

In the context of the first objective of the project (grid optimization strategies for large 2D coastal simulations), and in particular of identification of error measures for grid generation, we completed the following steps:

- analysis of local mass conservation errors in finite element, unstructured-grids, tidal circulation models, inclusive of implications of non-conservative flow fields on mass conservation in Eulerian-Lagrangian transport calculations (Oliveira et al. 1999).
- analysis of the sensitivity of the local propagation of free waves relative to grid refinement, and of the role of energy conservation as an error norm (Myers and Baptista 1999).

A three-dimensional, baroclinic circulation model was developed and tested. The model, temporarily denoted ELCIRC (Eulerian-Lagrangian CIRCulation), re-uses code from ADCIRC (Luettich et al. 1991 and Luettich and Westerink 1995). However, rather than using ADCIRC's continuity-equation Eulerian finite element method, ELCIRC is based on the Eulerian-Lagrangian finite volume method for unstructured grids proposed by Casulli and Zanolli 1998. While not initially foreseen, the need for development of ELCIRC in the context of this project became apparent after Casulli and collaborators made a strong case for the potential advantages of Eulerian-Lagrangian finite volume methods in coastal applications, including dramatic improvements in performance and enforced local mass conservation. Modules for calculation of error norms were also developed for ADCIRC and ELCIRC.

RESULTS

For the circulation problems and complex grids being targeted by this research, there appears to be no unique local error norm that optimally caracterizes the accuracy dependency of a simulation on grid refinement. However, for finite element models based on either primitive or continuity-wave equation formulations, several local error norms provide valuable and generally self-consistent guidance that can be converted into criteria for grid optimization. The variance among local error norms is strong enough to recommend overarching control of the grid quality through domain-wide error measures.

One of the norms that we consider most informative is local mass conservation. While finite element methods are typically written to ensure global mass conservation, they can not enforce local mass conservation, which is achieved only in the limit of adequate resolution. In an extensive analysis of mass conservation in tidal circulation and transport models, we found (Oliveira et al., 1999) that:

- Important local flow mass errors are present in simulations of circulation at typical grid resolutions, for both wave-equation and primitive-equation formulations. Spatial patterns are distinctive, with local errors occuring primarily in areas of sharp geometric changes, such as bathymetric gradients and boundary complexity. Errors appear unrelated to non-linearities. We hypothesize that strong velocity and elevation gradients lead to large truncation errors, which in turn are responsible for the local mass errors. *Implications for grid generation*: local flow mass errors properly identify areas in need of grid refinement.

- Even if domain-wide continuity is respected, local mass imbalances in flow models lead to significant local and global mass errors in Eulerian-Lagrangian transport simulations based on those flows. For the typical resolutions used in tidal simulations, the transport mass errors caused by the flow mass imbalances are dominant, and severe enough to question the usefulness of the transport simulations. *Implications for grid generation*: global transport mass errors (unlike global flow mass errors) may be used for overarching control of the quality of citculation grids.
- By refining the flow and transport grids, we reduce mass errors in flow and transport simulations. However, refining the flow grid alone accomplishes most of the error reduction for both types of simulation (at least for the high-accuracy ELM transport models used in the analysis), and at a much smaller cost. *Implications for grid generation*: optimal flow and transport grids will in general be different.

Energy conservation offers an interesting contrast to mass conservation as the basis for error norms. None of the shallow water equations specifically enforces energy conservation. Therefore, global energy is not preserved domain-wide, and is a natural (if somewhat cumbersome) overarching control for grid quality. Also, local measures of energy conservation are not simple to compute, and thus energy does not offer direct guidance for local refinment. We have recently shown that global energy conservation is a very sensitive indicator of insufficient grid refinement in free wave simulations (Myers and Baptista, 1999b). The same analysis demonstrated that refinements typical of current practice may artificially loose more than half the energy of a tsunami, and are not sufficient to simulate local amplification effects.

Unstructured-grid Eulerian-Lagrangian finite volume models of circulation (e.g. Casulli and Zanolli 1998) have recently become a viable alternative to unstructured-grid finite element models. Because the underlying concepts and numerical performance are so distinct, it is unclear how well error norms such as elemental residuals, local error conservation and energy conservation will perform. In theory, some norms may not even be applicable. An example is local mass conservation, because such conservation is strictly enforced at the elemental level. The unavailability of a public-domain Eulerian-Lagrangian finite volume circulation model forced us to develop and test such a model (ELCIRC, Myers and Baptista, 1999a). Early analysis of performance of the model suggests that:

- The model can withstand Courant numbers one to two orders of magnitude above unity. *Implications for grid generation*: direct implications are primarily for time (not space) discretization; however, potential for drastic improvements in computational performance may reduce the pressure for fine optimization of the spatial refinement.
- Early analysis suggests that estimation of meaningful surrogates for local flow mass errors is feasible by mapping globally the elemental values of elevations and velocities (which loosely corresponds to changing the control volume for conservation calculation). *Implications for grid generation*: at stake are whether a whole new set of error norms is necessary, and, ultimately, whether finite element and finite volume grids will have fundamentally different optimal grids.

TRANSITIONS

Through Cheryl Ann Blain, structured transition of grid generation and modeling software to the Naval Research Laboratory (NRL) will occur in year 2 of the project. NRL projects provide testbeds for the grid generation software, and will rely on its capabilities for enhanced computational performance. A transition demonstration is currently being prepared based on an Arabian Gulf example.

Minimally structured transition to the scientific community at large will take place through the web. The web site for ACE/gredit (which enables, in particular, the download of source and binary code) has been released, and a similar ELCIRC site will be released in year 2 of the project. The intent is to enable both ACE/gredit and ELCIRC to grow as community resources. As an example of the use the ACE/gredit web site, C.C. Mei (Massachusetts Institute of Technology) and Masakazui Shibata (Japan) will be using and modifying ACE/gredit as a part of their joint research on nonlinear harbor resonance with hybrid element methods.

RELATED PROJECTS

Researchers from Laboratorio Nacional de Engenharia Civil (Anabela Oliveira and Andre Fortunato) and OGI (Antonio Baptista, Edward Myers and others) have for several years collaborated in the development of new modeling technology for coasts and estuaries. Results include the analysis of local mass errors discussed above (Oliveira et al. 1999), the OGI-granted PhDs of Oliveira and Fortunato, collaboration on the development and exchange of modeling and grid generation software, and several joint publications (http://www.ccalmr.ogi.edu/baptista/publications.html). This continuing collaboration will be extended through the project Environmental Enhancement and Protection of the Portuguese Coastal Zone, sponsored in the Portuguese side by FCT - Fundação para a Ciência e Tecnologia. The FCT project will, in particular, adopt and provide additional testbeds and technical feedback for our grid generation software.

The Columbia River estuary and plume have provided the initial motivation and the primary testbeds for our current grid generation research. Efforts supporting directly relevant Columbia River research include the following:

- A National Marine Fisheries Service (NMFS) led interdisciplinary team is investigating the ocean factors influencing salmon survival in the Columbia River system. As a part of the effort, the pilot observation and forecasting system CORIE (Baptista et al. 1999) is being extended by Antonio Baptista from an ONR-supported (N00014-96-1-0893) original emphasis on the estuary to a more balanced estuary-plume scope. This has included the installation and maintenance of an offshore station (to complement 12 estuarine stations), and the on-going development of a forecasting infrastructure for the plume. The research is supported by NOAA/NMFS and Bonneville Power administration. See http://www.ccalmr.ogi.edu/nmfs.
- A NMFS-led interdisciplinary team is developing a conceptual model to assess estuarine influence on recovery and resilience of salmon populations in the Columbia River. The research is supported by NOAA/NMFS and Bonneville Power administration. See http://www.ccalmr.ogi.edu/bpa.
- Since 1990, a University of Washington-led interdisciplinary team has been investigating the geochemical and ecological role of estuarine turbidity maxima (ETM) in the Columbia River estuary. The studies have principally utilized intensive research cruises (annually, 1990-1992 and 1995-1996; seasonally 1997-1999). CORIE observations and simulations have since 1996 provided temporal and spatial context for the analysis of cruise data, and have constituted the basis for supporting investigations on residence times and residual circulation in the Columbia River. The research is sponsored by NSF. See http://depts.washington.edu/cretmweb/CRETM.html.

A contrasting testbed (because related to *free*, rather than *forced* waves) has been provided by tsunami research at OGI and collaborating institutions. In collaboration with George Priest, of the Oregon Department of Geology and Mineral Industries (DOGAMI), Antonio Baptista and Edward Myers have developed models for predicting and mapping tsunami inundation of the Oregon and Washington coasts from Cascadia Subduction Zone and remote earthquakes. The research is sponsored by NOAA and DOGAMI. The analysis of energy conservation as an error norm (Myers and Baptista 1999), referred above, is an example of the inter-relation between the tsunami and grid-generation projects.

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